Impact of Riveting Parameters on Mechanical Properties of Aluminum Alloy (LY-12) Sealant Applied Lap Joint of an Aircraft

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ABSTRACT

The assembling process includes various techniques, out of which riveting has been employed most successfully in fields like construction of enormous structures, auto-motives, and most notably in the aerospace industry. This process includes marking, drilling followed by riveting. Furthermore, being a successful process, most of the aircraft structure is assembled using rivets. However, various factors contribute to the result. Therefore, the effect of riveting process parameters such as Sheet Thickness, Rivet Diameter, Rivet Type, and Riveting Sequence have been studied on responses, i.e., Deformation and Joint Load Capacity of lap joint composed of Aluminum Alloy sheets (LY-12) at T0 condition by sandwiching aerospace-grade sealant (XM-22B). Each of these parameters is studied on three levels and the experimental setup is designed using Response Surface Methodology (RSM). The main objective of this work is to demonstrate the effect of riveting parameters on lap joints with sealant and analyze the effect through careful measurement of deformation and joint load capacity of the test specimen. Finally, a variance analysis (ANOVA) is performed to identify significant factors influencing response parameters using Design Expert Software V-12.

Keywords: Deformation, Joint load capacity, RSM, ANOVA.

Introduction

Riveting is a standard process used in the aerospace industry, which is categorized as a cold working process. As a result, riveting [1]causes changes in the mechanical properties of metallic parts being riveted, especially aluminum sheets. These mechanical properties include the changes in fatigue strength, tensile strength, deformation, etc. "The mechanics of load transfer in lap joint structure (and resulting damage) is influenced by the through-thickness restraint offered by the installed rivet" [2]. In addition, these rivets often affect the fatigue life of the sheets being joined and sometimes lead to the initiation of surface cracks around the rivet hole due to depreciation in fatigue strength [3].

It has been seen in the aerospace industry that during the sub-assembly process (assembling process of sub-assemblies), most of the sheet metal parts show some sort of deformation in millimeters after riveting is carried out, increasing lengths of panels or changes in the radius of panel/ribs [4]. These deformations are mainly observed at the end of a riveting process in aluminum sheets[5]. However, these deformations are seen to be controlled to some extent when observed in lap joints with sealants [6]. As the effect of deformation in aluminum, sheets are required to be studied. To study this factor, the effect of different variables is also required for the riveting process, which is mostly considered in-feasible as all of the variables cannot be studied simultaneously [7]. Therefore, some variables may be kept constant to study a few of those variables[8]. Few of these variables like rivet material, the thickness of skins, riveting process, rivet type, rivet diameter, riveting sequence, countersunk height, etc., will be considered during this study[9]. The dimensional accuracy of the panels casts a significant effect on the feasibility of the subsequent assembly process and the aerodynamic performance [10]. The non-uniform expansion of the wall of rivet holes is a major factor inducing the deformation of riveted joint structure [11]. Aluminum alloys, usually Al 5754 or LY12 [12], are used in the aerospace industry. However, this material selection plays an essential role in tensile/ shear testing[13, 14].

Riveted lap joints[15] are affected by materials of sheet and rivets and process parameters that are mostly not given much consideration. Teerawut *et al.* studied the effects of the drilled hole, bucktail length and upset distance on lap joint of Aluminum grade A1100 specimens with pan head rivets which resulted in the use of big diameter rivet gives more strength with smaller buck head[16]. Loads on riveted lap joints induce stress which ultimately leads to failure. This phenomenon was studied by S. Venkateswalu *et al.* for carbon fiber reinforced plastic single lap joint with three joining methods that are bonded, riveted and hybrid, which suggested the efficiency of hybrid design compared to boded one[17].

