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Improving The Strength Of Adhesively Bonded T-Peel Joints

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ABSTRACT

Adhesively bonded joints normally have low peel strength due to the concentration of stresses on the small bondline. It has been reported that the geometry parameters of bonded peel joint have significant effect on strength of the joint. The aim of present work is to investigate the effect of geometric parameters and their interactions on the peel strength of these joints.
In the present work, geometry parameters namely: bondline thickness, adherent thickness, adhesive spew fillet ratio as well as the flange radius were thoroughly investigated. Finite element analysis has been implemented in order to evaluate the possible parameters combinations. Moreover, statistical analysis was conducted and a mathematical model has been developed and validated. The results showed that the geometry parameters of the bonded peel joint have significant effect on the predicted strength of the joint. The results also showed the predicted peel strength increases with increase in bonded line thickness adherend thickness, fillet spew parentages and decrease with flange radius reduction.

Keywords: T-peel Joint, Adhesively Bonded Joint, Finite Element Analysis, Mathematical model.

1. Introduction

Joining of metal components is usually achieved by different joining techniques such as mechanical fastening (rivets, bolts and screws), welding, or adhesive bonding. The widespread popularity of adhesive bonding can be attributed to the following factors (Darwish, S. M. H. (2011); Campilho, R. *et al*, (2012):

- Uniform stress distribution along bonded joints is promoted.
- No need for drilling operations.
- Improved fatigue performance.
- Weight reduction when compared with riveting and mechanical fasteners.
- Better corrosion resistance between dissimilar materials.
- Unreformed external joint surfaces are promoted.

With the rapid growth in the use of adhesive bonding process more investigation is required to enhance the strength of bonded structural joints. Several research works (Darwish, S. M. H. (2011); Beevers, A. *et al*, 2001) have been conducted to investigate enhancing the strength of adhesively bonded peel joints.

Matsui (Matsui, K. (1990) compared the peel strength of T-peel joint having different bondline adhesive thickness. It has been found that peel joint strength increases with the increase in bondline thickness (adhesive layer thickness). Darwish (Darwish, S. (2004)) also evaluated the effect of adherend thickness dissimilarity on the peel strength of spot-welded and weld-bonded T-peel joint. His results showed that dissimilarity of adherend thickness increases the stress concentration, at the boundaries of weld nugget. Furthermore, it was reported that stress concentration located in the thinner member of the joint is higher than that in thicker adherend. Beevers (Beevers, A. *et al*, 2001) studied the effect of spew fillet ratio (0, 25, 50, 75 and 100%) on the T-peel joint stiffness. His results showed that spew fillet parameter of T-peel joint had a significant influence on the T-peel stiffness. It was observed that the T-peel stiffness increased by 11 times for the case of 100% spew fillet ratio as compared to non- spew fillet model.

Accordingly, the aim of the present work is to run a parametric study in order to come up with the best combinations that enhance the peel strength of these joints.

2. Finite element model

Pre-processing and post-processing of finite-element (FE) model are performed using GID program (GID Ver. 6.2 Software, 2001). Computational process was carried out by Tochnog FE program which runs under Linux operating system (http://tochnog.sourceforge.net).

2.1 Solid modeling

Solidworks 2011 software has been used for generating the solid models which also were used as input file for FE preprocessing GID program. In the present work adhesively bonded T-peel joints have been modeled according to ASTM standard D (1876 - 01) (www.astm.org). The configuration and dimensions of modeled specimen are shown in Figures (1 and 2).

As shown in figures the T-peel joint consists of two bonded 90º bend substrates having L-shape, with dimension of 100 mm vertical length 75mm and a width of 12.5mm with a 1.6 mm sheet metal thickness, The bend substrates were joined together by an adhesive layer, having thickness of 0.1 mm. In order to reduce computational time, it was decided to consider only half model.

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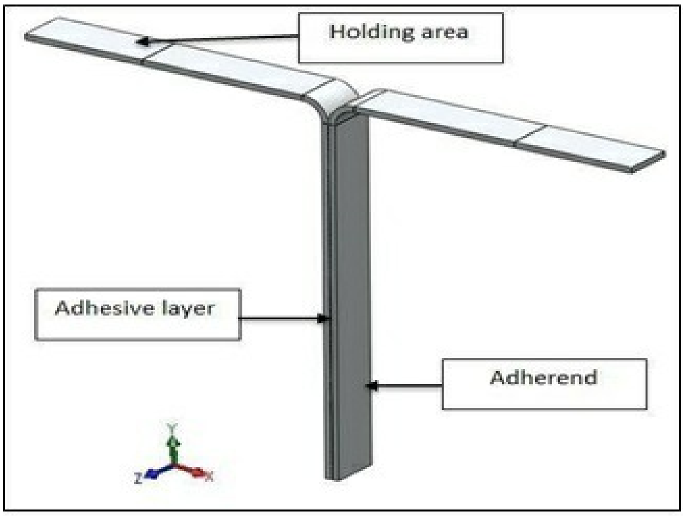

Figure 1: Configuration of adhesively bonded T peel joint.

