Statistical Analysis of Adhesive Bond Parameters in a Single Lap Joint System

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Abstract. The design and sizing of adhesives used for bonding of two or more similar/dissimilar materials in aerospace and automobile structural engineering studies have always been important. A vast number of studies have reported via experimental, numerical, and analytical methods of lap joint system with adhesive bonding. Optimization studies of the adhesives used in joints are highly necessary which can be done either with numerical or experimental data in determining the suitable parameters for the specified solution through the design of experiments analysis. In this study, a single lap joint with different variables has been modelled and the resulting stress was measured in each case. A standard two-dimensional plane stress element was used for modelling of single lap joint stress elements. Furthermore, a statistical analysis method was used to optimize the selected parameters for the improvement of current solutions with suitable parameters. The results showed that the response values of stresses were influenced by input parametric variables which control the stresses and reduces the risk of damage to the adhesive bonds used in the joints. Moreover, based on the present optimization results it has been found that the thick adhesive bond will result in higher shear stress transfer with less width and suitable for the lower applied voltage.

Keywords: Lap joint, FE Method, DOE, Adhesive bond.

1. INTRODUCTION

In recent research, adhesive-bonded techniques are gaining more interest. When adhesives are used over the composites, the load is distributed more evenly, thereby facilitating lighter structures. The reinforcing of rivets, bolts, or other forms of joint systems in composite structures can result in damage. In this regard, a literature study also demonstrates the adhesive significance of joint structures. Numerous experiments have been carried out using the theoretical method on the adhesive joints process of metals and non-metals [1]. Comparing or merging the analytical studies to numerical work is the solution to this problem. Computational structural models can be used to test the shape functions for the assumptions of the model. For a given problem, these types of shape functions can be used to solve the stiffness matrix. Provided the assumptions should remain valid, that elements the accurate solutions of the elements can be afforded regardless of the element number used. This type of technique was used to measure the stiffness matrix on the elastic base problems on various types of beams [2]. A modified analysis technique with closed-form solution was used for the adhesively bound double-lap joints with stepped-out adherent to assess the standard stresses and interfacial shear under uniform uniaxial tensile tension stress [3].

Chan *et al*., [4] presented the research on double lap joints using an empirical approach. They used elasticity theory to obtain the equilibrium equation in the adherent bond overlap field. Further, the authors showed the governing equation for shear and peel stresses in the adhesive bond and then validated the analytical approach with numerical simulation results. With the numerical approach, including strength, stiffness, and fracture behaviour, examined the fracture parameters of a single lap joint, in addition to this back-face strain along the joint part was also studied [5], [6]. The obtained results of the numerical simulation were validated with the digital image correlation (DIC) results.

On the other hand, optimization techniques have become popular and a number of studies have been reported from the last decade [7-13]. This approach is a cost-effective and efficient method to predict the accuracy in results and reduces energy and time to get optimum solutions. The experimental design technique of Taguchi was used by Silva *et al*. [9] to measure the effect of the adhesive, the adherent, the overlap, and the surface preparation on the lap shear strength. The effect of overlap length, adhesive layer thickness, and cure temperature on the efficiency of adhesive joints tested experimentally then the joint's static behaviour was studied using L_9 orthogonal array experiment method design [10]. The type of adhesive, the adhesive thickness, the adherent thickness, and the overlap length were varied to measure the effect of the

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substructure angular pattering, and the design of Taguchi's experimental technique was used [11]. In two points, the mechanical activity of the hybrid joint using composite as adherents undergoing tensile loading was observed to fail. The various parameters were analyzed using Taguchi's L_9 orthogonal array, such as overlap length, bolt size, tightening torque, and adhesive thickness [12]. The experimental matrix Taguchi L_9, describing varying combinations of overlap length and adhesive thickness, is used to consider the failure load and shear strength behaviour of adhesive-bonded single-lap composite joints [13].

After reviewing some recent articles, it has been found that the optimization technique is useful to determine the suitable parameters. Hence, the objective of this article is to perform a statistical analysis of adhesive bond single lap joint parameters through the DOE method. The response values of statistical analysis were obtained through the finite element (FE) method. The stress values were considered from the critical portion of the joint system.