Riveted lap joints of Aluminum alloy AL8081 were studied and experimentally verified [18]with and without reinforcement (sandwiched between sheets) of Glass laminate reinforced epoxy (GLARE) on a Universal Testing Machine (UTM). Experimental tests revealed that the ultimate load and tensile stress for reinforced specimens are far better than without reinforcement [19]. Lap joint of Aluminum alloy AL4047 with self-piercing rivets was designed and analyzed and was experimentally verified. It revealed that rivet size and velocity of loading play a pivotal role in the strength of the joint [20]. Mao Feng Fu *et al.* studied the effects of self-piercing rivets on Aluminum alloy 5754. Experimentation revealed that die tip height is the most significant factor [21]. Baoding Xing *et al.* studied the effects of varying rivets and distribution patterns on Aluminum alloy AA5052 lap joint samples with steel self-piercing rivets. Static strength and ductility of self-piercing rivet joints are influenced by the number of rivets and their distribution pattern[22]. J Kang *et al.* studied the effect of steel self-piercing[23] riveting on the lap joint of Aluminum 6111 T82 alloy (T4 condition) and Carbon Fiber Reinforced Plastic (CFRP). Experimentation revealed that crack growth along the width of the sheet is a reason for tensile loading [24].

This study will present the effect of different riveting parameters and control these parameters on riveted sealed joints. Understudy material will be LY-12 which is bonded using aviation-grade sealant (XM-22B). Results will then be analyzed using the RSM technique for three levels of riveting parameters. Finally, each of the results will be utilized to control strength and deformation in joints by varying input parameters.

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Material and Methodology

Design of Experiments (DoE) is a tool to develop mathematical models that significantly understand the impact of input parameters on output parameters [25]. The response surface methodology (RSM) is a widely used mathematical and statistical method for modeling and analyzing a process in which the response of interest is affected by various variables [26]. The objective of this method is to optimize the response [27]. The parameters that affect the process are called independent variables, while the responses are called dependent variables [28]. RSM investigates an appropriate approximation relationship between input and output variables and identifies the optimal operating conditions for a system under study or a region of the factor field that satisfies the operating requirements [29, 30]. The Box Behnken design of RSM includes 16 factorial points, 8 axial points, and 6 center points(Three extra runs taken at the center make it a complete factorial design)[31]. Four factors, as mentioned earlier, have been analyzed at three levels to study their effect on response parameters (Deformation and Joint Load Capacity) through the Box Behnken design of RSM DoE.

Aluminum alloy is the material of choice for aircraft structure due to its strength, corrosion resistance, and lightweight, providing a perfect mixture of properties required in this industry. Aluminum alloys such as Al 2024, 2219, 6063, 7075, and 7079 are being used in aviation for a long time and a lot of research has been carried out on the significance of these alloys. In this study, Aviation grade Aluminum Alloy (LY-12) at T0 condition will be utilized to prepare test pieces and similar material rivets are also used to avoid corrosion. Major constituents of this material are Cu (3.8 ~ 4.9 %), Mg (1.2 ~ 1.8 %), Mn (0.3 ~ 0.9 %), Si (0.5 %), Fe (0.5%), Zn (0.5 %), Ti (0.15 %) and (Cr 0.1%).

The specimens for experimentation were designed in CATIA software, keeping in view the basic requirements of riveting standards as per dimensions mentioned in Fig. 1.

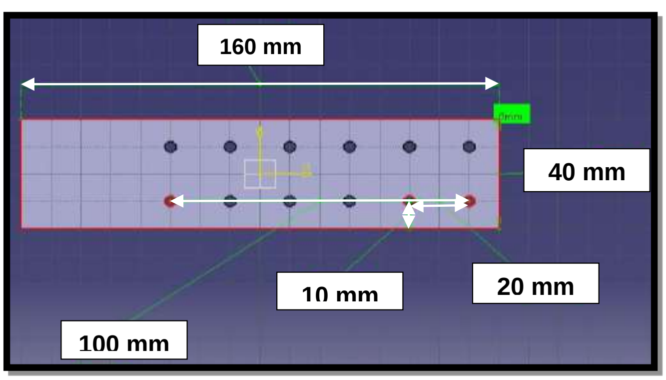

Fig 1: CATIA Model of Test Specimen

The riveting process was performed keeping in view the complete requirements as per aerospace standards [32]. The configuration was followed as per RSM Matrix. The riveting process included sheet cutting, marking holes, center punching, drilling of holes, de-burring, sealant application and its curing followed by riveting. After riveting, each rivet was inspected per standards and then primer was applied to avoid any corrosion.