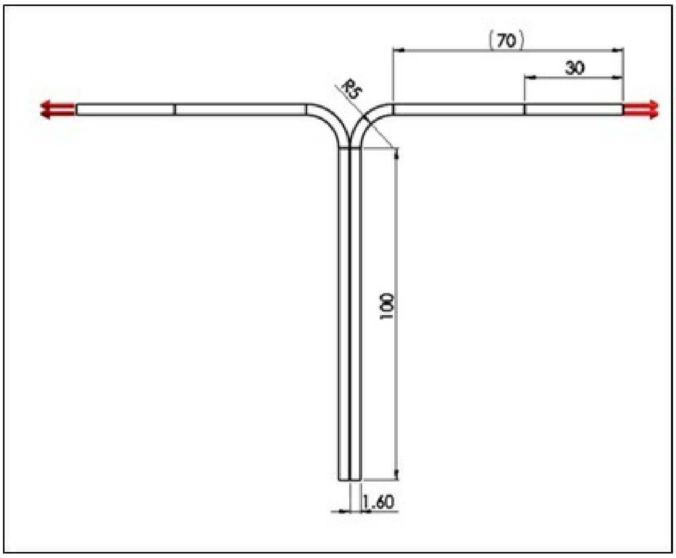

Figure 2: Dimensions of adhesively bonded T peel joint.

2.2. Assigning materials properties

The second step of FE modeling is assigning materials properties. Table 1 shows the assigned mechanical properties for both adherend and adhesive material used. It worth mentioning that, it was decided to use Epoxy of Araldite 2011 adhesive material due to its practical repetition.

Table 1: Mechanical properties of assigned materials

Martial	Elastic modulus (MPa)	Poisson's ratio	Yield strength (Mpa)	Density g/cm^3
Aluminum 2024-T3	73100	0.33	358.16	2780
Epoxy adhesive	185.22	0.37	36.3	1.035

2.3. Assigning boundary and loading conditions

Two types of boundary conditions, namely fixed and movable boundary conditions were applied to the model, as shown in figure (3). Fixed boundary conditions were assigned to one edge of the joint (X,Y and Z directions), while roller constrain conditions were applied along 30 mm of the length on upper and lower siders of joint (Y-direction) as shown in figure (3) (in order to simulate peel joint testing conditions (GID Ver. 6.2 Software, 2001; (http://tochnog.sourceforge.net). Furthermore, symmetrical boundary conditions have been assigned along model plane (XY).

It was decided also to assign a relatively small load of 100N to on the top edge of the joint, as shown in figure (3). This small load was adopted in the FE analysis in order to insure the elastic behavior for the joint under loading conditions. The assumptions considered for the developed FE model were as follows:

1. The problem is three dimensional.
2. Isotropic and homogeneous materials.
3. Stresses and strain are in the elastic zone.
4. The joint undergoes cohesive type of failure after peel testing.

