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Variation of Adhesive Strength in Single Lap Joint (SLJ) with Surface Irregularities

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Abstract - Single Lap Joints are used extensively in the aerospace industry due to their lower weight and absence of stress concentration due to drilling of holes. However, their lesser strength remains an important limitation. Different modes of failures have been reviewed here. The bond strength of a Single Lap Joint can be varied by varying its overlap length, however, the strength does not strictly increase with increasing bonding length. Rather, it increases up to an optimum value and decreases further. This optimum value has been obtained, and is found to be in agreement with previous studies in this regard. The surfaces of the bonded aluminum plates have been modified by generation of patterns. A notch shaped pattern has been used for the present study and its included angle has been varied for obtaining an optimum value. Here also, the strength increases up to 75° and then decreases with further increase in included angle. Graphs depicting the same have been plotted. Such a Single Lap Joint has been simulated using an FEA Package (ANSYS). The FEA procedure has been reviewed in this article along with the elements used for the purpose.

Keywords: Single- lap joint, Adhesive, Surface irregularities, Epoxy resin, Aluminum, Bond strength,

1. Introduction

If the load is not very large adhesive joints become very useful in joining metallic or non–metallic dissimilar materials. No special device is needed. But the disadvantage of this joint is that the joint gets weakened by moisture or heat and some adhesive needs meticulous surface preparation. In an adhesive joint, adhesive are applied between two plates known as adherend. The strength of the bond between the adhesive and adherend arise become of various reasons given below. Adhesive bonding of metal-to-metal accounts for less than 2% of the total metal joining applications [1]. Industries involved with aircraft and automobile construction are the major users of adhesive bonding of metals. Adhesive bonded assemblies may comprise over 50 percent of the total area of a modern airplane [2].Many structures are manufactured as single parts, and then connected through joints. The commonly used methods for joining composite parts are either through mechanical fastening or bonding. Mechanical fasteners including bolts, rivets, and pins have been commonly used for several decades. The key problem with these is that high stress concentrations can develop around the fastener holes, and the joint can be brought to failure at far lower stress levels than expected. Hence adhesive bonding is used due to its larger bond area to distribute loads and eliminate stress concentration as well as keeping structure integrity. It have other benefits that include improved stiffness, rigidity, impact behaviour and energy absorption, less vibration and sound deadening. Adhesives also resist the separation loads up to a particular point and avoid permanent damage to the material. Factors, including the geometry and the material properties of the adherends and the adhesive.

The commonly used adhesive joint configuration in load carrying structures is the single lap joint (SLJ). Despite its apparent simplicity, the stress and strain states and the failure mechanisms in SLJs are complex. The structured way of analyzing the stress and strain responses as well as the failure process of adhesive bonded composite joints are synthesized and reviewed based on the information and material properties obtained from experimental tests. Different failure modes associated with single lap joint are shown in Fig.1.

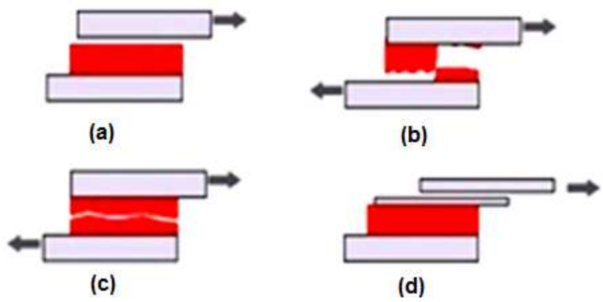

Fig.1 Adhesive Failure Modes(a) Adhesion Failure, (b) Adhesion/Cohesion Failure, (c) Cohesion Failure and (d) Substrate Failure

The failure load is found to increase with overlap length and adhesive thickness. Material properties and geometry size have been investigated to significantly affect the joint strength and failure modes. On account of the effect of factors mentioned above, A. Ghumatkar [1] focused on improving the strength of the joints. The joint strength increased by modifying the shape of the joint and adding chamfer and fillets. The quality of the bonded joints depends highly on the manufacturing process.A. Ghumatkar [1] studied the effects on bond strength after varying roughness using emery paper. Surface preparation is one of the important parameters which is directly related to the quality of the bonded joint. Lucas da Silva [3] found that the mechanical response and failure behavior of adhesive bonded joints are strongly dependent on the geometry and material properties of the constituents. A. B. Ghani[4] focused on adhesive failure modes. Failure in bonded joints can occur in three distinctly different modes, namely failure in the adhesive (cohesive failure), failure in the constituent adherends and failure in the interfaces between the adhesive and the adherend materials. Yasmina Boutar[5] presented surface treatment on the overlap region and curing conditions such as pressure and temperature. One parameter that influences the strength of the adhesive joint, and therefore can be altered to obtain maximum shear strength, is the surface geometry.