Fig 2: Samples Preparation

Results and Discussion

Two different resultants were measured during this experimental phase, i.e., deformation (mm) and joint load capacity (N). First, axial deformation is measured using 3-Axis Coordinate Measuring Machine (CMM) with a total bed capacity of (2000 mm, 1500 mm, and 1200 mm). Second, axial deformation is measured before performing riveting [while holding with calicos (temporary fasteners)] and after riveting the test specimens from the same point each time. Results were then recorded as depicted in Table 1.

ANOVA was conducted at a 95% confidence level. The analysis of variance suggested that out of selected input parameters, Sheet Thickness and Rivet Diameter are significant terms as they have a p-value less than 0.005. In contrast, Rivet Type and Riveting Sequence are not significant as they have a p-value greater than 0.01. Therefore, by changing these input parameters, deformation in sheets due to the riveting process can be controlled

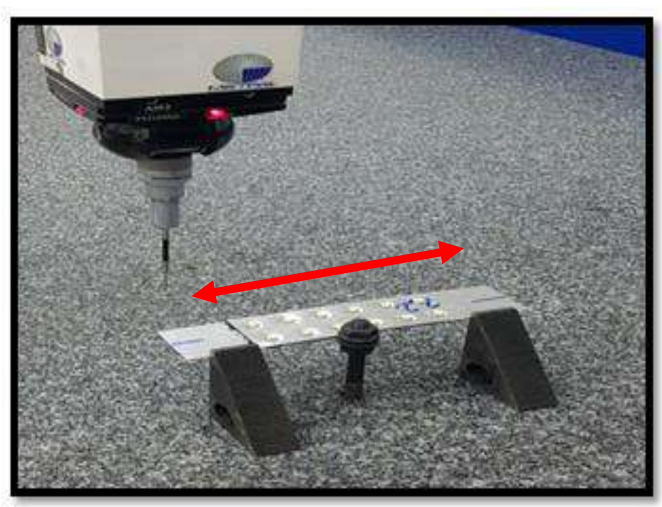

Fig 3: CMM for Axial Deformation Measurement

Table 1: Deformation Results

Exp	Factor 1	Factor 2	Factor 3	Factor 4	Before Riveting	After Riveting	Deformation
	Sheet Thickness (mm)	Rivet Diameter (mm)	Rivet Type (Head)	Riveting Sequence	a (mm)	b (mm)	δ = b-a (mm)
1	0.8	2.5	Pan Head	One to other end	199.3468	199.9	**0.5507**
2	1.5	2.5	Pan Head	One to other end	199.9043	200.37	**0.4694**
3	0.8	4	Pan Head	One to other end	200.2453	200.91	**0.6685**
4	1.5	4	Pan Head	One to other end	200.2862	200.85	**0.5622**
5	1.2	3.5	Countersunk	Inward to outward	200.1407	200.72	**0.5802**
6	1.2	3.5	Round Head	Inward to outward	200.6515	201.26	**0.6117**
7	1.2	3.5	Countersunk	Outward to inward	201.5158	202.13	**0.6102**
8	1.2	3.5	Round Head	Outward to inward	202.0407	202.6	**0.5576**
9	0.8	3.5	Pan Head	Inward to outward	199.1444	199.73	**0.5834**
10	1.5	3.5	Pan Head	Inward to outward	201.0911	201.61	**0.5187**
11	0.8	3.5	Pan Head	Outward to inward	199.5019	200.12	**0.6228**
12	1.5	3.5	Pan Head	Outward to inward	199.9522	200.44	**0.4859**
13	1.2	2.5	Countersunk	One to other end	202.0192	202.54	**0.5168**
14	1.2	4	Countersunk	One to other end	203.1834	203.8	**0.6117**
15	1.2	2.5	Round Head	One to other end	199.8006	200.34	**0.5359**