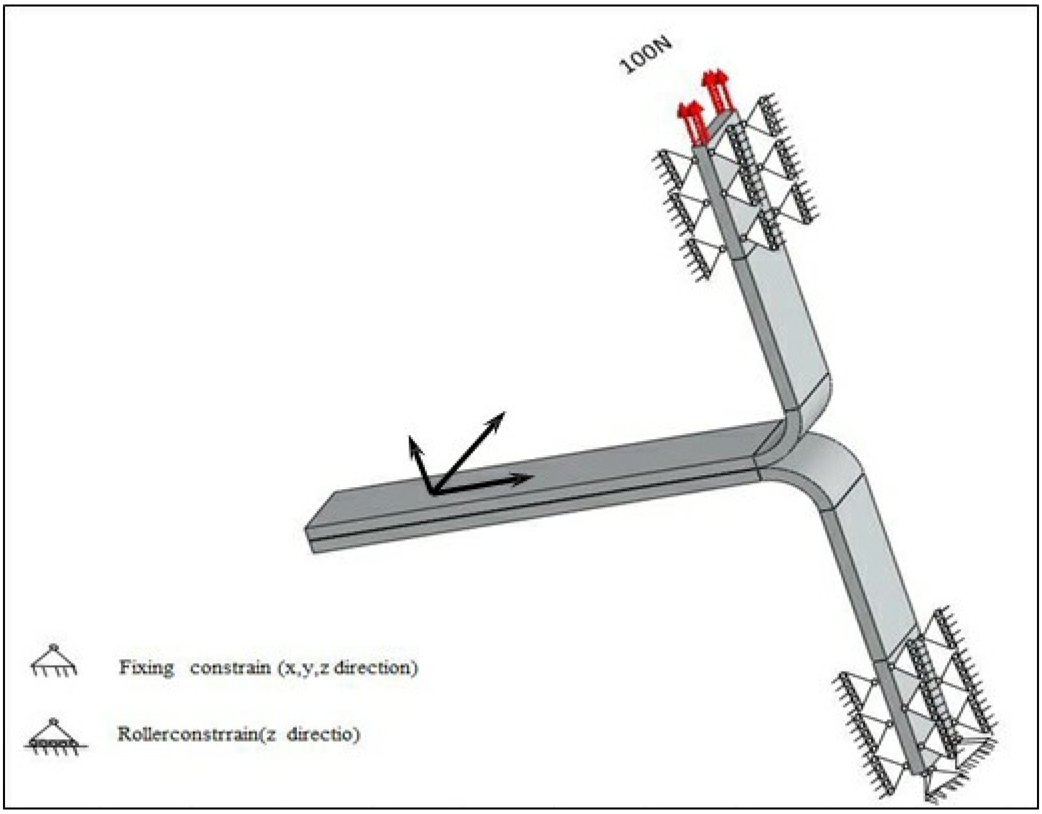

Figure 3: Constrains and loading assigned to bonded T peel joint

24. Finite element mesh generation

Tetrahedral elements were used throughout mesh generation. Fine mesh was considered for adhesive bonded zone while course mesh was considered for zones far from deformation. A mesh refine size of 7.0 mm in fine mesh zone, while 2.9 mm refined mesh size for course mesh zones. It is worth noting, different fine mesh sizes were used to insure solution converge. The Current FE mesh generated 43296 elements and 64196 nodes, (see figure 4).

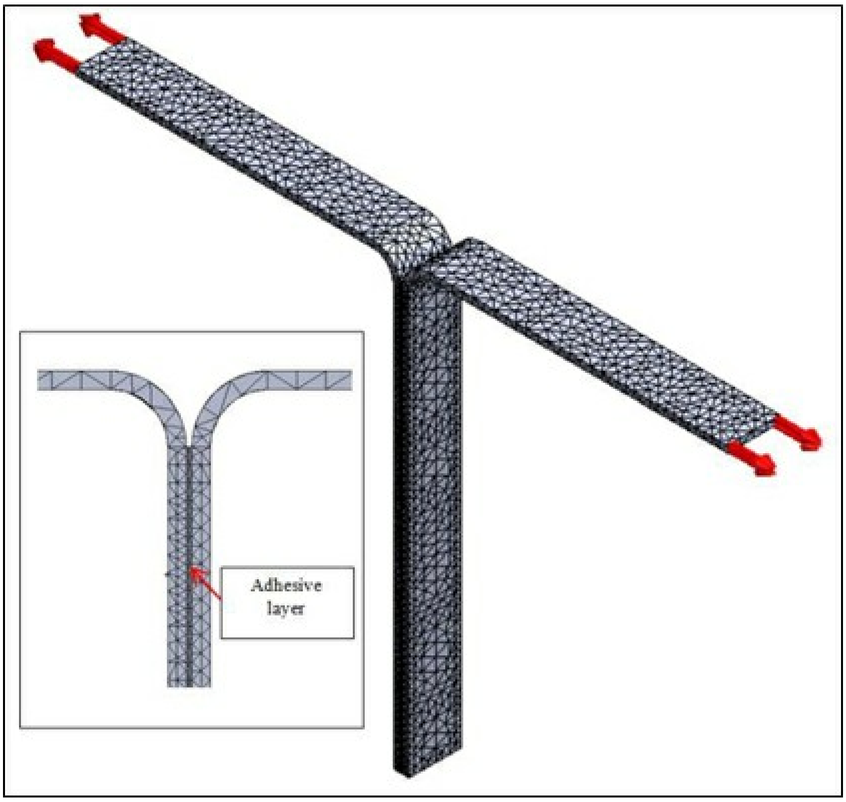

Figure 4 : Mesh generations of adhesively bonded T-peel joint.

