Experimental Parametric Study of Scarf Adhesive Joint under Static Tensile Load

Prabodh B. Horambe*, Kaushal Prasad, Sachin S. Mestry
Finolex Academy of Management and Technology, Ratnagiri, Maharashtra, India-415612

* Corresponding author. Tel.: +918793838146; email: prabodhhorambe@gmail.com
Manuscript submitted December 10, 2015; accepted June 8, 2016
doi: 10.17706/ijmse.2016.4.2.69-79

Abstract: Adhesive joints are used to join two materials by placing adhesive layer between them. Light weight, uniform stress distribution, ability to join dissimilar materials are the important advantages which differentiates adhesive joints from other conventional joints. Scarf adhesive joint is one of them. The strength of scarf adhesive joint greatly depends upon its geometry. The aim of this study is to determine the effect of geometric parameters like scarf angle, surface roughness, adhesive layer thickness, mixture ratio of components of adhesive on the joint strength. For this purpose, samples of scarf adhesive joints are produced in the combinations of three different levels of scarf angle, surface roughness, adhesive layer thickness and mixture ratio of adhesive. The strength of each joint is recorded by subjecting them to axial tensile load test. The large number of experiments reduced to few using Design of experimentation technique and Taguchi's methodology. With the help of MINITAB software results have analyzed and optimum levels of each controlling parameters are determined for maximum strength of scarf adhesive joint.

Keywords: Scarf angle, Breaking strength, Design of experimentation, Taguchi method.

1. Introduction

In engineering applications material joining is very old but important process. Almost everything that is made by industry has component pieces and these have to be fixed together. Often mechanical joining methods like bolting, riveting, welding, soldering are chosen. However, engineers now often choose to use adhesive bonding. Joining of two materials by placing adhesive between them and allow it to solidify is nothing but a adhesive bonding and that joint is called as an adhesive joint [1]. This joining technique is well proven and capable of replacing or supplementing mechanical fixing methods. The conventional methods like bolting, riveting, welding causes stress concentration on a surface of a joining material which results in damage of material parts. Hence adhesive joint rises as the alternative method to the conventional joining methods. Low structural weight, ability to join two dissimilar materials, reduced component and/or assembly costs, improved product performance and durability, greater design freedom, less finishing operations are the other advantages of adhesive joints. Whereas low strength is the limitation of adhesive joint. In order to increase the strength of adhesive joints different types of adhesive joints like single lap adhesive joint, double lap adhesive joint, butt adhesive joint, stepped lap adhesive joint etc. are invented. Scarf adhesive joint is one of them which is shown in Fig.1. The strength of scarf adhesive joint is highly depends on the geometrical parameters involved in its configuration in which scarf angle is a most critical parameter. Surface roughness, bond length, adhesive thickness, surface area (function of scarf angle), properties of adhesive to be used are the other important parameters to be considered. In order to find maximum strength of scarf adhesive joint it is necessary to find out optimum levels of affecting geometric parameters. This can be done by performing number of experiments to find strength of joint for different combinations of critical parameters with their different levels which will help to find out optimum level of each parameter. In present study by applying design of experimentation (DOE) approach, no. of experiments required have reduced without affecting the results. Taguchi's concept of orthogonal array is used to find optimize solution. Taguchi's simple, effective and systematic approach helps to find optimal scarf adhesive joint parameters. It is not only a reliable tool to find optimize solution but also helps to reduce experimental efforts.

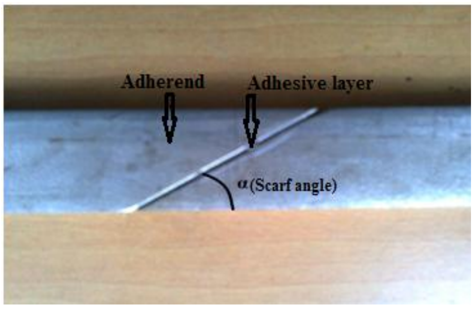

Fig. 1. Scarf adhesive joint

2.