2. Methodology

2.1 Geometry

The surface of the Aluminum plates is modified by generating patterns on the surface. To check strength of joint, triangular notch pattern are taken on both adherend plate at contact with adhesive.The pattern on adherend plate is shown in Fig.2.

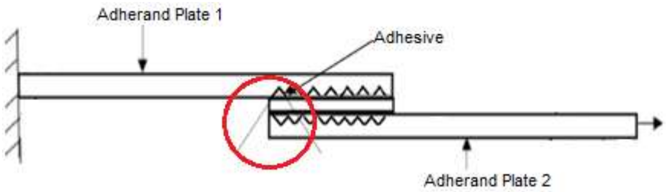

Fig.2 Single Lap Joint with Pattern

During pattern preparation some parameters are considered as inclination angle (Φ=75°) of triangular notch, depth of triangular notch (d=0.5 mm), plate thickness (t=6mm) and distance between two triangular notch (s=0.5 mm).

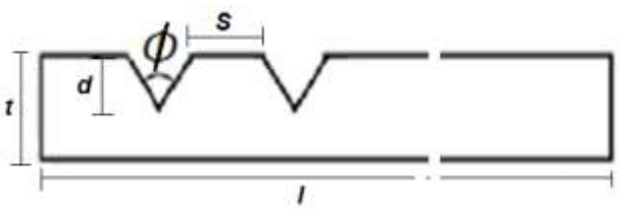

Fig. 3. Pattern with a Triangular Notch

2.2 Failure Analysis

For Failure Analysis, it is necessary to calculate area of overlap and the length of overlap which can be obtained from:

$$A_p = L_p \times (Width of bond) \qquad (1)$$

Further, the shear stress is related to shear force (V) as given below:

$$V = \tau \times A_p \qquad (2)$$

Hence, once the maximum shear force is experimentally evaluated, the shear strength can be calculated.Upon loading, the expected deformed shape is depicted below:

2.3 Theories of Failure

According to NPL Design Manual [8], the Maximum Principle Stress theory is used in adhesive joints, as it is the most successful theory for brittle materials. According to this theory,

$$\sigma_1 = \frac{\sigma_x - \sigma_y}{2} + \frac{1}{2}\sqrt{\left((\sigma_x - \sigma_y)^2 + 4\tau_{xy}^2\right)} \qquad (3)$$

Condition for failure is,

Max. Principle stress (σ_1) > failure stresses (S_{yt} or S_{ut}) and factor of safety (f_s) = 1.

If σ_1 is positive, then take S_{yt} or S_{ut}, else$\sigma_1$is negative, then S_{yc} or S_{uc}. Accurate criteria for polymeric adhesives may also be considered as follows:

Let σ be the maximum normal stress and τ be the maximum shear stress. Here, factor of safety (f_s)> 1

Max. principle stress (σ_1) ≤ Permissible stress (σ_{per}) where

$$\text{permissible stress} = \frac{\text{failure stress}}{\text{factor of safety}} = \frac{S_{yt}}{f_s} \text{ or } \frac{S_{ut}}{f_s} \qquad (4)$$

$$\sigma 1 \leq \frac{S_{yt}}{f_s} \text{ or } \frac{S_{ut}}{f_s} \qquad (5)$$

This is then fed to ANSYS® FEA package as a means to identify failure.