16	1.2	4	Round Head	One to other end	200.8168	201.44	**0.6276**
17	0.8	3.5	Countersunk	One to other end	199.5465	200.12	**0.5769**
18	1.5	3.5	Countersunk	One to other end	199.8818	200.42	**0.54**
19	0.8	3.5	Round Head	One to other end	199.6597	200.25	**0.594**
20	1.5	3.5	Round Head	One to other end	200.185	200.68	**0.4984**
21	1.2	2.5	Pan Head	Inward to outward	200.6533	201.2	**0.5441**
22	1.2	4	Pan Head	Inward to outward	201.1827	201.77	**0.5902**
23	1.2	2.5	Pan Head	Outward to inward	200.2261	200.74	**0.5101**
24	1.2	4	Pan Head	Outward to inward	201.6009	202.21	**0.6108**
25	1.2	3.5	Pan Head	One to other end	200.9746	201.49	**0.5146**
26	1.2	3.5	Pan Head	One to other end	201.2402	201.73	**0.4948**
27	1.2	3.5	Pan Head	One to other end	200.9648	201.47	**0.5077**
28	1.2	3.5	Pan Head	One to other end	201.7309	202.32	**0.5894**
29	1.2	3.5	Pan Head	One to other end	201.6308	202.2	**0.5675**
30	1.2	3.5	Pan Head	One to other end	201.9732	202.57	**0.592**

Table 2: ANOVA Results for Deformation

Source	Sum of Squares	df	Mean Square	F-value	p-value	Status
Model	0.0474	4	0.0119	13.21	< 0.0001	**significant**
Factor A (Sheet Thickness)	0.0227	1	0.0227	25.26	< 0.0001	**significant**
Factor B (Rivet Dia)	0.0247	1	0.0247	27.48	< 0.0001	**significant**
Factor C (Rivet Type)	9.577E-06	1	9.577E-06	0.0107	0.9185	
Factor D (Riveting Sequence)	0.0001	1	0.0001	0.0879	0.7694	
Residual	0.0224	25	0.0009			
Lack of Fit	0.0129	20	0.0006	0.3392	0.9625	Not significant
Pure Error	0.0095	5	0.0019			
Cor Total	0.0699	29				

To measure the Joint Load Capacity, the test specimen was held in the jaws of a Numeric Controlled Universal Tensile Tester with the capacity of 50 kN. The load was applied on the riveted test specimen axially and the results were measured by the machine automatically upon fracture point. Results were recorded and tabulated in Table 3.
ANOVA was conducted at a 95% confidence level. The analysis of variance suggested that out of selected input parameters, Sheet thickness and Rivet Type are significant as they constitute a p-value less than 0.005. In contrast, Rivet Diameter and Riveting Sequence are not significant as they have a p-value greater than 0.01. Therefore, by changing these input parameters, Joint Load Capacity can be controlled.

