Experimental and Numerical Strength Analysis of Stepped Lap Adhesive Joints Subjected to Static Tensile Loading

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Abstract - **Majority of automobile and aerospace parts, mainly their body components are joined together by different types of adhesives. So these growing needs demand the detailed study on stress concentration and strength analysis of adhesive joints.[39] With the help of structural analysis simulations we can identify the problem areas, failure loads and solutions can be validated in computers without any expensive shop floor operations prior to any tool construction.[40] Structural analysis simulation is also helpful at the joint design stage to decide various parameters, like adhesive thickness, overlap length, overlap area and load applied etc. In the recent years the use of finite element analysis is increased in the strength analysis of sheet metal joints. Finite element analysis helps to analyse the process virtually.**

The present work reports a detailed investigation of a stepped lap adhesive joint with similar metals. This joint is subjected to static tensile loading and the ANSYS software package is used to carry out the analysis. The analysis results helps in depicting the effects of varying load, adhesive thickness, overlap length and overlap area on stress induced and hence on the joint strength. The metal to metal stepped lap adhesive joint specimens using Aluminium as adherend and Araldite® as adhesive under gradually applied static tensile loading are tested on UTM and the results obtained by FEA are validated.

Keywords: Stepped Lap, Adhesive Joints, Static Loading, and Strength Analysis.

INTRODUCTION

Adhesively bonded structure joints have emerged as one of the primary means of bonding in response to the demand for light weight, high strength, low cost products, especially in the automotive and aerospace industries.[13] Recently, adhesive joints have been widely used in mechanical structures because of the enhanced performance of the adhesive. [31]

Among the commonly used adhesive bonded joint configurations, scarf and stepped joints have been found to exhibit the highest structural efficiency because significant joint load path eccentricities (which ultimately act as stress raisers) are eliminated when compared with simple single or double lap joints. A scarf joint is the structurally most efficient adhesive joining method when compared with other adhesive joint configurations because the stress concentrations at the ends of the overlap area are minimized. On the other hand, a stepped lap joint can have the same mechanical / structural efficiency as a scarf joint from the view point of fatigue and joint strength. The stepped lap composite joints can be manufactured with relative ease compared with scarf joints because it is relatively straight forward to make the ply and sub-laminate steps / drops at the end of a composite substructure / part. [35]

Considerable amount of research has been carried out on the interface stress distributions and strengths of lap, butt and scarf adhesive joints subjected to static loadings. Some investigations have been carried out on the stress distributions in stepped-lap adhesive joints under static loadings. However, the characteristics of stepped-lap adhesive joints under static loadings have not yet been fully elucidated. Thus, it is necessary to understand the characteristics of stepped-lap adhesive joints under static tensile loadings. [13]

The influence of static tensile loading on stress distribution within the adhesive joint is analyzed by finite element method. Practically Von Mises stresses are maximum at edge and decreases away from edge. Similarly shear stresses almost vanish towards the middle of the adhesive. The shear stress contribution to the Von Mises stress is significant in the bond region close to the metal plate; this in turn results in possible failure of bonding in this region. In actual practice strength of adhesion to the metal surface is stronger than the strength of the adhesive itself. That means the joint will fail in midway of adhesive instead of at the adhesive metal interface.

ADHESIVE BONDING

A. *Adhesive and Adhesion*:

An adhesive is a substance which is capable of holding materials together in a useful fashion by means of surface attraction. Surface attraction results from placing a thin layer of adhesive between two objects. An Adherend is the solid material in the adhesive joint other than the adhesive (also referred to as substrate). The bond line is the space or gap between two substrates which contains the adhesive.

Adhesion is the process by which two surfaces are held together by interfacial forces (surface attraction) or mechanical interlocking. When an adhesive cures, it is converted from a liquid to a solid state. This may be accomplished by cooling, loss of solvents or internal chemical reaction. Curing generally implies some type of physical or chemical change in the adhesive, while hardening or melting is reversible.

B. *Theories of Adhesions:*

Currently there are several theories attempting to explain the phenomenon of adhesion of the adhesive on the substrates, there is currently no unified theory to justify all cases. It is required the use and combination of different theories to justify all cases.

- Mechanical theory of adhesion-

The mechanical theory explains the phenomenon of adhesion, It is directly linked to the porosity and surface roughness of the substrate with the degree of adhesion that can be obtained.