2. MATERIALS AND METHOD

Figure **1** shows the single lap joint model with the dimensions that were used for the present study [14]. In the present work, there are two types of materials considered, and one in the form of adhesive, which is lightweight aluminium material, the mechanical properties were considered with a Young module of 68.95 GPa and a Poisson ratio of 0.345. With Young's module of 5.1 GPa and a Poisson's ratio of 0.33, the other material is the adhesive used, which is Araldite 2014. There are two aluminium plates, one fixed, and another 10 MPa tensile load is applied in the x-direction, each of which has a width of 10 mm, a depth of 5 mm, and a length of 150 mm.

The adhesive materials were used to join aluminium plates in a single-lap joint form, and the adhesive dimension was 5 mm depth, 50 mm in length for the standard method. In addition, the parametric analysis was conducted to study the adhesive modeling of a single lap joint based on adhesive thickness, width, and loading conditions.

Using two-dimensional (2D) plane stress-quadri-lateral elements, the FE analyses were conducted through the ANSYS APDL commercial software. It is important to investigate the traction force (σ_a) at the free edge in the joint element system because of adhesive bonds and the shear stress transfers. The adhesive boundaries of free edges that are important to notice are that the models of the joint element are not capable of achieving the boundary condition of traction free (σ_a). The joint element and FE models are therefore not predictable for estimating parallel stresses at the free edges of the adhesive boundary. Furthermore, the stress singularity results in the formation of the inside of the adhesive edges in the FE method thus generating a mesh model depends on the edge singularity region. Figure **2** illustrated the FE mesh model with a zoom view. In this study, a 2D plane

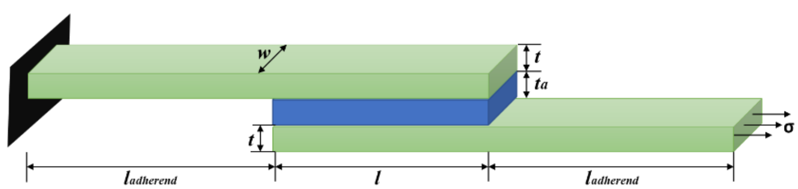


Figure 1: Finite element model and boundary condition.

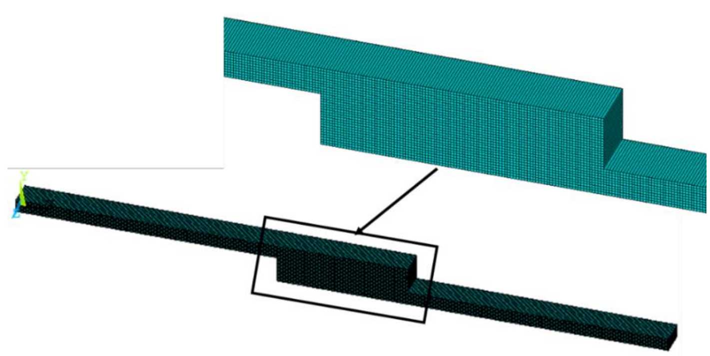


Figure 2: Mesh Model.

stress PLANE182 [7,15] element type was used. Generalized plane strain or an axisymmetric element without or with the torsion can also be used with the PLANE182 element type. In major studies, PLANE182 is recognized by the 4-nodes, including 2-degree of freedom (DOF) each node having the translations in a nodal of x- and y-directions. An element with an axisymmetric option in addition to torsion is well defined by 4-nodes, including 3-DF at each node having the translations in the same nodal x- and y-direction but rotation in the z-direction. The PLANE182 elements were having the hyper-elasticity, plasticity, stiffness, large strain capabilities, and large deflection. Also, having the ability of mixed formulation meant for simulation of incompressible elastic-plastic materials deformation, and abundantly hyper-elastic materials.

For statistical analysis, three useful parameters were considered with three levels. The parameters are thickness, width, and applied load. The two parameters are selected from the dimensions of the adhesive bond and one is loading conditions. The two-response variable has been considered: stress at y-direction and Von-mises stress to understand the structural strength of a single lap joint system. Variation of thickness is 1 mm, 3 mm, and 5 mm, width is varying 10 mm, 30 mm, and 50 mm, and last parameters load is 10 MPa, 20 MPa, and 30 MPa. A total of seven combinations of parameters was selected from its effective variation for statistical analysis via factorial design and orthogonal array. The analysis of the present parameters for an optimum solution a design of experiments method applied through the MINITAB software. The design will evaluate all possible variations of the parameters of an entity or repeat experimental trials based on DOE. The effect of a factor is defined as a response discrepancy caused by variation in the level of elements.