1. 2.3. Geometric parameters
2. 2.3.1. Bondline thickness

3. Geometric Parameters of Analysis

The geometric parameter analysis of single lap joint is discussed as below,

3.1. Bond-line Thickness

Venkateswara Rao [4] studied the effect of adhesive thickness on bonded joints using analytical models, finite element methods (FEMs) and experimental methods.For SLJs, it was shown that strength decreases as the adhesive thickness increases. The reduction in joint strength was attributed to the fact that thicker bond-line contain more defects such as voids, micro-cracks and higher interface stresses. Also, numerical results supported that the ductility of the adhesive increases as the adhesive thickness is increased. Moreover, there is no any generalized trend between strength and adhesive thickness and these mixed behaviour may be attributed to various factors such as the type of loading (mode I, mode II, or mixed), the adherend behaviour (elastic or plastic), type of adhesive (ductile or brittle), geometry of joints etc. which can modify the behavior of bonded joints as their thickness is varied In summary, it is important to consider the adhesive properties, geometrical parameters and also loading type for optimizing the adhesive thickness.

3.2. Joint Configuration

2.3.2. Joint configuration

The joint configuration that produces local stress concentrations, high peel stresses and interfacial stresses should be avoided because it leads to premature failure of joints. A wide variety of joint configurations are used in practices and most of them. All the geometrical parameters (i.e. adherend thickness, width, adhesive thickness,etc.) have an effect on bonded joints performance. Therefore, it's necessary to optimize these parameters for maximum strength of joints provided its feasibility.Here joint design is considered such that bond area equally shares the stress in optimum length.

3.3. Overlap Length

Increasing the overlap length increases the joint strength up to a certain limit. However, the increment rate depends on the adhesive material, adherend material and the type of loading. In a study performed by Balkova et al. [11], to test the shear strength of adhesively bonded single lap joints, four overlap lengths (10, 20, 30 and 40 mm) were tested and it was found that with increase in overlap length, the failure load increased parabolically. Actually, the ideal overlap length depends on the pairs of adhesive-adherends. Here first optimum overlap length is found which is optimum.

3.4. Material Properties

The material properties of adherend plate and adhesive is given as below,

3.4.1 Adhesive Properties

Most of the industries are demanding new adhesive materials with advanced properties which should satisfy the required conditions for a specific application. The selection of adhesive materials for a specific application depend upon adherend type to be bonded, curing temperature, expected environmental condition during service, type of load and cost.Epoxy resin is used as adhesive in this study. The primary reason for epoxy's popularity is its superb mechanical strength, light weighting, sound and vibration dampening, resistance to chemicals, corrosion and heat. Welding is often the only alternative. Epoxy is nearly always cheaper and faster than welding. The properties of adhesive and adherend material are given in Table 1.

Table 1 Properties of Materials

Property	Adherand (Aluminum T6061)	Adhesive (Epoxy Resin)
E (GPa)	72 *	3.790
ν	0.35 #	0.35
ρ (kg m^{-3})	2770	0.00113
K (Pa)	6.69×10^{10}	4.2×10^{9}
G (MPa)	2.6692×10^{4}	1400
S_{ty} (MPa)	2.8×10^{4}*	54.6

* From Tensile Testgiven in Fig 4, # from reference [3]

3.2.2. Adherend Properties

Special attention should be taken for the selection of the adherend materials, as different materials behave differently and affect the final performance of the joints.

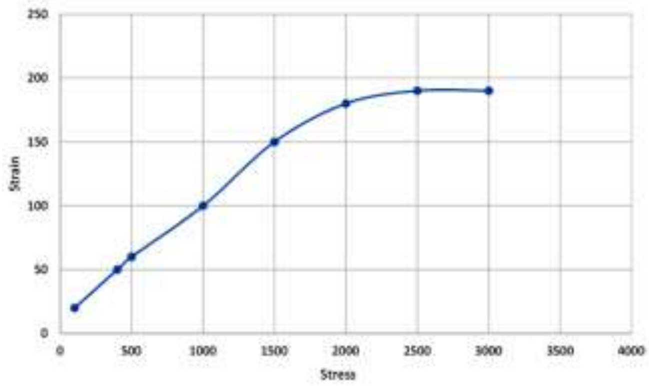

Fig. 4 Stress- Strain Plot of Aluminium T6061

A significant difference in strength was observed, in the case of joints bonded with the different adherend material, under the same conditions. Aluminium is used as adherend in this research article. The test was conducted at Praj Lab., Pune on Aluminium T6061 at 25° C at 5mm/min