- Adsorption theory-

The adsorption theory or model explains the phenomenon of adhesion based on concepts such as contact angle, wet ability and surface tension. The adsorption theory of adhesion is well explained in the figure 1 shown below.

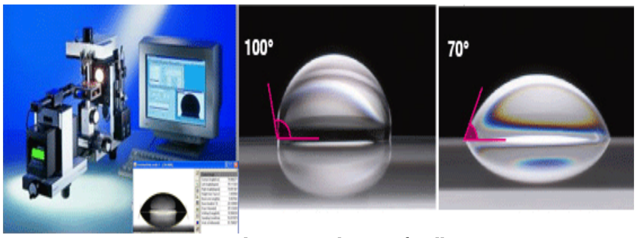

Figure 1: Adsorption Theory of Adhesion

- Chemisorption theory-

Chemisorption theory is an extension of the adsorption theory of adhesion, in which the adhesive has properly wet the substrate; the adhesion phenomenon arises when generating intermolecular or Van der Waals forces and chemical bonds between the adhesive and substrate.

- Diffusion theory-

The diffusion model explains the concept of adhesion by the compatibility between polymers and the movements that occur in the polymer chains. The diffusion theory of adhesion is well explained in the figure 2 shown below.

Figure 2: Adsorption Theory of Adhesion

- Electrostatic Theory-

The Electrostatic theory resembles the phenomenon of adhesion to a condenser, where the electrostatic charges of opposite sign attract each other causing the adhesion between the adhesive and substrate.

C. Types of Adhesives:

Modern adhesives are classified either by the way they are used or by their chemical type. The strongest adhesives solidify by a chemical reaction. Less strong types harden by some physical change. Key types in today's industrial scene are as follows.

- Anaerobics
- Cyanoacrylates
- Toughened Acrylics/ Methacrylates
- UV curable adhesives
- Epoxies
- Polyurethanes
- Modified Phenolics

The above types set by chemical reactions. Types that are less strong, but important industrially, are as follows:

- Hot Melts
- Plastisols
- Rubber adhesives
- Polyvinyl Acetates (PVAs)
- Pressure-sensitive adhesives

D. Applications of Adhesives:

Adhesive resins are used as an adhesive layer in numerous applications which consist of multiple layers of barrier materials. Not only does the adhesive resin ensure that manufacturers meet environmental, regulatory and industry requirements but it also enhances adhesive performance and durability.

Automotive Applications-

- Plastic Fuel Tanks
- Fuel Lines
- Fuel Filler Pipes
- Fuel Connectors

Packaging Applications-

Adhesive Resin for Cosmetic Packaging Applications:

- Body lotion containers
- Make up bottles
- Oval and round tubes

Adhesive Resin for Pharmaceutical Packaging Applications:

- Tubing
- PTP packaging
- Bottles

Adhesive Resin for Food Packaging Applications:

- Ketchup
- Salad dressing
- Pudding
- Meat and Soup
- Cheese
- Pasta and Apple sauce
- Beverages

Industrial Applications-

In industrial markets, epoxy resins as an adhesive ideal for a number of uses including floor heating pipe, aluminum sheathe and bottle applications. Also the emerging use of these adhesives is in aerospace and automotive industries. These are used for floor and ceiling fixing, external body building and also for interior designing of the compartments and dashboards. High temperature adhesives are employed in jet airplanes for sustaining high force and temperature developed at high speed and air resistance.

Oil and Gas Pipe Applications-

In the oil and gas sectors, pipeline bondings and coatings are expected to perform under severe conditions and extreme temperatures. These adhesive resins can be easily processed by co-extrusion with polypropylene or polyethylene with circular die for middle or small diameter steel pipes, and with flat die for larger diameter steel pipes.

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 6 Issue 09, September - 2017

E. Advantages of Adhesive bonding:
- The bond is continuous
- Stiffer structures
- Improved appearance
- Complex assemblies
- Dissimilar materials
- Reduced corrosion
- Electrically insulating
- Reduced stress concentrations
- Jointing sensitive materials
- Vibration damping
- Simplicity

All these advantages may be translated into economic advantages: improved design, easier assembly, lighter weight (inertia overcome at low energy expenditure), longer life in service.

