International Journal of Current Engineering and Technology
E-ISSN 2277 – 4106, P-ISSN 2347 – 5161

Available at http://inpressco.com/category/ijcet

Research Article

Single Lap Adhesive Joint (SLAJ): A Study

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Accepted 12 March 2017, Available online 16 March 2017, **Special Issue-7 (March 2017)**

Abstract

Adhesive bonding is widely used for sheet metal joining in automotive, marine, airplane, Space industries. Single lap joints are considered as a good category joint for sheet metals. The purpose of study was to find proper method of design, analysis and testing of single lap joint in various material and loading conditions. Here, study on single lap adhesive joint is to be done considering various factors which affect the loading capacity of single lap adhesive joint the structure of bonded parts is very important in order to obtained required strength different bonded areas can have different strength. And the strength of adhesive joint is also depends upon the surface roughness and its holding time. Study involve use of isotropic and orthotropic material as adherend same specimen size. Study gives some basis information about design of joint and FEA with using various analysis softwares to see the nature of changes in the joint. Validation of FE analysis will do using experimental testing of joint on Universal Testing Machine with study of surface roughness. Then possible results occurred due to different loading conditions are given for study. Adhesive joints compares with other fasteners taking its advantages and disadvantages in various applications.

***Keywords:** Adhesive Joints, Single Lap Joint, Design of Joint, FEA Software, Universal Testing Machine, Adhesive Joint Analysis*

1. Introduction

The adhesive bonding is used as a load-bearing joint in structural joining for various application areas as marine industry, aerospace, automobiles, trains and in civil constructions. Single lap adhesive joint offers many advantages such as time saving, cost saving, good damping characteristics, very high strength as compared to other conventional joining process. In this joint the load is smoothly transmitted from one plate to another plate via adhesive.

Structural adhesives are used in different types of joints. Commonly used adhesively bonded joints are shown in Fig 1 (Narasimhan 2005). Among these, single lap adhesive joint is widely used because of its simplicity. The adherend may be either metallic or fiber reinforced composite. Single lap joint is most common joint and various research are carried on it in order to analyze its strength and properties. In finite element the adherend can be orthotropic or isotropic. The adhesive material behaves elastically as well as plastically. Nonlinearity is based on large rotation small strain and large displacement. Nonlinear model is modeled as rigid body or semi-rigid body. The influence of various factors such as geometrical consideration and material nonlinearity on the deformation of adherend are studied by taking different material for adherend such as aluminium and fiber reinforced plastic with varying the adhesive thickness ratio. The data obtained from stress strain curve is compared with experimental solution and numerical results are compared with analytical result.

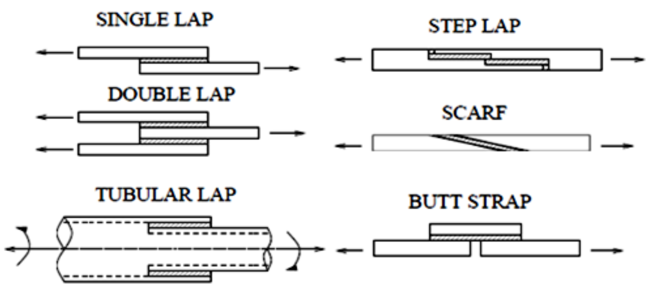

Fig.1 Types of Lap Joint

M.Lucic (M. Lucic, *et al*, 2006) gives frequently applied adhesive joint design in engineering practice. The analysis is focused on determination of an optimum overlap length. K. Mohamedbak (K. Mohamedbak, *et al*, 2012) from numerical and experimental results the maximum stress obtained at the edges of the joint by increasing the thickness of overlap adhesive there is reduction in stress strain distribution in the bonded area.