A statistical model based on empirical relation was recognized using the DOE analysis which represents the SY (σ_y) and SEQV (σ_v) has been obtained and illustrated in the below equations,

$$\sigma_y = -10.79 - 3.79t + 0.462w + 5.690\sigma \quad (1)$$

$$\sigma_v = -17.2 - 5.31t + 0.690w + 10.522\sigma \quad (2)$$

Where, σ_y is stress at y direction,

σ_v is Von mises stress,

t is the thickness,

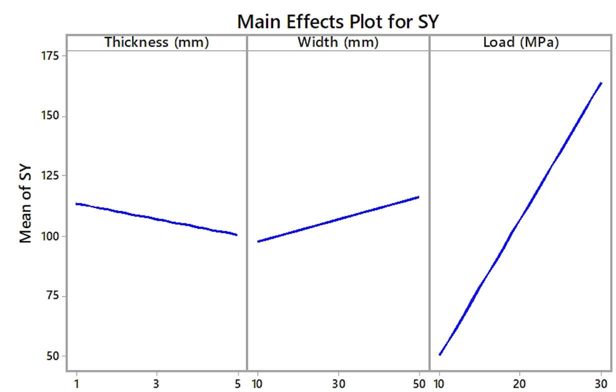
w is the width,

σ is the applied load.

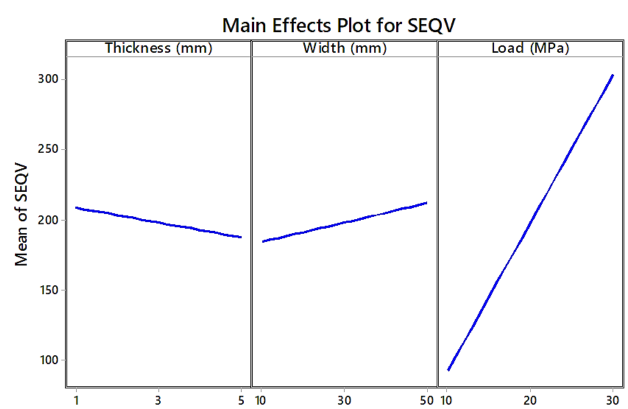
3. RESULTS AND DISCUSSION

The investigation was done based on the definition of the problem for the joint element to discover the adhesive model that is required to predict the peel and shear stress in a single lap joint. The results were obtained from a 2D-FE model and the different parametric effects to illustrate the accuracy of the joint element were investigated. Later, the FE results were used for statistical analysis.

For determining the superiority of the adhesive bond, a response variable of stresses for both SY and SEQV was considered. For this persistence, the adhesively bonded single lap joint system should be a minimum to maximum stress variations at the critical part of the bonded joint which has a higher stress concentration region, and to increase the strength in order to decrease the damage risk in the case of the aerospace or automotive engineering structures. Therefore, the main effect plot for the response factor for both SY and SEQV was determined by keeping the option smaller is safer to assist the structural applications. Figure **3**



(**a**)