4. Analysis of Adhesively Bonded Joints

Analysis of adhesively bonded joints can be carried out by analytical methods and finite element methods (FEM). Analytical methods analyse the joints easily, fast and with high accuracy, but certain assumptions are necessary for complex joints and that might limit the accuracy of the results. On the other hand, the FEM has the capability to analyse complex geometries, complex material model and without introducing any assumption, only the computing time is the constraint

4.1 Element

Hazimeh (2014) [7] described a process of building and testing of numerical models of adhesive bonds to study the dynamics of the joints. The adhesive layer was built up using 4 elements through its thickness, resulting in the smallest element dimension equal to 0.025mm. The bond edges were refined to the mesh size of 5 x 25 x 100 micrometres. To obtain accurate results for the analysis of adhesive joints, the models are usually meshed in extremely fine manner, using volume (brick) elements for the discretization of adhesive and adherends. This method allows for thorough examination of the joint stress pattern and strength, but precludes this type of FE simulations from real-life industrial applications, in which large scale systems often need to be assessed. The finite element mesh is generated using a three-dimensional brick element 'SOLID45' ass shown in Fig.5 [6,13]

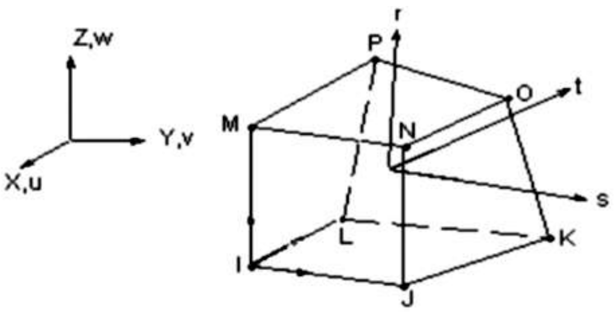

Fig. 5 Element SOLID 45

This element is a structural solid element based on three-dimensional elasticity theory. It 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.

4.2. Boundary Conditions and Loading

Various boundary conditions and loading conditions can be applied for analysis of single lap joint .These are given below,

Case 1: Optimum Overlap Length

For the case 1, analysis was first done for optimum overlap length. The overlap length is the length where adhesive is applied between the two plates.

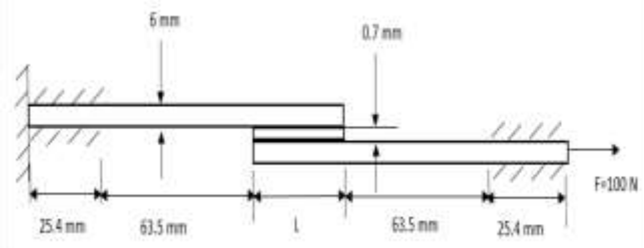

Fig.6. Optimum Overlap Length for Single Lap Joint

Boundary conditions for this case are as, fixed support on one end, frictionless support of 25.4 mm length on both ends of plates and a load of 1000 N on the other end of the plate.

Case 2: Optimum Angle

For the case2, analysis was done for optimum included angle of the slots. The included angle is the angle between the two adjacent faces of the notch shaped slots.

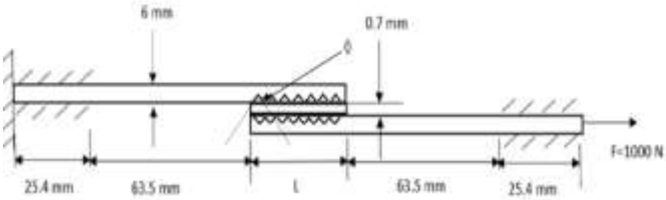

Fig.7. Optimum Anglefor Single Lap Joint

Boundary conditions for this case are as, fixed support on one end,force of 1000N at the other face and frictionless support of 25.4 mm length on either ends of plates.

4.3. FEA Procedure in Analysis

The Analysis procedure begins with 3D CAD Modelling (PTC Creo) and FEA analysis with ANSYS Package. The analysis procedure using ANSYS is as given below in Fig 8.