2.5. Finite Element results

Figure 5 shows Von-Mises stress along the mid-layer of the bondline for the T-peel joint. It can be clearly observed that applied stresses are distributed along small area of bonded line approximately 6mm while the remaining has a stress value of zero. The stress started from zero then increased gradually along the mid layer of bonded line to 3 N/mm^2 value then decrease to near of zero value after that the stress increased dramatically till reached the peak value of the stress. The peak value of stresses (21.9 N/mm^2) was record on the mid adhesive layer between the bonded joint adherends.

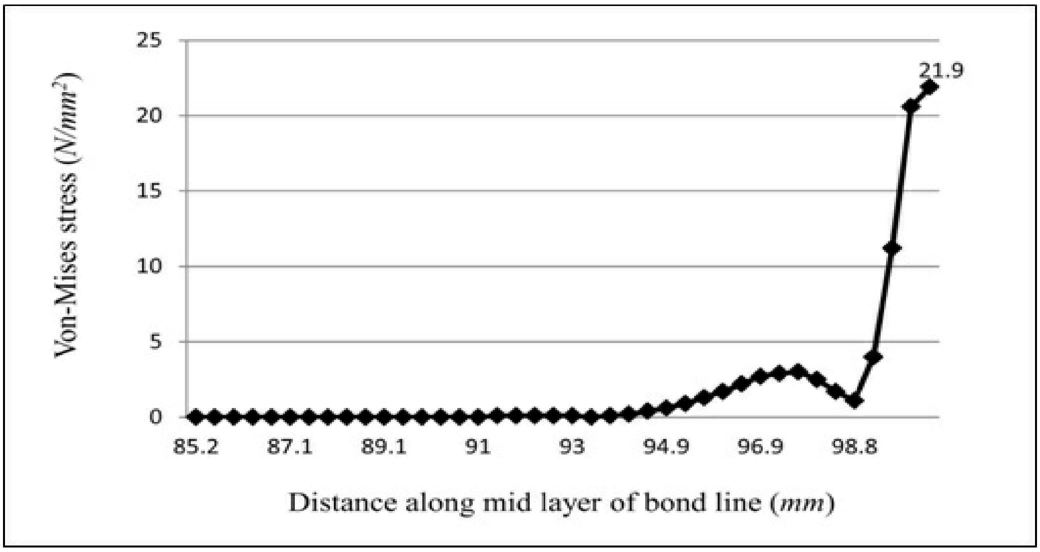

Figure 5: Von-Mises stresses along the centerline of adhesive layer

3. Bonded peel joint having different geometry parameters

The design of experiments (DOE) method was applied in the present study, in order to evaluate the effect of the number of geometric parameters considered. In this work, full factorial design of experiments which include all possible combinations was considered.

All factors and their corresponding levels selected in this study are listed in Table 2. Four factors have been adopted for the factor "amount of adhesive spew fillet" due to the fact that it significantly effects the strength results [*(81) ((82), (85), (86), (12)*]. The factors considered included: bond line adhesive layer thickness (A), adherend thickness (B), the amount of adhesive spew fillet (C) and flange radius (D), as shown in figures (6 and 7).

Table 2: Factors and their respective levels

Factors	Level 1	Level 2	Level 3	Level 4
Adhesive Layer Thickness *A (mm)*	0.1	0.3	0.5	
Adherend Thickness *B (mm)*	1.6	3.175	6.35	
Amount of Adhesive spew fillet *C (%)*	0	25	50	100
Flange Radius *D (mm)*	5	10	20	