F. Limitations of Adhesive bonding:
- Temperature resistance
- Chemical resistance
- Curing time
- Process controls
- In service repair

G. Epoxy Adhesive:
Epoxy Adhesives have been available longer than any engineering adhesive and are the most widely used structural adhesive. Epoxy adhesives are thermosetting resins which solidify by polymerisation and, once set, will soften but not melt on heating. Two part resin/hardener systems will solidify on mixing (sometimes accelerated by heat), while one part materials require heat to initiate the reaction of a latent catalyst. Epoxies offer very high shear strengths, and can be modified to meet a variety of bonding needs. Generally epoxy bonds are rigid: they fill small gaps well with little shrinkage.
The first production of epoxy resins was carried out by De Trey Frères SA of Switzerland. They licensed the process to Ciba AG in the early 1940s and Ciba first demonstrated a product under the trade name Araldite at the Swiss Industries Fair in 1945. In the UK Aero Research Limited. (ARL) - hence the name; Araldite, produced this new synthetic resin adhesive for bonding metals, glass, porcelain, china and other materials. Araldite sets by the interaction of a resin with a hardener. Heat is not necessary although warming will reduce the curing time and improve the strength of the bond. After curing, the joint is claimed to be impervious to boiling water and all common organic solvents. It is available in many different types of packs, the most common containing two different tubes, one each for the resin and the hardener.
Other variations include double syringe-type packages which automatically measure equal parts. This type of packaging, however, is not exact and also poses the problem of unintentional mixing of resin and hardener. Araldite® glues are so strong they help to build bridges, assemble racing cars and manufacture aircraft wings. It's why we call them 'professional adhesives'.

Advantages of epoxy adhesives:
- Usually low priced
- Good gap filling capabilities
- High strength: can be filled with metals
- Wide range of formulations
- Versatile
- Good temperature and solvent resistance

Limitations of epoxy adhesives:
- Adhesives thin during curing cycles
- Two component mixing and measuring required
- Exact proportions needed for optimal strength
- Single component usually requires refrigeration and heat cure
- Slow fixturing
- Short pot life creates waste
- Special equipment needed to weigh, mix and dispense

FAILURE OF ADHESIVE JOINTS

A. Failure modes for adhesive joints:
Structural bonding techniques play a key role in today's industrial assembly. As designers strive to bring lightweight and durable products to market in the quickest time possible, they increasingly choose industrial adhesives as the best solution for complex design issues.

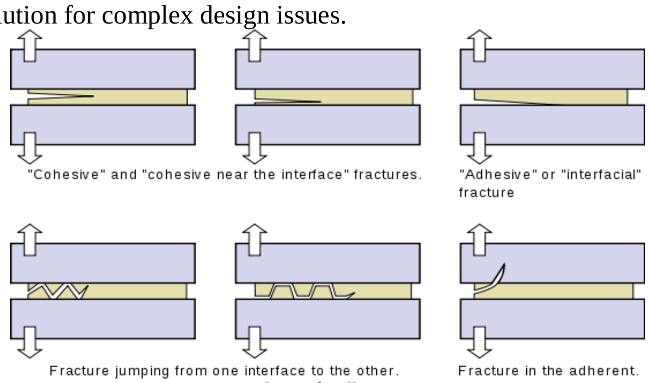

Figure 3: Failure of Adhesive Joints

Based on epoxy, polyurethane, and methacrylate chemistries, this Araldite® adhesives core range provides superior joining and bonding solutions for plastics, metals, composite materials and other substrates. Theoretically the failure of adhesive joint is in different modes and by different methods; the figure 3 shown above includes all these types of adhesive failures.

The three major failure modes of adhesive-bonded joints are as follows:
(1) cohesive failure,
(2) adhesive failure and
(3) adherend failure.

Because standard test specimens use aluminum adherends, their failure tends to be cohesive and/or adhesive failures. Cohesive failure is characterized by the failure of the adhesive itself. In the case of cohesive failure, the adhesive is left on both bonded surfaces of the adherends. However, sometimes it is difficult to judge cohesive failure for a specimen because of the random propagation of the failure surface inside the adhesive. The failure surface might develop inside the adhesive, propagate into the adhesive/adherend interface, and continue to develop along the interface.

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 6 Issue 09, September - 2017

It is also worthwhile to note that even though cohesive failure is the failure mode of the specimens, the apparent strength of the joint, which is obtained by dividing the failure load by the adhesive area (overlap area), cannot be regarded as merely material dependent. Their values are closely related to the configuration of the joint as well.