2 Single-lap Joint

The aim of this study is to understand the linear and nonlinear behaviour of single lap adhesives bonded

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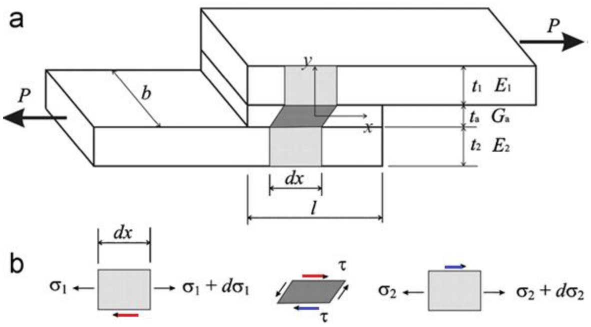
joints that are increasingly being used for bonding various structural components.it is important to study effect of material and geometric nonlinearities on joint deformation. Specific attention is devoted towards behaviour of bonded joints with similar and dissimilar adherends, joints with thick adhesive layers. It is envisaged here that nonlinear stress analyses could provide an enhanced understanding of the problem pertaining to selection of suitable types of adhesives and dimensioning of joints.



(a) Geometry (b) Elemental Diagram

Fig.2 Single-lap Joint Analysis

In adhesive joint analysis as shown in Fig.2 (Lucas F.M., *et al* 2009),the adhesive is going to fail only in shear. The shear stress value is equal to average shear stress on adhesive layer. The work is also done by volkersen and goland and reissner is very important in stress analysis of single lap adhesive joint. Nevertheless, their work had several limitations. (1)the adhesive stresses are not going to vary in thickness direction, but when failure occurs close to the interface then interface stresses are important.(2) The peak shear stress occurs at the ends of the bonded area, which violates the stress-free condition, as shown in Fig.3. Analyses that ignore the stress free condition overestimate the stress at the ends of the overlap and tend to give conservative failure load predictions. lastly, the adherends were considered as thin beam, which ignores the through-thickness shear deformation. Adherend shear is important in shear-soft adherends like composites.

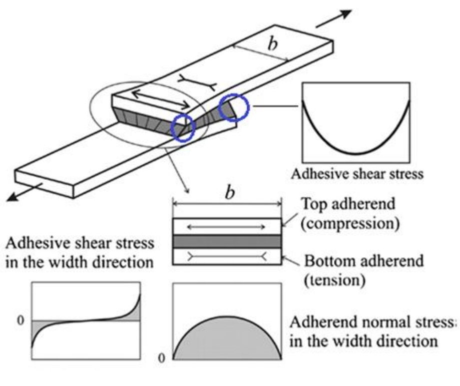


Fig.3 Stress Distribution in Single Lap Joint

3 Basic Design of Adhesive Joint

The following conditions should satisfy Design of a joint

- Allowable shear stress and tensile stress of adhesive should not exceeded
- 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),

- 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.
- 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.
- 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).
- 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.

2.1 Simplified Design Procedure

Chamis and Murthy presented the following simplified procedure for designing adhesively bonded joints (NPL Manual, 2007):

- Establish joint design requirements: adhesive, loads, safety factors, etc.
- Obtain the properties and laminate dimensions for the adherends.
- Obtain properties for the adhesive.
- Degrade adhesive properties for, temperature, moisture and cyclic loading.
- Select design allowables. These are either set by design criteria or are chosen as follows:
  - load factor on the force F (1.5 or 2)
  - safety factor of one-half of the degraded adhesive strength.
- Use this equation for the length calculation,

$$l = \frac{F}{S_{as}} \quad (1)$$

where F = load in adherends per unit width and S_{as} = allowable shear stress in the adhesive.

- using shear lag equations check minimum length and maximum shear and normal stresses in adhesive.
- use given equations for calculating the bending stresses in doublers and adherends.
- Calculate margin of safety (MOS) for all calculated stresses. This is usually done at each step where stresses are calculated and compared to allowables using:

$$MOS = \frac{Allowable\ Stress}{Calculated\ Stress} \quad (2)$$

- Calculate joint efficiency JE using:

$$JE = \frac{Joint\ Force\ Transfered}{Adherend\ Force\ Transfered} \times 100 \quad (3)$$

- Summarise joint design.

2.2 Design Data Requirements

In design and stress analysis of single lap adhesively bonded joints (NPL Manual, 2007), consideration should be given to the adherends (geometry and material properties) and adhesive, potential failure modes and actual, thermal properties, environmental conditions and magnitude nature of loading involved and. Basic property requirements for the design of single lap bonded structures are listed below, although not all of these properties necessarily be required for any given joint configuration. In-plane and through-thickness (elastic (i.e. moduli and Poisson's ratios) and strength (or yield stress) properties of the adherends (tension, compression and shear).