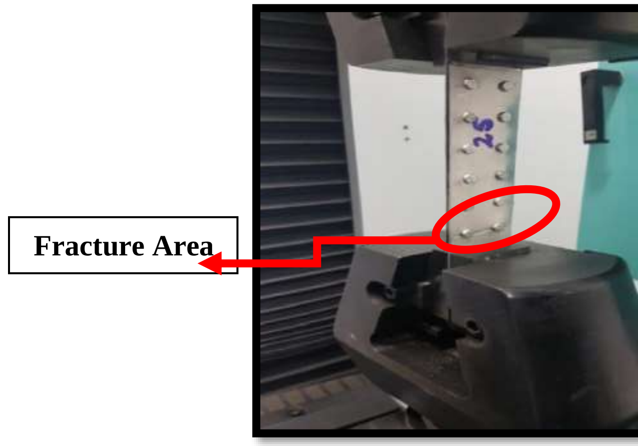

Fig 4: Joint Load Capacity Measurement

Table 3: Joint Load Capacity Results

Exp	Factor 1	Factor 2	Factor 3	Factor 4	Response
	Sheet Thickness (mm)	Rivet Diameter (mm)	Rivet Type (Head)	Riveting Sequence	Joint Load Capacity (N)
1	0.8	2.5	Pan Head	One to other end	**4589.6**
2	1.5	2.5	Pan Head	One to other end	**8375.3**
3	0.8	4	Pan Head	One to other end	**4134.2**
4	1.5	4	Pan Head	One to other end	**7753**
5	1.2	3.5	Countersunk	Inward to outward	**5237.9**
6	1.2	3.5	Round Head	Inward to outward	**6109.5**
7	1.2	3.5	Countersunk	Outward to inward	**5663.1**
8	1.2	3.5	Round Head	Outward to inward	**5807.5**
9	0.8	3.5	Pan Head	Inward to outward	**4018.6**
10	1.5	3.5	Pan Head	Inward to outward	**8106.8**
11	0.8	3.5	Pan Head	Outward to inward	**4108.8**
12	1.5	3.5	Pan Head	Outward to inward	**7388.2**
13	1.2	2.5	Countersunk	One to other end	**6649.4**
14	1.2	4	Countersunk	One to other end	**4873.9**
15	1.2	2.5	Round Head	One to other end	**6394.3**
16	1.2	4	Round Head	One to other end	**6763.8**
17	0.8	3.5	Countersunk	One to other end	**3638.9**
18	1.5	3.5	Countersunk	One to other end	**6912.3**
19	0.8	3.5	Round Head	One to other end	**4076.4**
20	1.5	3.5	Round Head	One to other end	**8149.6**
21	1.2	2.5	Pan Head	Inward to outward	**6080.9**
22	1.2	4	Pan Head	Inward to outward	**7057.5**
23	1.2	2.5	Pan Head	Outward to inward	**6090.8**
24	1.2	4	Pan Head	Outward to inward	**6924.1**
25	1.2	3.5	Pan Head	One to other end	**6289**
26	1.2	3.5	Pan Head	One to other end	**6243.6**
27	1.2	3.5	Pan Head	One to other end	**6131.1**
28	1.2	3.5	Pan Head	One to other end	**6017.7**
29	1.2	3.5	Pan Head	One to other end	**6896.1**
30	1.2	3.5	Pan Head	One to other end	**6689.2**

Table 4: ANOVA Results for Joint Load Capacity

Source	Sum of Squares	Df	Mean Square	F-value	p-value	Status
Model	4.666E+07	14	3.333E+06	20.92	< 0.0001	**significant**
Factor A(Sheet Thickness)	4.077E+07	1	4.077E+07	255.98	< 0.0001	**significant**
Factor B(Rivet Dia)	37833.87	1	37833.87	0.2375	0.6330	
Factor C(Rivet Type)	1.559E+06	1	1.559E+06	9.79	0.0069	**significant**
Factor D(Riveting Sequence)	32938.64	1	32938.64	0.2068	0.6558	
AB	6963.90	1	6963.90	0.0437	0.8372	
AC	1.599E+05	1	1.599E+05	1.00	0.3322	
AD	1.635E+05	1	1.635E+05	1.03	0.3270	
BC	1.150E+06	1	1.150E+06	7.22	0.0169	
BD	5133.72	1	5133.72	0.0322	0.8599	
CD	1.322E+05	1	1.322E+05	0.8301	0.3767	
A^2	7.027E+05	1	7.027E+05	4.41	0.0530	
B^2	3.764E+05	1	3.764E+05	2.36	0.1451	
C^2	1.340E+06	1	1.340E+06	8.41	0.0110	
D^2	1.592E+05	1	1.592E+05	0.9995	0.3333	
Residual	2.389E+06	15	1.593E+05			
Lack of Fit	1.807E+06	10	1.807E+05	1.55	0.3277	Not significant
Pure Error	5.820E+05	5	1.164E+05			
Cor Total	4.904E+07	29				