B. Failure Criterion for Adhesive Joints:

The four main types of loading conditions are: Short term static, Fatigue, Long term static (creep) and Impact. As such the criteria differ in absolute sense between the load types:

- Criteria for static and impact loadings attempt to predict the load the joint will carry;
- Criteria for fatigue loading attempt to predict the lifetime of the joint under an applied mean and cyclically varying load of some frequency in terms of cycles to failure;
- Criteria for creep loading attempt to predict the lifetime of the joint under some constant load in terms of time to failure.

Numerous failure criteria for adhesive joints have been proposed and used with varying success. The majority of the early failure criteria were based on critical values of stress or strain for unflawed joints and linear elastic fracture mechanics for cracked joints. For short term static loading conditions following different failure criteria's are used as per the applications.

- Maximum stress/ strain
- Stress/ strain and a distance
- Limit state analysis
- Fracture mechanics
- Bi-material singularities
- Damage modeling

A large number of researcher's have proposed and used various failure criterions. Maximum stress/ strain failure criteria are the most intuitive starting point for joint strength prediction. Such a form of failure criterion assumes that the joint will fail when a critical value of stress/ strain is reached at any point within the joint. We are using this criterion of failure because in our problem statement a simple stepped lap joint is subjected to static tensile loading.

C. Maximum Shear Stress Criterion:

This criterion, is based on the Maximum Shear stress theory. This theory predicts failure of a material to occur when the absolute maximum shear stress (τ_{max}) reaches the stress that causes the material to yield in a simple tension test. The Maximum shear stress criterion is used for ductile materials.

D. Maximum von Mises equivalent stress criterion:

The von Mises Criterion (1913), also known as the maximum distortion energy criterion, octahedral shear stress theory, or Maxwell-Huber-Hencky-von Mises theory, is often used to estimate the yield of ductile materials. The von Mises criterion states that failure occurs when the energy of distortion reaches the same energy for yield/ failure in uniaxial tension.

E. Stress analysis of adhesive joints:

Adhesive strength is affected by the many physical and chemical factors. Hence, the knowing of the strain-stress distribution through the adhesive joint might be of great help to designer by integrity assessment of engineering component. In accordance with the fact that aluminium has a wide application for many engineering components, adhesive joints of aluminium as adherend sheet material have been focused here. The aim was actually to determine the tensile stress σ_x, shear stress τ_{xy}, and Mises equivalent stress σ_{eq} distribution in adherend and adhesive as well for different designs of single-lap joint. Adhesively bonded joints have the potential to replace conventional fastener and rivet joints, especially in laminated composite structures. Adhesive bonding has merits over other jointing methods through the avoidance of drilled holes and the reduction of stress concentrations. [Tong and Soutis, 2003]

To carry out the stress analysis of the adhesive joints for the prediction of the strength following methods are available.

(1) Analytical,
(2) Numerical and
(3) Experimental.

Out of these I am using numerical and experimental methods for strength prediction.

FAILURE OF ADHESIVE JOINTS

- Finite element analysis:

Due its versatility and computational power, the FEM is commonly used in the analysis of modern engineering and scientific systems. In this study, the FEM is used to model and analyze the adhesive joint through the well-known finite element package ANSYS. The system consisting of the joint and two-bonded aluminum specimens are subjected to tension. The resulting shear and von Mises stresses are computed for various adhesive and adherend thicknesses to see their effects on the mechanical strength of the joint. These stresses are chosen, because it is expected that the tensile shear stress is the mode of failure for the adhesive joint and the von Mises stress is a measure on the state of equivalent stress.

- Material properties:

The material for the plates used is Aluminium 5052, as it is lightweight, easy to process and readily available in local market. And the material used for the adhesive is Araldite an Epoxy adhesive, which has low cost and having good adherence between metals. The material properties of these two are as mentioned in table 1.

Table 1: Material Properties

Specimen	Material	E in MPa	ν	ρ in Kg/m³
Plate	AL-5052	6.9×10^4	0.33	2700
Adhesive	Epoxy	2.8×10^2	0.41	1100

- Element Selection:

A proper selection of an element for the specimens used is a very important step in the numerical analysis of a system. "PLANE82" element is used for plates where as "SOLID95" element is used for the adhesive.

- CAD models of joints:

The CAD drawings of joint prepared in numerical method for 3 steps and 2 steps are shown in figure 4 and 5.