2.1. Problem Definition

As we discussed earlier, adhesive bonding technology has several advantages over conventional joint processes still they are not used effectively in practice [1][2]. The main reason behind that is the non uniformity in the joint strength due to the involvement of geometrical and fabrication variables in the configuration of scarf adhesive joint. Hence to make the adhesive joint more reliable, deep study of geometric parameters of the joint is essential.

In every adhesive joint, load is transmitted from one adherend to another adherend through adhesive layer. Whenever scarf adhesive joint is loaded under tensile load, due to the scarf angle, tensile stresses along with shear stresses are getting developed within the joint. The failure of joint is decided by these stresses which varying with variation in scarf angle. Hence scarf angle is the important parameter of consideration. Along with it, the strength of scarf adhesive joint depends on various other parameters involved in its configuration like adhesive layer thickness, surface roughness of adherend, mixture ratio of parts of adhesive used etc. With variations of these controlling parameters strength of join varies, but the variation is not uniform. So it is important to study the effect of variations in controlling parameters of scarf adhesive joint on its strength. Also it is necessary to find optimized values of controlling parameters which will result in maximum strength. Hence problem can be defined as experimental parametric study of scarf adhesive joint under static tensile load.

2.2. Objective

The main objective of this study is to understand and analyze the scarf adhesive joint. To study the variations in the strength of scarf adhesive joint due to the variations in the parameters involved in the configuration of scarf adhesive joint. Also to find out optimum values of controlling parameters in order to get maximum strength of a joint.

3. Experimental Research

3.1. Taguchi Methodology

Experimental procedure is designed and carried out according to Taguchi methodology. The major steps required for the experimental design using Taguchi method are [3]:

3.1.1. Establishment of Objective Function

The overall objective of the Taguchi method is to obtain high quality product at low cost to the manufacturer. So it is very important to clearly define the objective function at the beginning. The objective of the present work is to determine the optimum levels of the parameters configuring scarf adhesive joint that result in the maximum strength of joint.

3.1.2. Determination of Controllable Factors and Their Levels

In Taguchi's methodology, all factors affecting the process quality can be divided into two types: control factors and noise factors. Control factors are those which can be easily controlled while the noise factors are usually uncontrollable, such as environmental conditions like ambient temperature, humidity which always cannot be eliminated and which causes variation in the output. Noise factors are difficult, some times impossible or expensive to control. Control factors are the most important in determining the quality of the product.

In the present study, after reviewing the literature following are the control factors selected for experimentation: scarf angle, surface roughness, adhesive layer thickness, mixture ratio between parts of adhesive i. e. resin and hardener[4][5]. While noise factors are surrounding temperature, moisture content in air, acidic environment etc. The selected levels for control factor are as shown in Table 1.

Table 1. Selected Levels of Control Factors

	Levels		
Control factor	**1**	**2**	**3**
Scarf angle (degree)	30	45	60
Surface roughness (μm)	1	2	3
Adhesive layer thickness (mm)	0.5	1	1.5
Mixture ratio (Resin: Hardener)	1	1.5	2

3.1.3. Design of Taguchi Orthogonal Array Layout

The orthogonal array is an array in which columns are mutually orthogonal i. e. for any pair of column, all combinations of factor level occur, and they occur for equal number of times. In a simple words in orthogonal array, equal chance is given to the every level of every parameter [6]. L9 orthogonal array is selected for the present investigation in which nine experiments need to be performed with four parameters having three levels each. The selected orthogonal array along with the details of levels of each parameter is shown in Table 2 and Table 3 respectively.

3.1.4. Signal-to-noise ratio

To determine the effectiveness of a design, there must be some measure to evaluate the effect of the design parameters on the response characteristics. Signal-to-noise ratio used for that purpose. The term signal represents the desirable component of the output characteristics, which should be close to its specific target value while the term noise represents the undesirable component and is measure of the variability of the output characteristics[6]. The Taguchi method uses the signal-to-noise ratio (S/N) to express the variations about a target value. A high value of S/N means that the signal is higher than the effect of the noise factors[6][7]. Depending on the desirable response, three different approaches are used to analyze the response. In the present study objective is to maximize the breaking strength, hence larger the better approach is used.