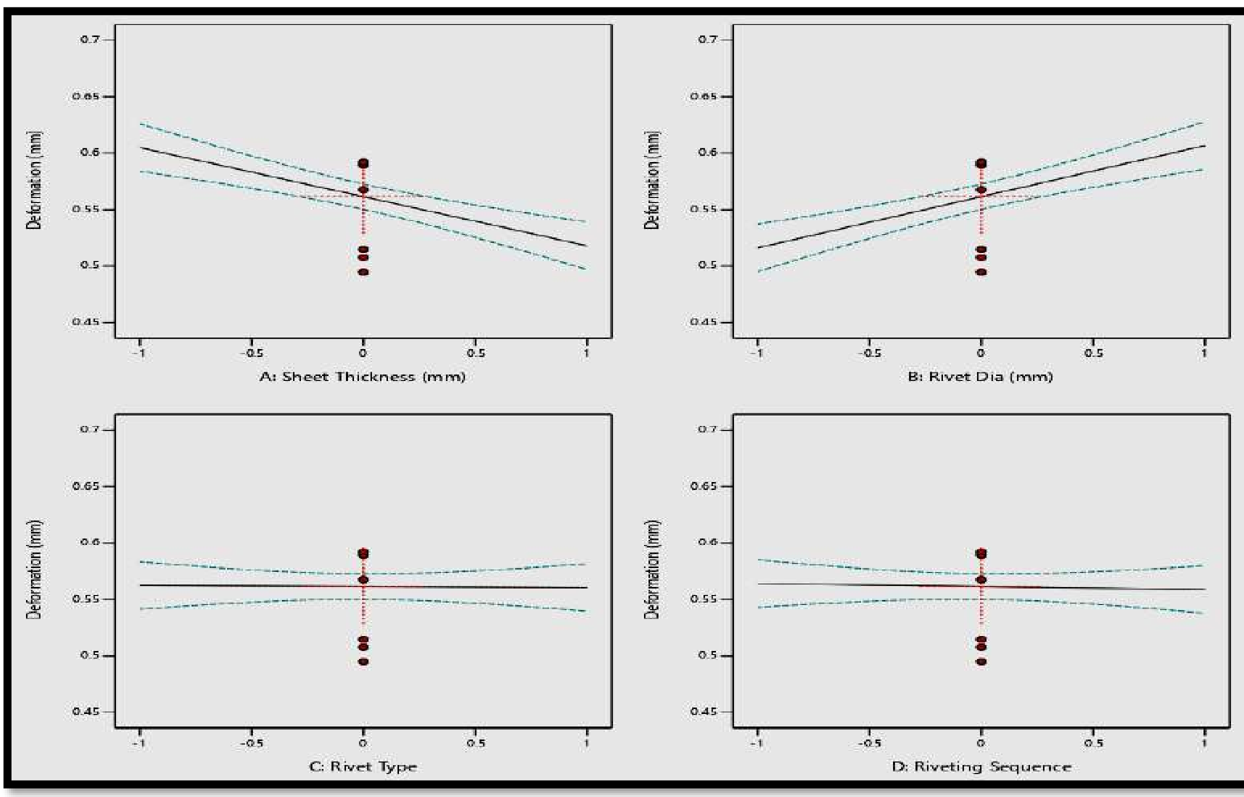

Fig 5: One Factor Analysis of Deformation

By considering Fig-5 (one-factor analysis of deformation), each factor considered during this study has been mapped graphically against deformation results. For example, by increasing the sheet thickness of the test specimen from 0.8 mm to 1.5, an apparent decrease in deformation is observed. In contrast, a similar but inverse case is observed when the rivet diameter is changed from 2.5 mm to 4 mm sudden increase in deformation is observed. However, for the remaining two factors, the contribution is relatively minimal. Thus, to conclude, sheet thickness and rivet diameters must be controlled to attain optimal results; hence decreasing the deformation due to riveting is the primary goal.