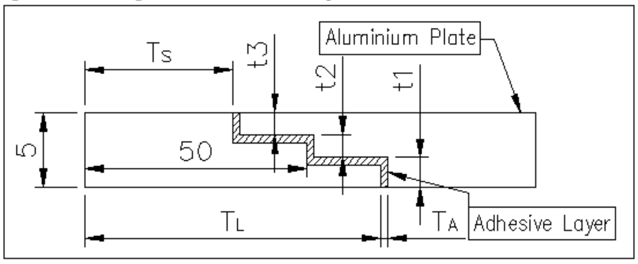

Figure 4: CAD drawing of 3 stepped adhesive joint

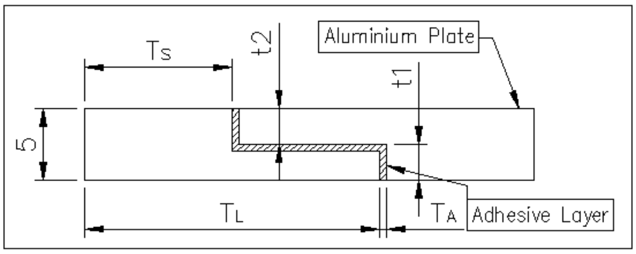

Figure 5: CAD drawing of 2 stepped adhesive joint

Where,

T_L and T_S are the large and small sides of the plate respectively and t1, t2, t3 are the step thicknesses.

- FEA results:

The FEA results obtained by analysis using ANSYS software and these values are plotted on a graph of joint strength verses adhesive thickness. In these plots the thickness at which two lines i.e. tensile strength line shear strength line cross each other is the Optimum thickness where as the average of all thicknesses or the mean of the minimum and maximum thickness is the Mean thickness. Figures 6 to 9 below shows these plots obtained by FEA of stepped lap adhesive joints.