- Strength and Elastic properties of the adhesive (tension and shear)
- Maximum strain in the adherends and adhesive (tension, compression and shear)
- Adherend and adhesive non-linear elastic/elastic-plastic stress and strains
- Coefficients of thermal expansion of adherends and adhesive
- Mode I and mode II strain-energy release-rates (fracture mechanics based design)
- Thickness of adherends and adhesive layer, Length and width of bonded regions
- Safety factors

Cyclic fatigue, creep or high-rate (impact) data is required, which depends on the loading conditions. Fatigue or creep modelling of joint behavior would require S-N data or time-dependent properties in addition to the static material properties of the adhesive-adherend system

3 FEA Programs

Numerical analysis techniques, such as FEA, are widely used in the design and stress analysis of single lap adhesively bonded structures.FEA technique is a popular method which offers a solution to complex problem. A large number of FEA codes are available. These codes provide in-built constitutive models for simulating the behaviour of most adhesives, allowing for non-uniform stress-strain distributions, geometric non-linearity, hygrothermal effects, elastic-plastic and visco-elastic behaviour, static and dynamic analysis, and strain rate dependence. Orthotropic element types include two-dimensional (2-D) solid plane-stress or plain-strain elements, axisymmetric shell or solid elements, three-dimensional (3-D) solid or "brick" elements and crack-tip elements. A number of automatic mesh (element) generators are available with post-processing capabilities (e.g. ANSYS, PATRAN and FEMGV).

It is important that the designer/analyst is aware of the limitations of the numerical techniques being applied and has a fundamental understanding of the mechanics of bonded joints (i.e. stresses and failure mechanisms). Stress analyses (especially FE methods) are often used to compare stress/strain distributions obtained from different joint configurations (e.g. lap, scarf and butt joints) or geometries (varying adhesive and adherend thickness, overlap lengths, fillet shapes). Hence, finite element stress analysis can be used as a tool for optimising the design of a joint. Evolutionary optimisation method EVOLVE has been used to optimise the shape of adhesive fillets.

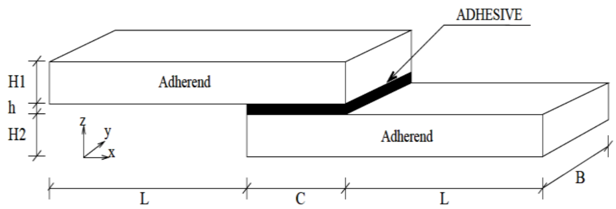


Fig.4 Geometry of the single lap joint

3.1 Material Properties

For analysis of isotropic and orthotropic materials various material mechanical properties required. Two sample material properties are given in Table1 (M. Lucic, *et al*, 2006),(Venkateswara Rao, *et al*,2008)

Table 1 Adhesive and Adherend Properties

Adhesive		Adherend	
For Isotropic Material	For Orthotropic Material	Isotropic Material	Orthotropic Material
Loctite 3241	Epoxy	Aluminum Al99.5	T300
E=1400 MPa; ν =0.35; σ_m=38 MPa	E = 2.8 GPa; ν = 0.4	E=70,000 MPa; ν =0.3; σ_m=115 MPa	E_L = 127.5 GPa; E_T = 9.0 GPa; E_Z = 4.8 GPa, ν_{LT} = ν_{LZ} = 0.28; ν_{TZ} = 0.41, G_{LT} = G_{LZ} = 4.8 GPa; G_{TZ} = 2.55 GPa

3.2 FEA Elements

The number of FEA elements are used for analysis of joint. The finite element mesh is generated using a three-dimensional brick element 'SOLID45' (As shown in Fig.5) (Venkateswara Rao, *et al*,2008) (ANSYS Guide, 2013),

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 directions.

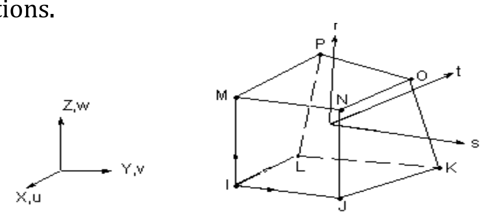


Fig.5 SOLID 45 Element

In the modeling of the isotropic material specimen an another one element used is PLANE82 (As shown in Fig.6) (M. V. Sulakhe,2008) (ANSYS Guide, 2013), which is a higher order version of the 2-D, four-node element (PLANE42). It gives more accurate results for mixed (quadrilateral-triangular) automatic meshes and can tolerate irregular shapes without as much loss of accuracy. The 8-node elements have compatible displacement shapes and are well suited to model curved boundaries. The 8-node element is defined by eight nodes having two degrees of freedom at each node: translations in the nodal x and y directions. The element has plasticity, creep, swelling, stress stiffening, large deflection, and large strain capabilities.