By considering Fig-6, increasing the sheet thickness from 0.8 mm to 1.5 mm, an apparent increase in joint load capacity of the test specimen can be observed. While moving from countersunk head rivet to round head gives better strength to lap joint. However, the combined contribution of the remaining two factors is minimal. Hence, the main contribution of sheet thickness and rivet type show that joint load capacity can be controlled by varying the above-said factors. The rupture of samples was verified with finite element analysis using ANSYS V-16. Analysis verified that the joint would rupture in net tension of sheets, as shown in the following figure.

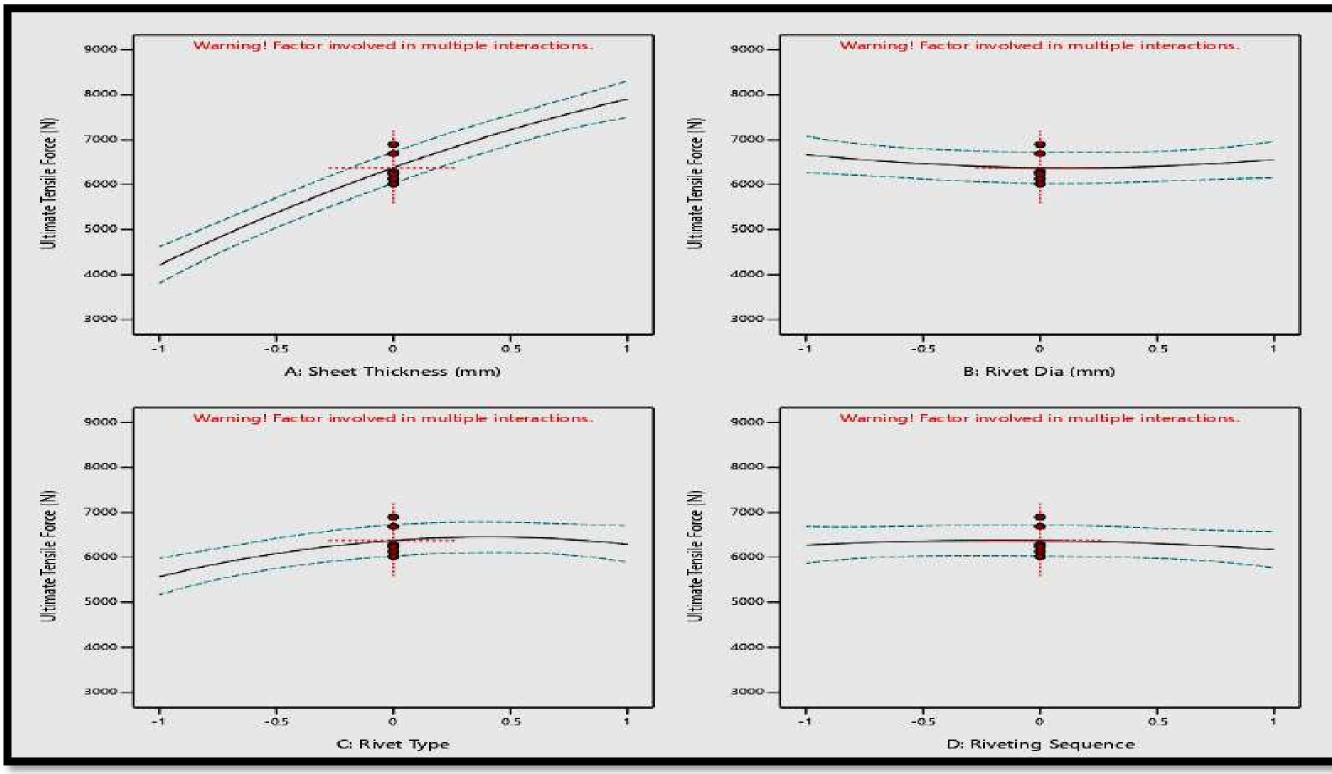

Fig 6: One Factor Analysis of Joint Load Capacity