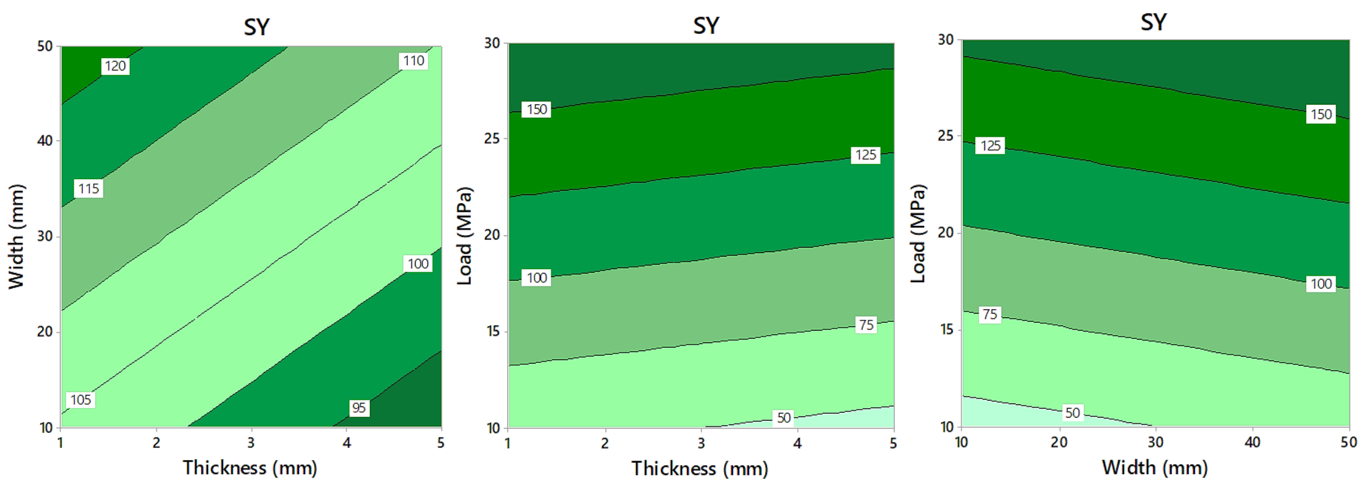


(**b**)

Figure 3: Main effect plots.

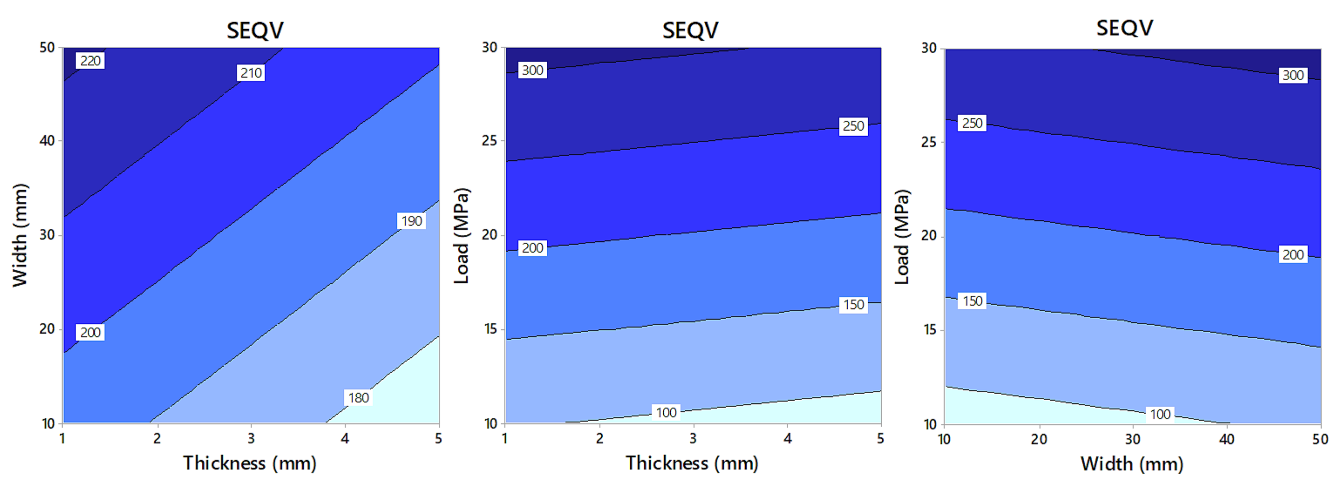
shows the main effect plot for both cases (a) SY (b) SEQV. Figure (**3a**) shows that the suitable parameter for minimum stress to be found for applied load at level 1 ($\sigma = 10\,MPa$), width at level 1 ($w = 10\,mm$), and thickness at level 3 ($t = 5\,mm$). Whereas, for SEQV, it is found that a similar parameter with their levels is needed for optimum solutions.

Second, the results for the contours were obtained from some of the parameter combinations identified for the available combination using screening design of DOE approach from MINITAB tool. With these results, we can find the lowest value of stresses. From Figure **4**, it can be understood the stress variation by the color of the contours varying from dart to light blue. Figure **4** (a) shows the lowest value of stress at y-direction (SY) less than 95 MPa which has been found when the thickness of adhesive bond to 5 mm, and width is lower range whereas for Figure (**4b**) stress reduces at lower applied stress with higher thickness of adhesive bond. For the load vs. width, both required a lower level of parameters to control the stresses which are shown in Figure (**4c**). This result has been found similar for Von mises stress (SEQV) which is illustrated in Figure (**5a**, **b**, and **c**). This means that this parametric combination will affect more stress variation particularly when applied stress has changed. The changes which have been found for SY and SEQV are only stressed numerical reading. For example, for the same parameter combination, SY was found minimum stress of 95 MPa whereas SEQV has been found 180 MPa.