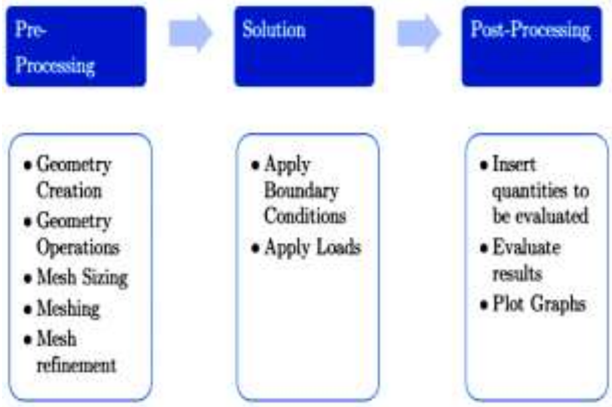

Fig.8 FEA procedure using ANSYS

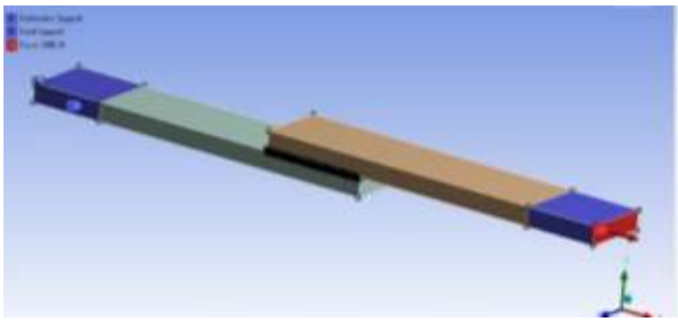

Fig. 9FEA Model of SLJ with Boundary Condition

FEA analysis of adhesive joint gives some important observations 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 radial fillets minimize the stress concentrations at the free ends of the joint.
- Unsupported single-lap joints used for thin metallic adherends.

- Peel stresses in fibre-reinforced plastic adherends are very severe so it is not advised to use this geometry for structural applications with these materials.

5.Testing of SLJ

Two aluminum T6061 plates with epoxy resin were used to form a Single Lap Joint without notch. The method of sample preparation is as follows:

- A single strap joint geometry is used for the experiment
- The bonding surface area is cleaned with acetone before the application of the adhesive.
- The adhesive is applied on the adherend surface and spread over it with a spatula.
- The adherends are then bonded by applying constant pressure on the specimen up to 48 hrs.
- The joints were cured at room temperature for 48 hrs. The adhesive thickness is 0.35±0.05 mm.

First standard single lap specimens prepared [10] for evaluating the load bearing characteristics. Then bond surfaces cleaned to free from grease and dust particles. Then Activator applies on both surfaces of one adhered plate and adhesive on an adhrend surface.

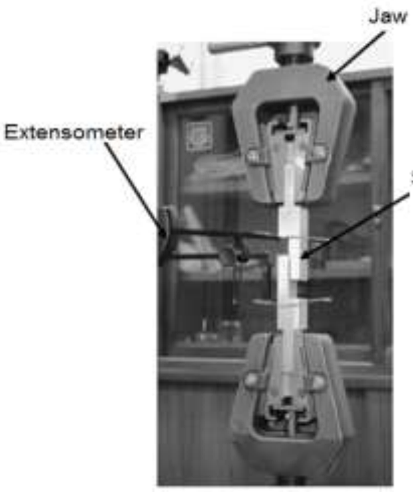

Fig. 10 Experimental Setup for SLJ using UTM

Then bonded plates clamped under the uniform fixture for bonding. Then adhesive joint specimens under goes testing on UTM.

5. Results

The single lap joint undergoes two analysis phases for this article. This is given is following two case studies.

5.1 Case 1: SLJ without Notches

First, analysis was performed on different overlap lengths as 30mm to 37mm. From the results minimum stress was obtained for overlap length of 36mm. Thus 36mm is the optimum overlap length. The Maximum principle stress distribution is given in Fig. 12.