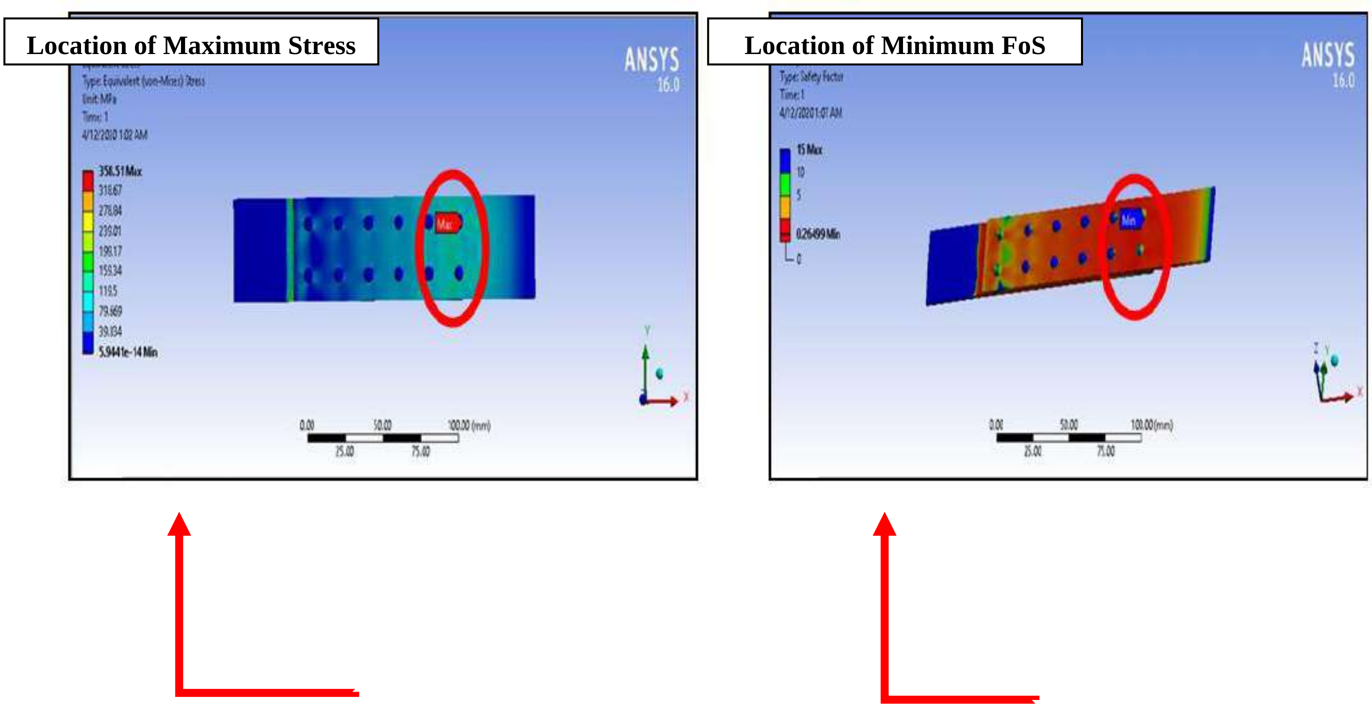

Fig 7: ANSYS Verification

Conclusion

This study presented that undesired deformation phenomena can be controlled by controlling sheet thickness and rivet diameter as both are significant factors. In contrast, the type of rivet and riveting sequence has no significant effect. Similarly, process parameters like sheet thickness and rivet type are significant terms for joint load capacity, while riveting sequence and rivet diameter have no major effect. Thereby controlling above mentioned significant factors can help optimize the riveting process and prevent undesired results like deformation and less strength of joints.

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