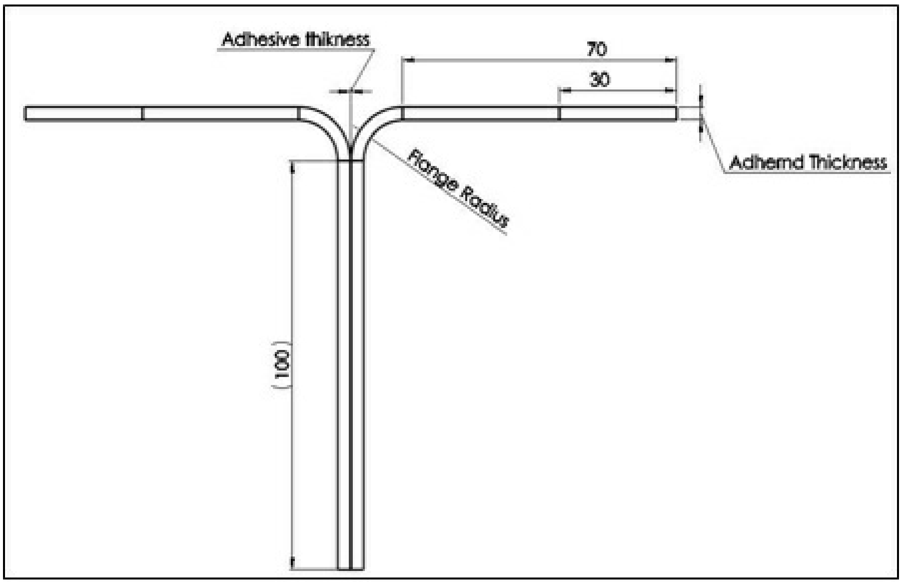

Figure 6: Peel joint geometric parameters.

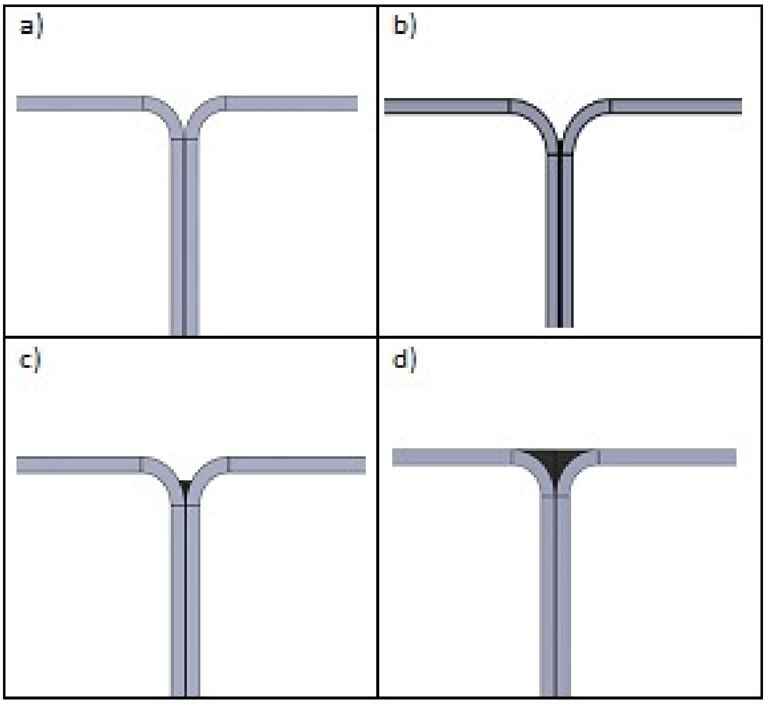

Figure 7: Peel joint with a) No spew fillet b) 25% spew fillet c) 50% spew fillet d) Flush spew fillet (100%)

The same FE mesh was used for all 108 combinations for this analysis using (DOE). The predicted peel strength was evaluated by monitoring the Von-Mises stress distribution along bond-mid-layer. Table 3 shows samples of factorial design and peak stresses resulted in adhesive layer.

Table 3: Samples of factorial design and peak stresses in adhesive layer results

No.	*A(mm)*	*B(mm)*	*C(%)*	*D(mm)*	R *(MPa)*
1	0.3	1.6	0	10	25.2
2	0.3	6.35	25	10	1.6
3	0.5	1.6	50	10	4.8
4	0.1	1.6	0	20	49
5	0.5	1.6	50	5	3.9
- -	- -	- -	- -	- -	- -
107	0.1	1.6	100	20	1.7
108	0.1	1.6	50	5	3.7

3.1. Data Normality Test

Normal test plot was used to check the normality of data points obtained from FE results)see figure 8). From figure 8 it can be concluded that data fails the normality test due to following reasons:

1. Existence of deviated points in normal probability plot.
2. Presence of cluster of points in residual plot.

Therefor in order to achieve the normality assumption, a data transformation process (square root) was conducted. Then normality test was re-run to evaluate whether the distribution of the transformed data is normal or not. Finally, the data points followed normal distribution after transformation are shown in figure (9).