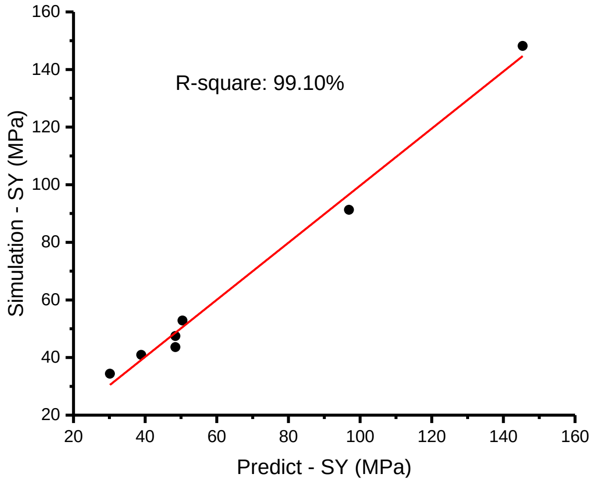
(**a**) (**b**) (**c**)

Figure 4: Contour plots for SY.



(**a**) (**b**) (**c**)

Figure 5: Contour plots for SEQV.



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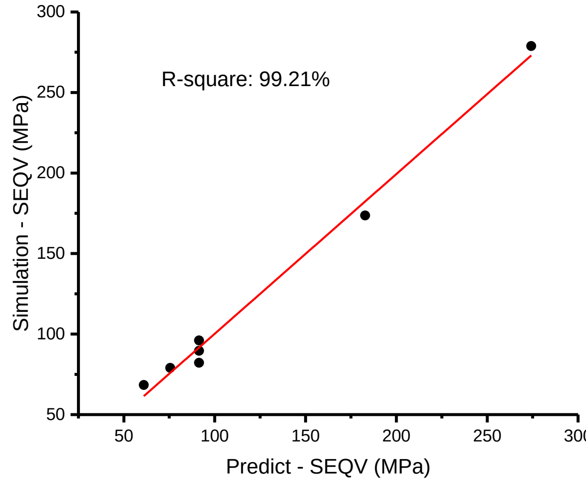

(**b**)

Figure 6: Comparison of results from simulation and predictable data (a) SY (b) SEQV.

From the empirical relation (Eqn. 1 and 2), response variables have been calculated to find the percentage deviation from simulation and optimization (predicated) results (Figure **6**). The significant residual errors of each test and the maximum errors were found ±1.25% for SY (Figure **6a**) and SEQV (Figure **6b**). Furthermore, to validate these results the R-square approach was used for each run. There are several steps needed for the actual measurement of the R-square study by taking the observations of variables that are simulations and predicted of the present work. From there, expected values can be measured, real values subtracted, and the effects squared. That will subtract the average real value from each of the actual values, square the results, and count them to determine the overall variance. The following can be expressed for comparison through the R-square,

$$R^2 = 1 - \frac{SS_{RES}}{SS_{TOT}} = 1 - \sum_i \frac{(y_i - \hat{y}_i)^2}{(y_i - \bar{y}_i)^2} \quad (3)$$

Then Eqn. (3) represents that there is divide the second sum (total variance) by the first sum of errors (explained variance), deduct the result from one, and will have the R-square. In the present study value of R-square found 99.10% and 99.21% for SY and SEQV, respectively (Figure **6**). It means that our simulation results with the present parametric combination have effective results in structural strength.

4. CONCLUSION

A simple two-dimensional adhesive-bonded single lap joint was numerically studied, and different levels of stresses were applied to measure the quality of the adhesive bond in this study. From the simulation and optimization results, we can conclude that:

The peel stress distribution for different adhesive bond thickness and width was explored in the single lap joint system using the finite element method.

Statistical analysis was performed for the suitable parameters of adhesive bonded single lap joint.

Successfully obtained the influenced parameters to increase the strength of the adhesive bond and reduce the risk of failure.

Results show that the suitable parameter for minimum stress to be found for applied load at $\sigma = 10\,MPa$, width at $w = 10\,mm$, and thickness at $t = 5\,mm$ for both SY and SEQV stresses.

The optimization technique was found useful to determine the lap joint stress analysis. Based on the present investigation it can be recommended for a higher order of lap joint system with different materials selections for host structures and adhesive bond.

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