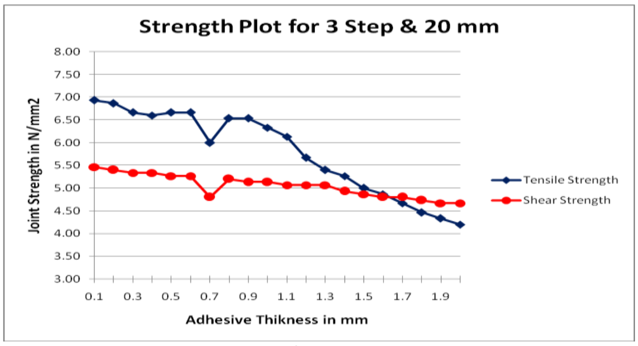

Figure 6: Strength plot for 3steps with 20mm overlap

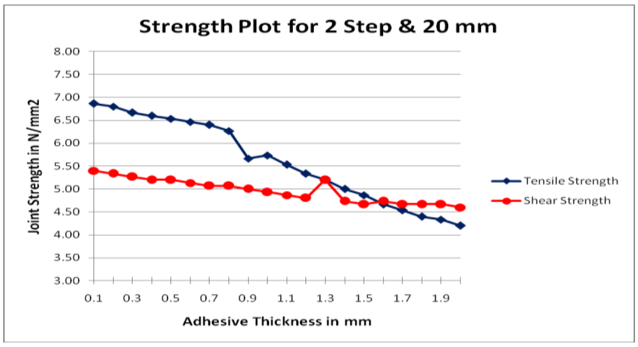

Figure 7: Strength plot for 2steps with 20mm overlap

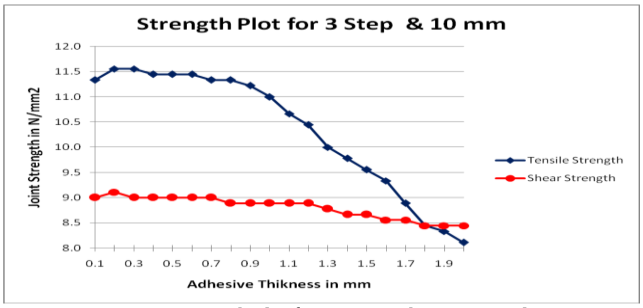

Figure 8: Strength plot for 3steps with 10mm overlap

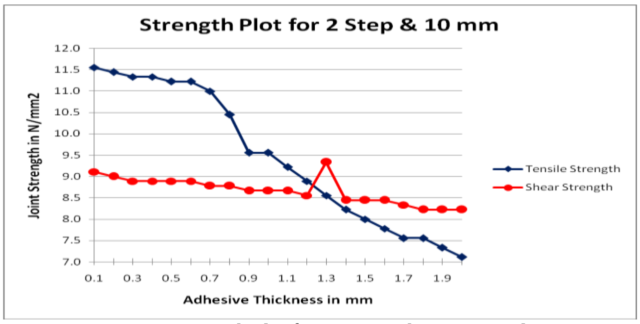

Figure 9: Strength plot for 2steps with 10mm overlap

- *Conclusions of numerical method:*

From all above plots and the results that are obtained by numerical method of analysis using FEA process on ANSYS software following conclusions are drawn,

1. For the same number of steps (2 or 3) the strength of the adhesive joint is inversely proportional to the overlap length and overlap area of the adhesive.
2. For lower overlap length (10 mm) and overlap area (450 mm^2) of the adhesive, the strength of the adhesive joint is inversely proportional to the number of steps.
3. For higher overlap length (20 mm) and overlap area (750 mm^2) of the adhesive, the strength of the adhesive joint is directly proportional to the number of steps.
4. The strength of adhesive joint decreases with increase in the adhesive thickness.
5. At lower thickness of adhesive (less than 1.7 mm for 2 stepped joint and less than 1.3 mm for 3 stepped joint) the failure of the joint is because of shear stresses developed at joint.
6. At higher thickness of adhesive (greater than 1.7 mm for 2 stepped joint and greater than 1.3 mm for 3 stepped joint) the failure of the joint is because of tensile stresses (equivalent stresses) developed at joint.

FAILURE OF ADHESIVE JOINTS

- Material selection:

The epoxy adhesive used in this investigation is a general purpose, two-part epoxy Araldite® obtained from local market. The adhesive is prepared by mixing equal volumes of the resin and hardener parts. The mixed adhesive cures fully in 24–48h at room temperature with handling strength in about 8h. The aluminum plates used as adherends in making aluminum joints are cut from locally obtained aluminum flats (30mm width X 5mm thk). After cutting these flats we are getting small plates of 55 or 60 mm lengths. Then these plates are machined on milling machine to prepare the steps (2 or 3) and as per overlap length (10 or 20mm).

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 6 Issue 09, September - 2017

- Specimen preparation:

The following procedure is adopted for cleaning the aluminum sheets before adhesively joining them to form a stepped lap configuration.

1. Degrease by dipping shortly in trichloroethylene and isopropyl alcohol, separately.
2. Wash with water.
3. Roughen surfaces by abrader cleaning (mechanical cleaning) by 400 grit silicon carbide grinding paper.
4. Degrease by dipping in trichloroethylene and isopropyl alcohol (30 min each).
5. Immerse for 2–4h in a solution of H_2SO_4, sodium dichromate and distilled water in proportion: 22.5, 7.5 and 70 by weight, respectively (chromic–sulphuric etching process).
6. Wash with distilled water.
7. Dry with clean paper or tissue and keep in desiccators until use.

The stepped-lap adhesive joints are then prepared by bonding surface cleaned/treated aluminum sheets together with neat epoxy adhesive. Equal volumes of the epoxy resin and the hardener are mixed. An available fixture in college workshop is used to assemble the adhesive joints. The actual adhesive thickness of the cured joint is measured by a digital micrometer. The preparation of adhesive joint specimen is shown diagrammatically in figure 10.

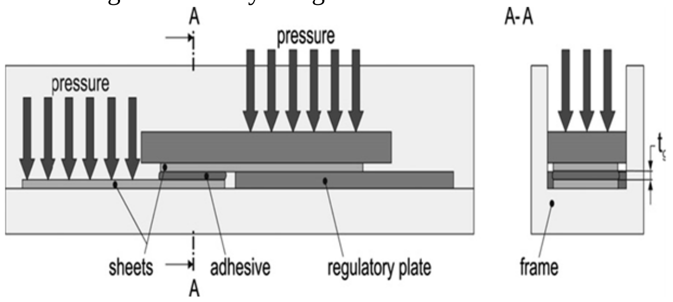

Figure10: Adhesive joint specimen preparation

As maximum of the adhesive joints are failed in cohesive and/or adhesive mode, the values of maximum strength of the Araldite® epoxy adhesive used in this thesis are as mentioned below in table 2. These values are used as a failure criteria or strength limits for the adhesive joints.