Table 2. Taguchi's L9 Orthogonal Array

Expt. no.	Control factors			
	A	B	C	D
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

Table 3. Taguchi's L9 orthogonal array in detail

Expt. no.	Control factors			
	SA	SR	LT	MR
1	30	1	0.5	1
2	30	2	1	1.5
3	30	3	1.5	2
4	45	1	1	2
5	45	2	1.5	1
6	45	3	0.5	1.5
7	60	1	1.5	1.5
8	60	2	0.5	2
9	60	3	1	1

3.2. Preparation of Specimen

The schematic diagram for the experimental specimen for tensile test is as shown in Fig. 2. Geometry of the specimen joint is decided as per the ISO standard, ISO 6922:1987(E) [8]. Dimensions for prepared specimen are 25×10×400 mm. SS-304 is selected as an adherend material while adhesive selected is standard Araldite epoxy adhesive which is two part adhesive, mixture of resin and hardener. Different levels of scarf angles are given by cutting the specimen at centre. Three levels of surface roughness achieved by trial and error method. Mitutoyo Surftest SJ - 400 surface roughness measuring device is used for that purpose. The adherends were then cleaned by an appropriate surface preparation method, as per the guidelines provided by ASTM standard ASTM D 2651-01 [8]. Surface preparation carried out in three steps, first degreasing then abrading followed by chemical treatment[5]. After surface preparation, components of epoxy adhesive i. e. resin and hardener were mixed thoroughly before bonding. To maintain the proper mixture ratio small tubes of resin and hardener are used. Araldite epoxy adhesive in the form of a paste is used. After mixing the adhesive, a thin layer is applied on both surfaces of the adherend which required to be joined. This thin, continuous layer assures that the entire surface is wetted and helps the adhesive to spread uniformly. Adhesive was then added uniformly over the entire surfaces. While doing so special care was taken to keep the amount of air bubbles trapped in the adhesive as minimum as possible. In this study, the epoxy adhesive used is room temperature curing epoxy adhesive, so procedure of joining is carried out at room temperature only. The bond thickness, t was adjusted using a special arrangement, traveling microscope is used for that purpose. All specimens were cured at room temperature for more than 24 hours.

After specimens were totally cured, the excessive adhesive was removed. The actual bond thickness, t was then measured with the help of travelling microscope. Prepared scarf adhesive joint is shown in Fig. 3.

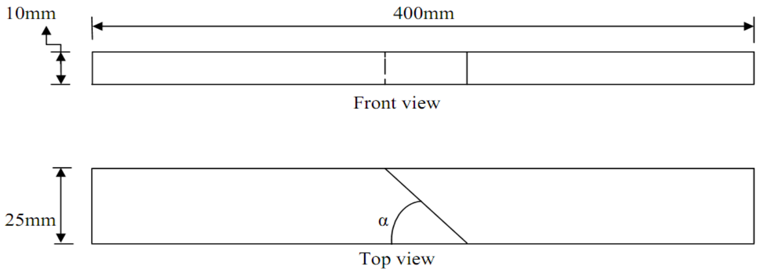

Fig. 2. Specimen for tensile test

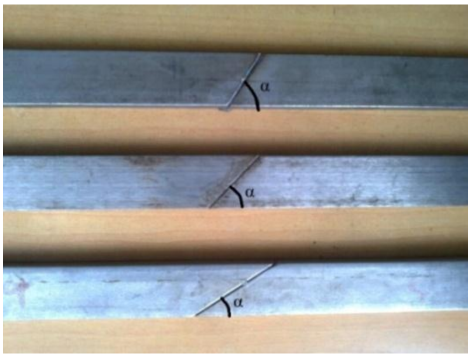

Fig. 3 Prepared scarf adhesive joint

4. Experimentation and Measurement

Tensile test of each specimen of scarf adhesive joint was conducted at room temperature using universal testing machine (INSTRON) manufactured by Fine spavy associates and engineers pvt. ltd. having 60 KN maximum load as shown in Fig. 4 [9]. As the tensile load applied on joint, tensile stresses induced within the joint goes on increasing, finally it reaches to the maximum limit and adhesive joint fails. This load is nothing but a failure load which is recorded for every specimen. Failure load i. e. breaking strength for all specimens is shown in Table 4.