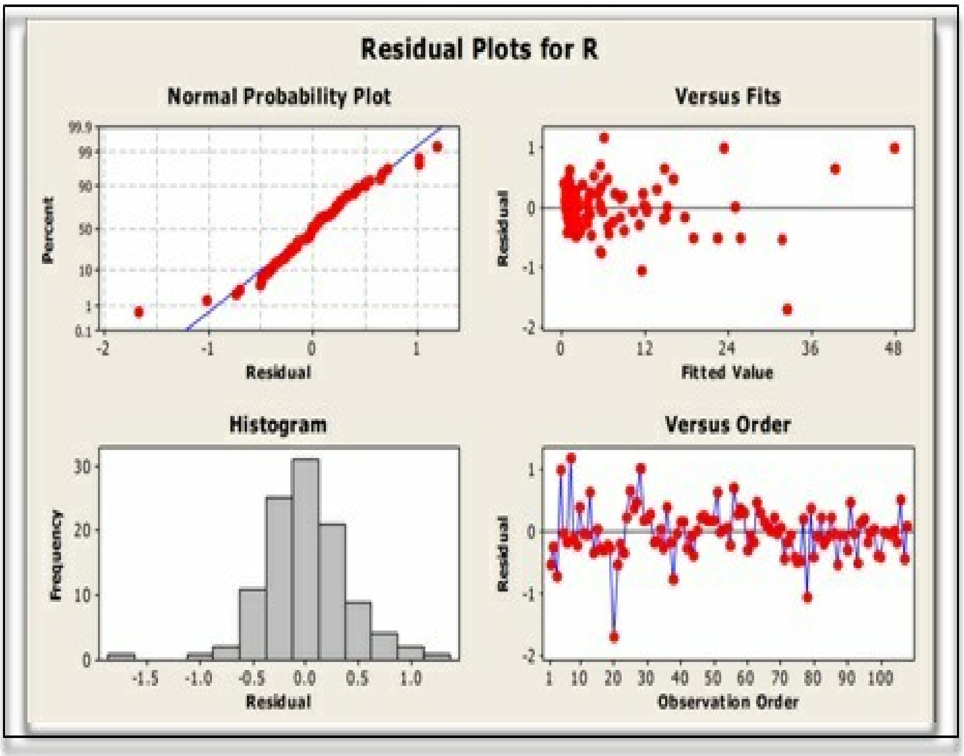

Figure 8: Normality test

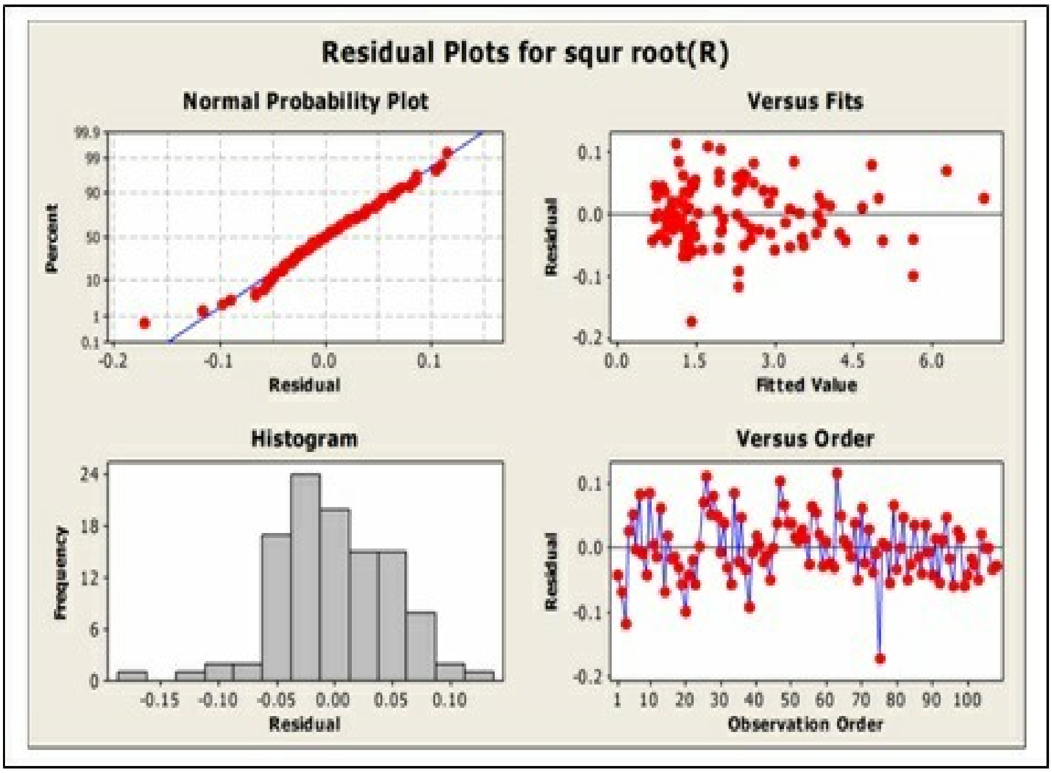

Figure 9: Normality test

3.2. Analysis of Variance (ANOVA) Test

Analysis of Variance (ANOVA) test is very useful to determine the significance of the parameters as well as the interaction between them. ANOVA table (Table 4) present results at 95% confidence interval involve values including sum of squares (SS), degrees of freedom (df), mean squares (MS), variance ratio (F) and significant factor (P). Main effect plot is analyzed and displayed in figure 10. It can be seen from Table 4, that most of the adopted terms have significant effect on the peak Von-Misses stress except (A, A2, D2 , A*B and A*D) terms. Furthermore, it can be observed that the bondline thickness has very low significance on the strength of joint.

Table 4: Analysis of Variance

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	14	190.11	190.11	13.5793	203.49	0·000
Linear	4	147.013	45.947	11.4867	172.13	0·000
A	1	1.085	0.188	0.1884	2.82	0.066
B	1	43.497	11.441	11.4414	171.45	0·000
C	1	97.452	34.333	34.3326	514.47	0·000
D	1	4.979	1.026	1.026	15.37	0·000