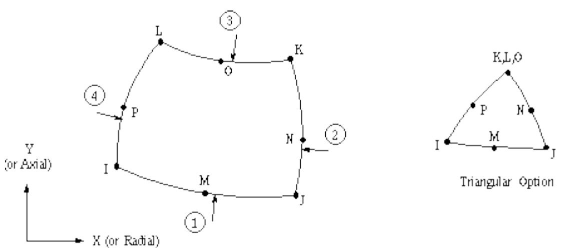


Fig. 6 PLANE82 Element

3.3 Boundary Conditions and Loading

Boundary conditions (BC) required for analysis of single lap joint various. Few are given as below. In the first case i.e. for longitudinal loading, one end of the joint is clamped and the other end is constrained to move in the transverse direction. In the second case (i.e. for transverse loading), the following end conditions are applied.

i. End of top adherend simply supported and end of bottom adherend clamped
ii. End of bottom adherend simply supported and end of top adherend clamped
iii. both the ends simply supported

The following types of loads are applied for validation and prediction of the response of the structure for the present analysis.

i. A uniform longitudinal displacement in mm for the validation purpose.
ii. A uniform transverse load in MPa for the present analysis.

Here in Fig.7 both loading and boundary conditions are given for one of above case for reference.

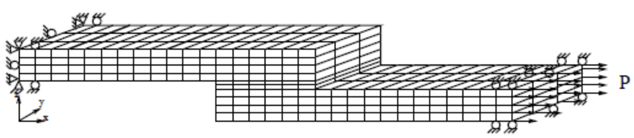


Fig. 7 BC with loading in Single Lap Joint

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.
- Unsupported single-lap joints should only be employed for thin metallic adherends.
- Peel stresses in fibre-reinforced plastic adherends are generally very severe, and therefore it is not advised to use this geometry for structural applications with these materials.

4 Testing

Before testing of adhesive joint, adherend surface roughness is checked by following method. The average surface roughness, *Ra* value, which was used for comparison purposes, is defined as follows

$$R_a = \frac{1}{L_m} \int_{x=0}^{x=L_m} |y| dx \tag{4}$$

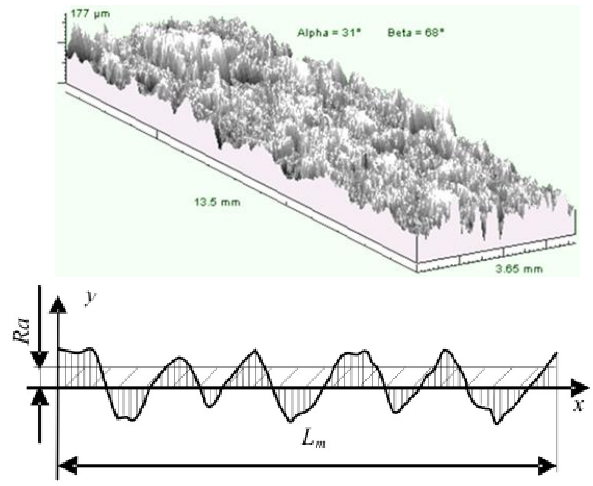


Fig. 8 Roughness on Adhered Surface at Contact

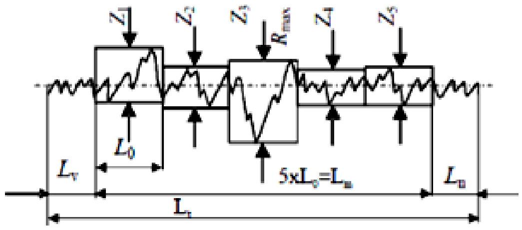


Fig.9 Calculation of Mean Roughness Depth R_z

where Lm is the scanned length in the x (horizontal) direction. The Taylor-Hobson perthometer also provides mean roughness depth, *Rz* values. The *Rz* value is the arithmetic mean from the peak-to-valley heights of five successive sampling lengths as shown in Fig. 8 and Fig. 9. (H.S. daCosta, *et al*, 2011), (M. Lucic, *et al*, 2006).

$$R_Z = \frac{1}{5}(Z_1 + Z_2 + Z_3 + Z_4 + Z_5) \quad (5)$$

First standard single lap specimens for evaluating the load bearing characteristics prepare. Then clean bond surfaces to free from grease and dust particles. Then Activator applies on both surfaces of one adhered plate and adhesive on an adhrend surface.