5. Result Analysis and Discussion

After the experiments have been conducted, the next step is to determine optimum levels of control factor and to perform analysis of variance (ANOVA).The obtained values for breaking strength are used to find out optimum levels and their contribution to joint strength.

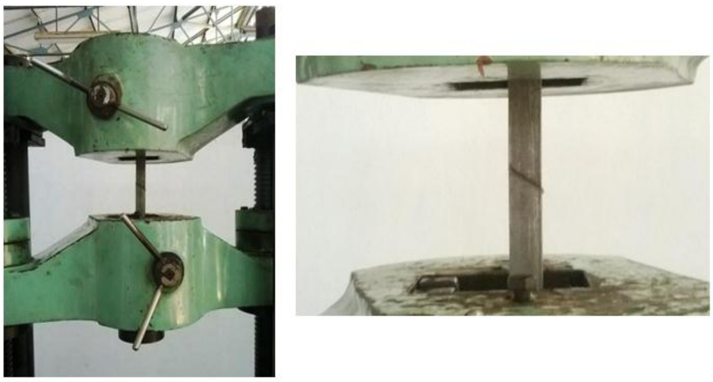

Fig.4. Testing of scarf adhesive joint on UTM

5.1. Analysis and Determination of Optimum Parameters:

To determine the optimum levels, S-N ratio approach is used. Hence S/N ratio of every response is to be found out.

5.1.1. Response Table for S/N Ratio for Breaking Strength

S/N ratios for all responses are shown in Table 5. Response table for S/N ratio for breaking strength given by MINITAB software is shown in Table 6. Every value in the response table for S/N ratio gives average of S/N ratio for a parameter for each level. For example, the first value in a table is 3.309 which is an average of three values of S/N ratios for scarf angle for first level i. e. 30^0. Similarly all average values for S/N ratios are given in a table.

Table 4. Experimental values for breaking strength

Experiment number	Control factors				Breaking strength (KN)
	Scarf angle (degree)	Surface roughness (μm)	Layer thickness (mm)	Mixture ratio (Resin : Hardener)	
1	30	1	0.5	1	1.6
2	30	2	1	1.5	1.4
3	30	3	1.5	2	1.4
4	45	1	1	2	1.5
5	45	2	1.5	1	2.3
6	45	3	0.5	1.5	2.1
7	60	1	1.5	1.5	1.7
8	60	2	0.5	2	2.1
9	60	3	1	1	2.4

Table 5. S/N ratio for breaking strength

Sr. No.	Scarf angle (^{0})	Surface roughness (μm)	Layer thickness (mm)	Mixture ratio (Resin: Hardener)	Breaking Strength (KN)	S/N ratio
1	30	1	0.5	1.0	1.60	4.082
2	30	2	1.0	1.5	1.40	2.922
3	30	3	1.5	2.0	1.40	2.922
4	45	1	1.0	2.0	1.50	3.521
5	45	2	1.5	1.0	2.30	7.234
6	45	3	0.5	1.5	2.10	6.444
7	60	1	1.5	1.5	1.70	4.608
8	60	2	0.5	2.0	2.10	6.444
9	60	3	1.0	1.0	2.40	7.604

Table 6. Response Table for Signal to Noise Ratios
Larger is better

Level	Scarf angle	Surface roughness	Layer thickness	Mixture ratio
1	3.309	4.071	5.657	6.307
2	5.734	5.534	4.683	4.659
3	6.219	5.657	4.922	4.296
Delta	2.910	1.586	0.974	2.011
Rank	**1**	**3**	**4**	**2**

Delta value given in the table gives the difference in S/N ratio within the different levels of same parameter, more the delta value more is the variation in S/N ratio and hence more is the contribution of that factor in the response. The rank for each control factor given in a table gives the order in which every factor is contributing for a particular response and it is decided by the value of delta. From higher to lower value of delta, ranks of all factors are decided. It can be seen from the Table 6 that for a breaking strength delta value of scarf angle is maximum followed by mixture ratio, surface roughness and layer thickness. Hence in the same order rank is given to the control factors.