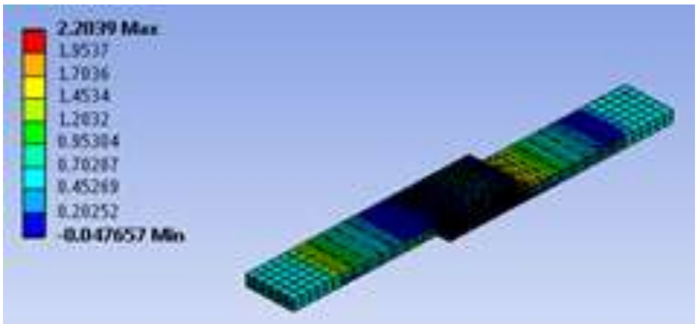

Fig.12 Maximum Principle Stress for SLJ without notches

The plot of the strength of the joint vs the overlap length is given in Fig.13.

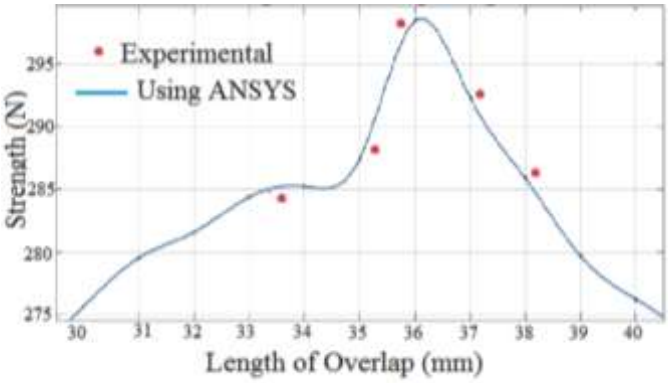

Fig.13 Strength vs. Overlap Length of SLJ (Without notch on adherend surface)

It's seen that the strength of the SLJ increases with increase in overlap length up to 36 mm for our setup. Thereafter it decreases with further increases in overlap length. Hence 36 mm is the optimum overlap length.

The distribution of the maximum principle stress across the width of the specimen is plotted in the following Fig. 14.

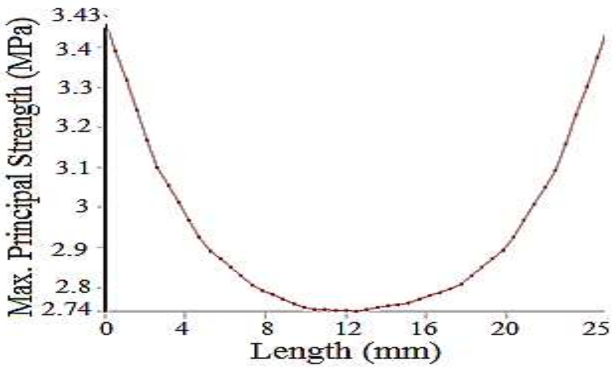

Fig.14 Variation of Maximum Principle Stress across width of the Single Lap Joint (Without notch on adherend surface)

It's observed that the maximum principle stress in the SLJ occurs at the edges. The maximum principle stress is minimum at the centre of the SLJ

5.2. Case 2: SLJ with Notches

FEA analysis was done for different angles of triangular notches (Case 2) for angles varying from 0° to 180°. It was found that 75° is the optimum angle where the bond strength

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will be maximum. The distribution of maximum principle stress is as shown in Fig. 15

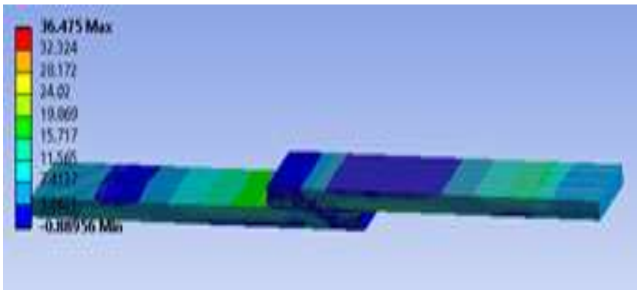

Fig.15. Maximum principle stress for optimum angle of notches on the SLJ (With notch on adherend surface)

The plot of strength of the SLJ with notches vs the notch angle is as shown in Fig. 16