Table 2: Strength criteria for adhesive

Sr. No.	Property	Notation	Value in MPa
01	Ultimate tensile strength	S_{ut}	84.30
02	Maximum shear strength	S_{sh}	31.44
03	Tensile yield strength	S_{yt}	65.00

Table 3: Experimental and FEA Results

Sr. No.	Joint Configuration	Adhesive Thickness T_A in mm	Failure Load in N	Joint Strength in N/mm^2	
				EXP	FEA
01	3 steps 10mm Overlap O	1.8	4280	09.50	08.44
02	3 steps 10mm Overlap M	1.0	4530	10.10	11.00
03	3 steps 20mm Overlap O	1.6	5040	06.72	04.87
04	3 steps 20mm Overlap M	1.0	5500	07.33	06.33
05	2 steps 10mm Overlap O	1.3	4070	09.00	08.56
06	2 steps 10mm Overlap M	1.0	4390	09.80	09.56
07	2 steps 20mm Overlap O	1.6	4620	06.16	04.67
08	2 steps 20mm Overlap M	1.0	4850	06.47	05.73

After carrying out test for all these eight joint configurations the results including the failure load and the joint strength are observed and note down in tabular form as shown in table 3 below. (O= Optimum thickness, M= Mean thickness)

- Conclusions of experimental method:

From above obtained results and plotted graphs following conclusions were drawn,

1. The results for mean and optimum thickness obtained by experimental methods are well agreed with results obtained by FEA and follow the same pattern.
2. The strength of the 3 stepped joints is greater than that of the 2 stepped joints.
3. The strength of the 10% overlap adhesive joints is greater than that of the 20% overlap adhesive joints.
4. The slight variation in the results obtained by both methods is because of the assumptions made in the FEA process and the measurement errors and cavities formation during joint preparation in the experimental method.
5. The mean thickness is nothing but the uniform thickness of 1 mm which is mean of thickness variations.
6. The optimum thickness are those at which the joints are fail by both tensile and shear failure, it means at these thicknesses tensile and shear strengths are equal.
7. The results obtained by FEA are hence hereby validated by the experimental results for both optimum as well as mean thicknesses.
8. The errors in the specimen preparation, like unequal thickness, cavities are well understood by observing figure 11.

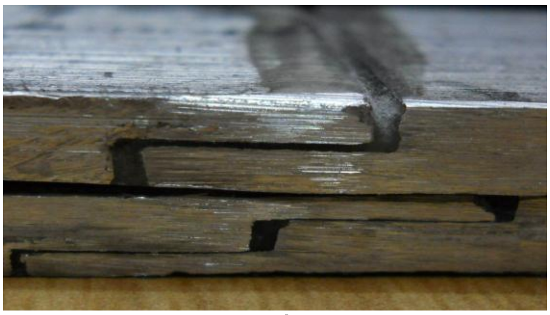

Figure 11: Errors in the specimen preparation

Future Scope

- The adhesive joint is very vast area in which many opportunities are there to carry out research on recent trends and technologies developed. Now days the use of adhesive in industrial and household appliances is so increased that it replace the other types of conventional joints.
- The adhesive and adherend materials can be altered to observe its effect on the strength of the joint. Also the design pattern of steps can be varied as wide varieties of designs are used in industries in current practices. Two different materials of adherend can be used at opposite sites to form a hybrid joint configuration and apply the same adhesive to test its strength.

CONCLUSIONS

From results obtained by FEA and experiments following conclusions were drawn,

- The strength of stepped lap adhesive joint is directly proportional to the number of steps provided or used in the joint.
- The strength of stepped lap adhesive joint is inversely proportional to thickness of the adhesive applied between the plates.
- The strength of stepped lap adhesive joint is inversely proportional to overlap length and the overlap area of the adhesive applied.
- For all types of stepped lap adhesive joints at adhesive thickness less than optimum thickness, joints will fail by shear failure.
- For all types of stepped lap adhesive joints at adhesive thickness greater than optimum thickness, joints will fail by tensile failure.
- Stepped lap adhesive joints are useful in automobile and aerospace industries as it overcomes limitations of all conventional joints (bolted, riveted and welded) and also the single lap, scarf and butt type adhesive joints.

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