5.1.2. Main effects plot for Breaking Strength:

The main effect plot obtained from MINITAB software is shown in Fig. 5. The main effects plot graphically represents the effect of factors on the response which helps to compare the effect of each level of the control factor on the response under study. The reference line drawn is showing the average S/N ratio for overall response. From the main effect plot it is clear that the breaking strength will maximum at level 3 for scarf angle and surface roughness while level 1 of layer thickness and mixture ratio will result in maximum response.

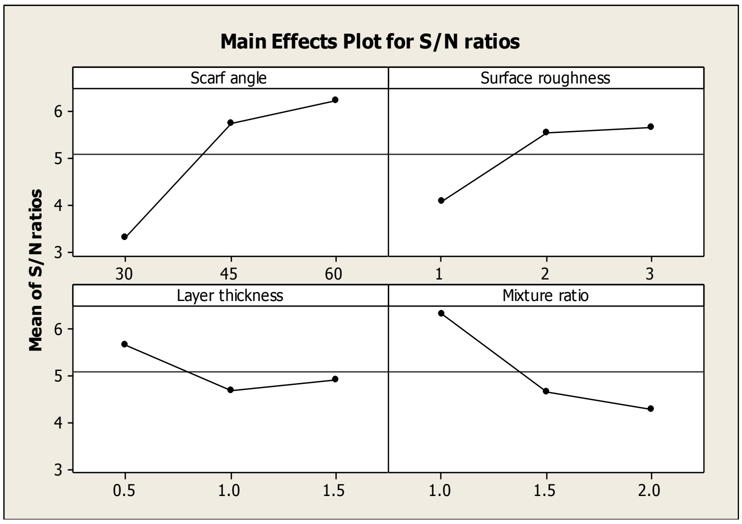

Fig.5. Main effects plot for S/N ratio of Breaking Strength

5.1.3. Percent contribution of parameters on response:

In order to find out significant factors involved in the analysis determination of their percent contribution is required. With the help of ANOVA it can be done. The ANOVA for breaking strength is shown in Table 7. The percent contribution is a function of sum of squares of each control factor. It is shown in the Table 7. A problem with ANOVA is that, in L9 array which is chosen for analysis, total degrees of freedom available are 9-1= 8 [6][7]. Three levels of each factors are considered, so all four factors are assigned with 2 degrees of freedom each. Hence degrees of freedom can be assigned to the error is zero, because of which it was not possible to calculate the mean sum of square for error and hence the F ratio. To solve this problem the concept of pooling is used, in which one of the controlling parameter having least percentage contribution can be 'pooled' to the error that means its contribution is considered as an error and added into it. Which allowed to assign 2 degrees of freedom to the error from which mean sum of square is calculated and ultimately F ratio can be found out. The modified ANOVA table is shown in the Table 8. The percent contribution given by ANOVA is shown in Fig. 6. For the breaking strength it is clear that percent contribution of layer thickness is minimum so it is pooled to error which is shown in Table 8.

Table 7. ANOVA for Breaking Strength

Sr. No.	Factor	SS	DOF	MSS	F	Percent contribution
1	SA	0.620	2	0.31		50.00
2	SR	0.246	2	0.123		19.89
3	LT	0.046	2	0.023		3.76
4	MR	0.326	2	0.163		26.34
5	Error	0	0	-	-	-
6	Total	1.24	8			100

5.2. Confirmation Experiment

The experimental confirmation test is the last step in a verifying results obtained based on Taguchi's methodology. In this step the experiments are performed for the combination of all parameters with their optimum levels and response is recorded. Then the results from the confirmation experiments are compared with the predicted results based on parameters and level tested. The predicted results is only a point estimate based on the averages of the results obtained from the experiments. While performing the confirmation experiment it is better to have a range of value than having a exact value of predicted results within which the observed values should fall with some confidence, which is nothing but a confidence interval. This is shown in Table 10. The configuration of joint to be tested is as given in Table 9. This joint is tested on Universal testing machine by exerting tensile load and obtained results are shown in the same Table 9.