Square	4	23.651	23.651	5.9127	88.6	0·000
A*A	1	0.013	0.013	0.0129	0.19	0.661
B*B	1	5.94	5.94	5.9397	89.01	0·000
C*C	1	17.696	17.696	17.6957	265.17	0·000
D*D	1	0.002	0.002	0.0024	0.04	0.85
Interaction	6	19.446	19.446	3.2411	48.57	0·000
A*B	1	0.014	0.014	0.0139	0.21	0.649
A*C	1	0.697	0.697	0.6975	10.45	0·000
A*D	1	0.014	0.014	0.0142	0.21	0.646
B*C	1	12.267	12.267	12.2666	183.82	0·000
B*D	1	1.392	1.392	1.3915	20.85	0·000
C*D	1	5.063	5.063	5.0627	75.86	0·000
Residual Error	93	6.206	6.206	0.0667		
Total	107	196.316				

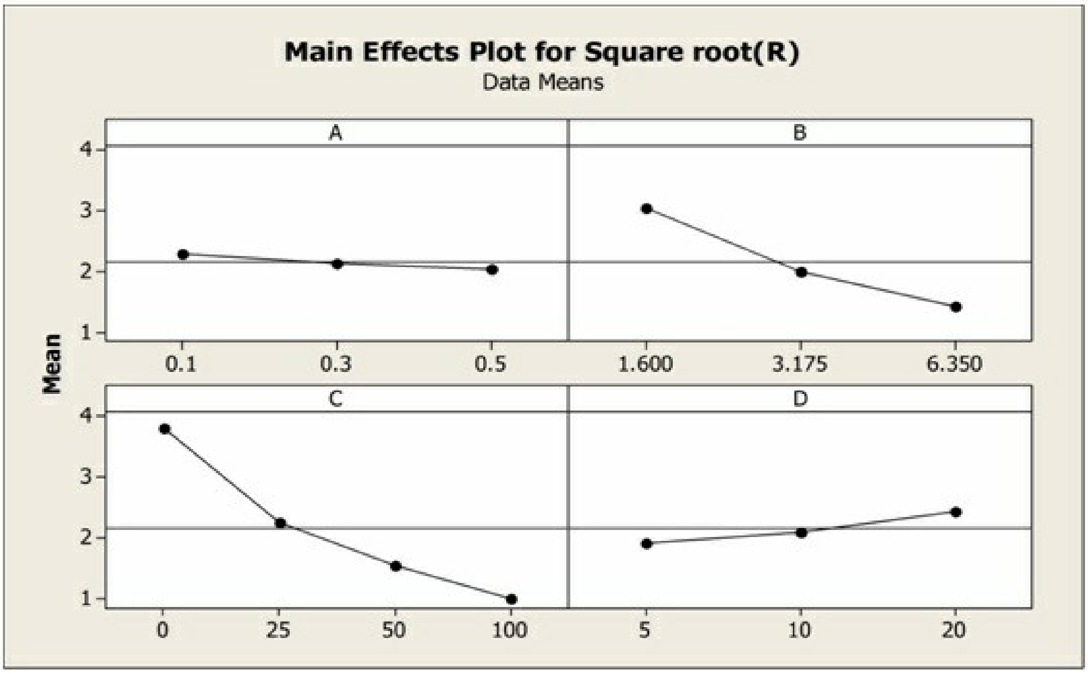

Figure 10: The main effects plots of parameters

3.4. Predictive Model for stress concentration

Full quadratic predictive mathematical model peak stresses along mid adhesive layer of peel bonded joint was developed using response surface methodology (RSM). The reduced model was achieved by eliminating unaffected terms. The response predictive model is given in equation 1.

$$\textbf{Square Root of R} = 5.86506 - 0.61382\,A - 1.24440\,B - 0.06968\,C + 0.10968\,D + 0.10135\,B^2 + 0.00037\,C^2 + 0.00461\,BC - 0.00921\,BD - 0.00094\,CD \qquad \text{Eq. 1}$$

R-Square = 96.46%, R- Square (adjust) =96.14%.