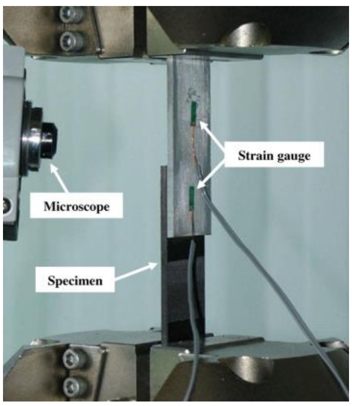


Fig. 10 Experimental Set-up for Testing

Then bonded plates clamped under the uniform fixture for bonding. Then adhesive joint specimens under goes testing on UTM. To record strain at time of loading strain gages are mounted on both plates as shown on Fig.10 (M. Lucic,2006), (Myeong-suseong, 2008) . Also microscope is used to see crack imitation at bonding.

5. Failure

The different types of load act on adhesive joint which cause different types of failure as given below,

5.1 Loading Modes

A single lap adhesively bonded joint will simultaneously experiences several loading components. The main loading modes of bonded joints (As shown in in Fig.11) are:

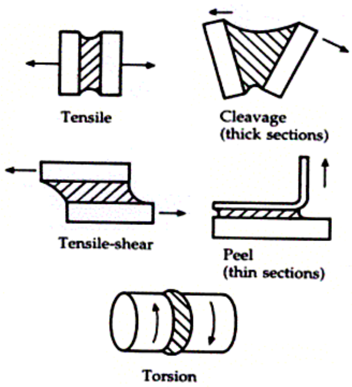


Fig.11 Basic Loading Modes in Adhesive Joints

- Peel loads is produced out-of-plane loads which acts on thin adherends.
- Shear stresses are produced due to tensile, torsional or pure shear loads which acts on adherends.
- Tensile stresses also produced by out-of-plane tensile loads.
- Cleavage loads produced by out-of-plane tensile loads acting on stiff and thick adherends at the ends of the joints.

5.2 Failure Modes

Our aim is to design a joint to fail by bulk failure of the adherends. A margin of safety is generally incorporated in the design to account for factors, such as service environment, degree of control, type of loading in adhesive application, etc. It is important to ensure that the adhesive is not the weakest link. The different failure modes of adhesive are as shown in Fig.12 (Tae-Hwan Kim, *et al*, 2008) like delamination, failure at corner region and interface.

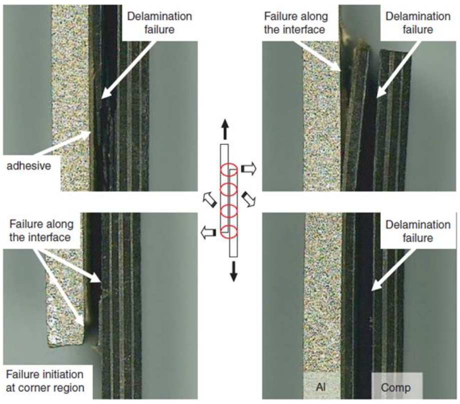


Fig.12 Failure Modes in Adhesive Joints

6. Advantages and Disadvantages

The adhesive bonding is used as a load-bearing joint in structural joining for various application areas as marine industry, aerospace, automobiles, trains and in civil constructions. One application is shown in Fig. 13 (K. Mohamedbak, *et al*, 2012).