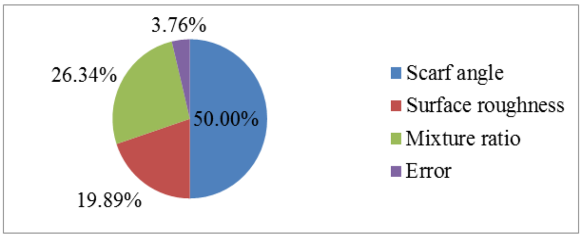

Fig. 6. Percent contribution in Breaking Strength

Table 8. Modified ANOVA Table for Breaking Strength

Sr. No.	Factor	SS	DOF	MSS	F	Percent contribution
1	SA	0.620	2	0.31	13.285	50.00
2	SR	0.246	2	0.123	5.285	19.89
3	LT			Pooled		
4	MR	0.326	2	0.163	7	26.34
5	Error	0.046	2	0.023		3.76
6	Total	1.24	8			100

Table 9. Configuration of Joint for Confirmation Experiment along with Results

Response	Control factors				Observed results	Predicted Results
	Scarf angle (^{0})	Surface roughness (µm)	Layer thickness (mm)	Mixture ratio (Resin :Hardener)		
Breaking Strength (KN)	60	3	0.5	1	2.6	2.683

Table 10. Summary of Results with Confidence Interval

Sr. No.	Response	Predicted Results	Confidence Interval (C. I.)		Observed Results
			Lower	Upper	
1	**Breaking strength (KN)**	2.683	2.031	3.336	2.6

5.3 Discussion

Observing joint surfaces after failure, brittle failure were observed in all joints. The failure were either adhesive failure or cohesive failure. The surfaces were damaged and it was the combination of breaking and peeling. From the S-N ratio plot it can be seen that with increase in scarf angle breaking strength increases but the slope is getting reduced for 45^0 to 60^0 of scarf angle and at 60^0 of scarf angle maximum breaking strength is obtained. With variation in scarf angle surface area available for bonding varies but at the same time tensile and shear stresses developed along the surfaces limits the higher value of scarf angle.

To derive these stresses, geometry of the joint is important. Consider the section according to Fig.7, principal component of stress can be determined as,

$$P = \frac{F}{Q} \tag{1}$$

Force F can be resolved into normal and tangential components, the individual force components are

$$N = F \text{ x } \sin \alpha \qquad \text{Normal component} \tag{2}$$

$$T = F \text{ x } \cos \alpha \qquad \text{Tangential component} \tag{3}$$

Bonded surface area S is

$$S = Q / \sin \alpha \tag{4}$$

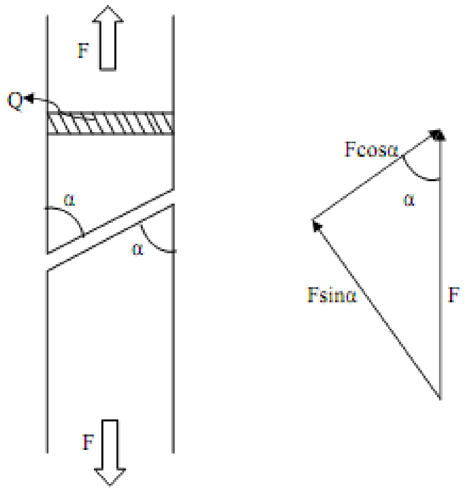

Fig. 7. Stresses in scarf adhesive joint

Introduce equation (3) and (4) in the basic equation of shear stress, relation between scarf angle and shear stress can be given as,

Shear stress $\tau = \frac{T}{S} = \frac{F * \cos\alpha}{\frac{Q}{\sin\alpha}}$

$$= \frac{F}{Q} * \cos\alpha * \sin\alpha$$

$$\tau = \frac{P}{2} * \sin 2\alpha \tag{5}$$

Similarly tensile stresses at bonded surface can be found out by introducing equation (2) and (4) in the basic equation of tensile stress as,

$$\sigma = \frac{N}{S} = \frac{F*\sin\alpha}{\frac{Q}{\sin\alpha}}$$

$$= \frac{F}{Q} * \sin^2 \alpha$$

$$\sigma = \frac{P}{2} * (1\text{-}\cos 2\alpha) \quad (6)$$

Using expression given in (5) and (6), tensile and shear stresses developed along the joint can be found out for angles 30^0, 45^0 and 60^0 and after calculating resultant stresses it can be seen that at 60^0 of scarf angle maximum stresses can be achieved.