The developed predictive model has high adjust *R -Square* value which means *96.14%* of model variation conducted by involved terms. Hence, it can be confirmed that the developed model is adequate.

This predictive model can be utilized for predicting the stresses concentration along the mid adhesive layer of adhesively peel joints.

3.5. Validation of model

In addition to the adjusted R-square value obtained in previous section, the adequacy of developed predictive model was confirmed using two-sample t-test of 95% confidence interval. It was found that P value for entire fitted model is equal to 1 which is greater than α value (α= 0.05). Hence, that null hypotheses H0: μ1= μ2 can be accepted which mean no significant difference between numerical and mathematical data.

A comparison of the measured results with predicted ones is shown in Figure 11.

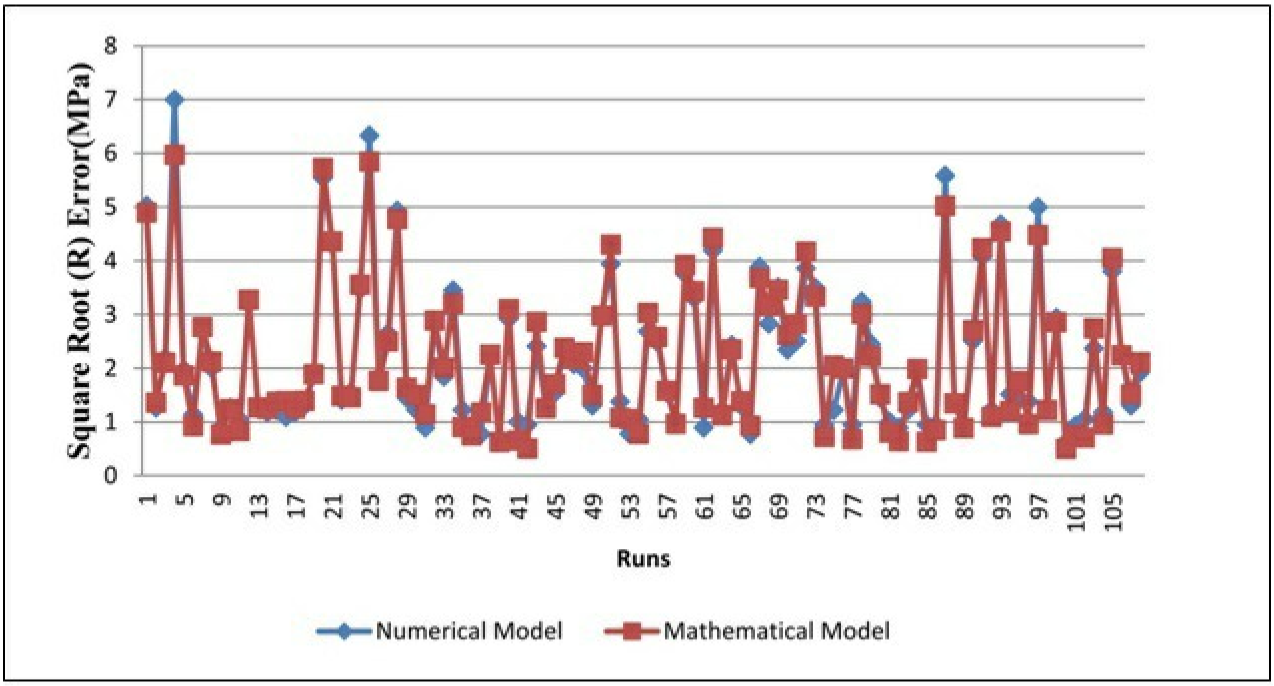

Figure 11: Comparison between measured values and fitted values

4. Conclusions

The following conclusions emerged from this research work:

- Bonded T-peel joint geometry parameters have significant effect on the predicted peel strength.
- Predicted peel strength increases with increase in bonded line thickness adherend thickness, fillet spew parentages and decrease with flange radius reduction.

Acknowledgment

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