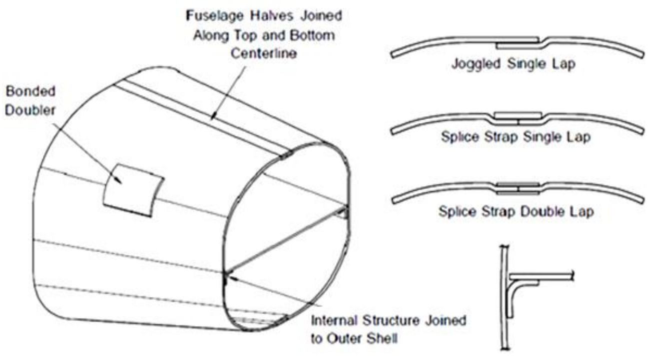


Fig.13 Bonded Joints used in Aircraft Structure

In earlier days, for fastening bolted and welded joints are used in above applications. Thus adhesives joints advantages and disadvantages in connections compare with other fastening techniques like bolts and welding connections are given as below,

6.1 Advantages

- No damage to parent material and no damage to exposed surfaces Fewer pieces required to form connections
- Smaller additional pieces required e.g. gusset plates, required to form connection
- High uniform strength and effective stiffness of joint and improved fatigue performance, because of reduction in stress concentrations
- Dissimilar materials can be joined readily, elimination of bimetallic corrosion,
- Faster fabrication, Good noise and vibration damping, efficient method of joining thin materials.

6.2 Disadvantages

- Require skilled labour to operate softwares.
- Proper cleaning of surface is required to obtain high strength of joint.
- Curing of joint is very difficult task because it requires continuous supervision.
- Safety and Possible Health implications
- Complete connection is not achieved
- Connection cannot be disassembled
- temperature and humidity affects adhesive properties. Creep effects may be significant, particularly at elevated temperatures

7 Results

Two-dimensional analysis gives evaluation of normal, sheer and peel stress along ovelap length and adhesive thickness in joint. Few results from literature are given in Fig. 14.

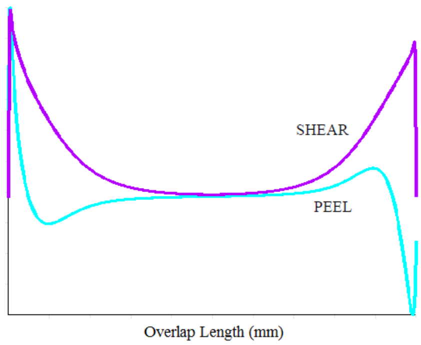


Fig.14 2D Peel and Shear stresses along the overlap length for lap joint along the middle adhesive layer

Three-dimensional analysis gives evaluation of the inter-laminar stresses at the interfaces of the adherends and adhesive, and the out-of plane stresses at the middle surface of single lap joint made of FRP laminates of generally orthotropic nature subjected to transverse loads with different end conditions. Few results from literature are given in Fig. 15 (Narasimhan, 2005).

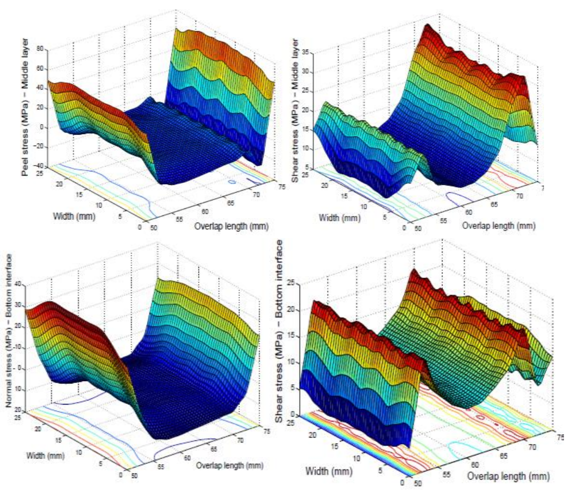


Fig.15 3D Normal and Shear Stress Distributions at Top and Bottom Adhesive layer for the joint

Discussion

This study presented single lap adhesively bonded joint configurations that are employed in various applications. The main outcomes of this study is to understand joining of two plate using adhesive joint and see failure analysis using FEA and experimental testing. For parametric study on Metal-Composite single lap joint, the analyses gives that if the same adhesive thickness is maintained for composite adherend, sooner the joint attains plasticity. This has highlighted the need for compromise when it comes to dimensioning of size/type of adherends and adhesive thickness for use in practical purposes. Anticlastic effect resulting in reduction of peel stresses at 3D corner for a dissimilar lap joint. From practical design considerations, this study has highlighted the importance of the selection of appropriate adherend type/thickness when dissimilar materials are bonded.

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.

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