Joint strength also increases with increase in surface roughness from 1 μm to 2 μm but from 2 μm to 3 μm there is no significant change observed in a joint strength. Layer thickness of 0.5 mm and Mixture ratio of 1:1 have given the more strength of joint.

6. Conclusion:

After performing experimental tests on scarf adhesive joint and analyzing the results for the scarf adhesive joint using the signal to noise ratio approach, analysis of variance (ANOVA) and using Taguchi's optimization approach following are the conclusions from the present study:

1. Statistically designed experiments based on Taguchi methods were performed using L9 orthogonal arrays to analyze the breaking strength of scarf adhesive joint as response variables. S/N ratio and ANOVA both have given similar results which are verified by confirmation experiment.
2. The most dominating factor in scarf adhesive joint is scarf angle which affect the joint strength greatly as compared to other factors like surface roughness, layer thickness, mixture ratio. Whereas adhesive layer thickness is the least dominating factor.
3. Design of joint with optimum levels of control factors especially scarf angle results in maximum strength. The scarf angle of 60^0 resulted in high breaking strength.
4. It is seen from results that the optimum level for remaining control factors like surface roughness, layer thickness and mixture ratio are 3μm, 0.5 mm and1:1 respectively.
5. After observing the failure surfaces it is seen that in most of the cases failure was cohesive failure but in some cases it was adhesive failure in which surface roughness was low.

References

[1] Banea M. D., Silva L. F. M. Da. (2009). Adhesively bonded joints in composite materials: An overview *Journal of material design and applications*, vol. 223.

[2] Mohd A., Tokuo T., Hairul B. (2011). Strength prediction of epoxy adhesively bonded scarf joints of dissimilar adherends. *International Journal of Adhesion & Adhesives 31*, 402–411.

[3] Kishore, R. A., Tiwari, R., Dvivedi, A., Singh, I. (2009). Taguchi analysis of the residual tensile strength after drilling in glass fiber reinforced epoxy composites, *Journal of Materials and Design* (*30*), 2186-2190.

[4] Sinan A., Muraz Y. S., Aydin T. (2012). The effect of adhesive thickness, surface oughness and overlap distance on joint strength in prismatic plug-in joints attached with adhesive, *International Journal of Physical Sciences*, vol. 7(17), 2580-2586.

[5] Mohd A., Tokuo T., Akihiro M. (2011). Strength and fracture characteristics of SUS304/Al-alloy scarf adhesive joint with various adhesive thicknesses, *Key Engineering Materials*, vols. 462-463, 768-773.

[6] Tapan B. (1992). Taguchi Methods Explained: Practical Steps to Robust Design, Prentice-Hall India Ltd.

[7] Phillip J. R., Taguchi Technique for Quality Engineering. McGraw-Hill publication.

[8] ASTM-ISO Standard Comparative Guide.

[9] Dan H. E., Toshiyuki S., Takeshi I., Yuva H. (2010). Stress analysis and Strength evaluation of scarf adhesive joints subjected to static tensile load. *International Journal of Adhesion & Adhesives 30*, 387-392.

Mr. Horambe Prabodh B., the main author has born at Ratnagiri, Maharashtra, India on 22nd June 1989. He has graduated as B.E. in Mechanical Engineering at Finolex Academy of Management and Technology (University of Mumbai), Ratnagiri, Maharashtra, India in 2011. He has completed his post graduation as M.E. in Mechanical Engineering (Machine Design) at Finolex Academy of Management and Technology (University of Mumbai), Ratnagiri, Maharashtra, India in 2014. Machine design, material science, mechanical vibration are the major field of study for the Author. Currently He is working at Finolex Academy of Management and Technology, Ratnagiri, Maharashtra, India as an ASSISTANT PROFESSOR in Mechanical Engineering Department since 2011. Engineering Mechanics, Engineering Drawing , Mechanical Vibration are the different subjects of his current interest.