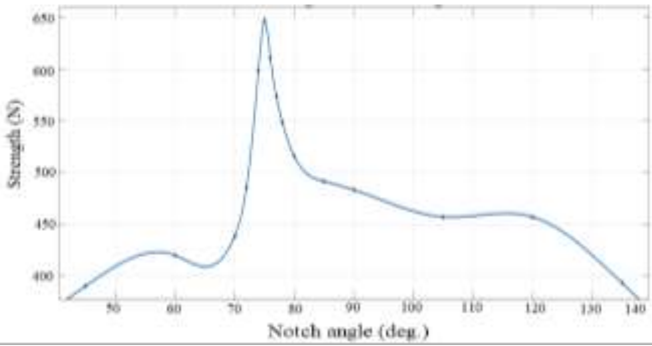

Fig.16. Strength vs. Included Angle (With notch on adherend surface)

It's seen that the strength of the SLJ with notches increases with increase in notch angle up to 60° , then it decreases up to 70° but thereafter it increases with further increases in notch angle up to 75° which seems to be the highest. Later on it decreases continuously. Hence 75° is the optimum notch angle.

The distribution of maximum principle stress across the width of the SLJ is shown in Fig.17.

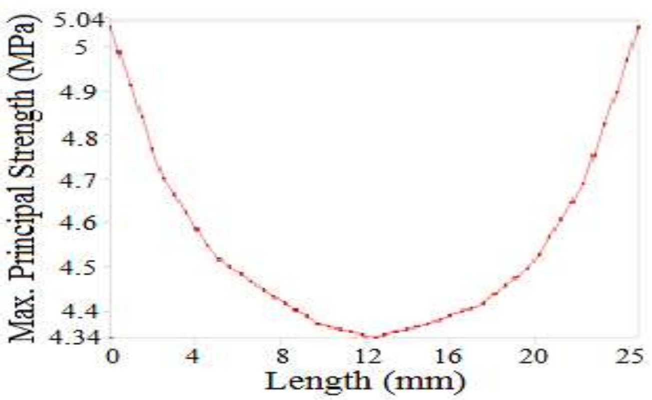

Fig.17 Variation of Shear Stress across width of SLJ (With notch on adherend surface)

It's observed that the maximum principle stress in the SLJ with notch occurs at the edges. The maximum principle stress is minimum at the centre of the SLJ with notches. This maximum principle stress distribution is similar to the SLJs without notches

The optimized bond parameters are as depicted in the Fig. 18.

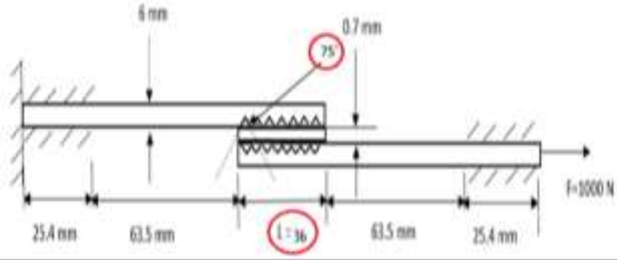

Fig.18 Variation of Shear Stress across Width of SLJ

FEA analysis and experimentation shown final results for single lap joining as, the optimum angle of notch on aluminium adherend plate is 75° and optimum length of adhesive joining is 36mm.

6. Conclusion

The study presented in this article 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 with varying surface roughness using adhesive joint and see failure analysis using FEA and experimental testing. Triangular slots were made on the surface of the plates. Maximum bond strength was obtained from optimum overlap length and triangular slots with obtained angle. 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. The tensile strength of structural adhesive is obtained by loading the bonded adhesive plates on UTM to fail against the tensile mode. Thus, the strength of a single Lap Joint is the maximum when the length of overlap is 36 mm and the included angle of the slot is 75° to achieve maximum strength of Single Lap Joint. In future, experimental validation of the results for SLJs with notches will be performed.

Acknowledgements

We are grateful for all the support given by department of Mechanical Engineering, MIT College of Engineering, Pune.

Nomenclature

t	Thickness of plate (mm)
l	Length of overlap (mm)
s	Distance between two slots (mm)
E	Young's modulus (N/mm^2)
v	Poisson's ratio
P	Pressure (N/mm^2)
K	Bulk modulus (N/mm^2)
G	Modulus of rigidity (N/mm^2)
S_{yt}	Yield Tensile strength (N/mm^2)
S_{yc}	Yield Compressive strength (N/mm^2)
S_{ut}	Ultimate Tensile strength (N/mm^2)

S_{uc} Ultimate Compressive strength (N/mm^2)

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