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Numerical Simulation of Bi-Adhesive Lap Joints

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ABSTRACT

The stresses in single-lap bonded joints are highest at the edges, where failure frequently originates, and lowest at the center. The stress concentration at the ends of a bonded lap joint is influenced by the relative stiffness of the adherend and adhesive used. The stress concentration is smaller and the joint strength may be increased the less stiff the adhesive used in the bond line for a particular adherend. With this technique, high joint strength can be attained. Adhesive joints have been used in a lot of investigations in the past. Numerous industries, including the automotive and aerospace sectors, conduct in-depth studies to ascertain how adhesive joints affect lap bonding. It has also been discovered that when bi-adhesive is utilized in a lap joint rather than mono adhesive, more uniform stress can be obtained. Bi-adhesive was applied with a firm adhesive in the overlap's center and a low-modulus adhesive at its edges, which were expected to undergo stress concentrations. A concentrated force was delivered to one side of the entire portion, which had one side fixed. The result shows that the stiffer adherend has higher strength. Through finite element modeling, the rise in apparent lap-shear strength was qualitatively predicted.

Keywords: Bonded joints, Bi-adhesive lap joint, Carbon fiber adherend, Shear stress, Peel stress.

1. Introduction

Due to its propensity to be so robust and long-lasting, metal is a crucial component in construction. Metal needs to be able to be joined together in order to be used in construction. Welding, a fusion technique that involves fusing materials together, is a frequent way to accomplish this. Welding can be used to unite most metals, including titanium, iron, steel, aluminum, nickel, and copper.

Any metal junction that relies on an overlap is referred to as a lap joint. Although the metal must overlap three times the thickness of the connection to have the best strength, they are one of the strongest types of welds. By far the most typical adhesive joint, single-lap joints have drawn a lot of attention throughout time. The geometric dimensions, as well as the adhesive and adherend qualities, influence the stress distribution within a joint. In the bonded area, the stresses generated on by forces acting externally on the joints are dispersed unevenly. Even with low-modulus adhesives, the bond line's strain is never distributed uniformly [1]. In single lap joint testing, the often employed metallic adherends exhibit substantial plastic deformation from yielding before failure.

In order to attain extremely high shear strengths to support enormous loads, adhesives with a high degree of stiffness and brittleness have been developed. Due to the enormous stress concentrations, they create, such adhesives are vulnerable to brittle failure. The stress concentration could decrease with a decreased stiffness of the glue employed in the bond line, increasing joint strength.

This study aims to investigate the effects of material and geometric properties on the finite element analysis-predicted critical stresses in adhesive single-lap joints and to analytically test this hypothesis.

When comparing all existing analytic solutions in 1992, Tsai and Morton [2] found that Oplinger's model [3] was the most reliable for calculating the edge moment in long joints and Hart-Smith's model [4] was the most accurate for calculating the edge moment in short joints. The shear strength of co-cured single-lap joints subjected to tensile loads was generally discovered by Shin and Lee's [5] research.

Carpenter [6] investigated the impacts of different mathematical hypotheses on adhesive stresses in single-lap joints and discovered that the majority of hypotheses had little to no effect on the maximum adhesive shear and peel stresses that were predicted, neglecting the adherends' shear deformation had a significant effect on the peel stress. Cooper and Sawyer [7] looked into finite element analysis in further depth, comparing geometrically linear and non-linear results. Lap joints have also been widely investigated in a variety of ways, both experimentally and numerically.

When using a spew fillet rather than a square adhesive termination, maximum adhesive stresses are typically noticeably lower, according to research by Crocombe and Adams [8] into the impact of spew fillets on stress distributions in a single-lap joint. At the bond's terminus, spew fillets are triangular adhesive fillets.

L.D.R. Grant used lap joints instead of spot welding in 2009. Following that, a detailed set of tests and a finite-element analysis were carried out at various loads. Permabond's ESP110 glue was utilized in this experiment. The part to be glued is mild steel, which is used to make automobile bodies and meets the specification BS1449 CR1E and is typically 0.95mm thick. Tension (which generates shear at the joint line), 4-point load (just deflection), and 3-point load were all evaluated on the lap joint (deflection and shear). ABAQUS was used to acquire both experimental and numerical data [9]. In 2009, it was discovered that peel chemicals are widely employed in the automotive industry. Especially in van cargo areas. It's usually manufactured by spot welding. However, this test uses adhesive joints rather than spot welds, and unlike lap joints, there is no stress concentration at the neck, hence these joints can withstand uniaxial tensile strains. A stiffer adhesive (Permabond ESP110) was employed in this study.

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The glue has a thickness of 0.95mm. This is made from the same lightweight steel that was used to make the white bodywork, and it's built to the BS1449CR1e specification. The exam was conducted in two scenarios. One is in the atmosphere, while the other is in a vacuum. In this experiment, the same parameters were measured. Semsettin Temiz experimented with a bi-adhesive double bond joint subjected to a bending moment in 2006. Two types of glue were used to make a double belt attachment. The first is hard, whereas the second is flexible. The connection was then subjected to a bending moment. Then we looked at the tension. The firm glue was used in the center, while the soft glue was used on the edges. The experiment's ultimate hypothesis was to obtain more loaded with the bi-adhesive junction [10]. Temperature fluctuations were used to test the mechanical characteristics of adhesive in 2010. A tensile test was performed on a bulk sample of the cured adhesive manufactured as French standard NFT76142 [11]. The strength of a lap joint filled with mono and bi-adhesive will be discussed in this study, but the load will be applied axially outward of the adherend, as Semsettin Temiz experienced. Permabond's ESP110, a hard adhesive, was used in the center of the overlap, and DP490, a softer adhesive, was used on the edges, which were more likely to experience stress concentrations.

2. Methodology

2.1 Computational Properties

Table 2.1 Dimension of the model [12]

Parameters	Adherend	Adhesive
Length(mm)	150	14
Width(mm)	10	10
Thickness(mm)	2.5	0.25

The two adhesives utilized were ESP110 by Permabond and DP490 by 3M, both of which were cured for 80 minutes at 120 °C.

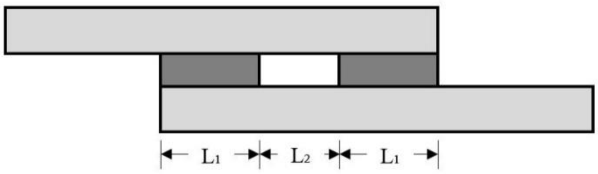

Fig.1 Developed model showing relative length of adhesives.

Table 2.2 Properties of Adherend [12]

Material	Aluminum 2024-T3	A4S carbon fiber
Young's modulus (GPa)	72.4	225
Poisson's ratio (GPa)	0.33	0.2
Yield stress (MPa)	345	2800
Tensile strength (MPa)	485	3900
Coefficient of Thermal expansion (mm/mm/°C)	23×10^{-6}	6.84×10^{-6}

In the middle of the overlap, Permabond's ESP110 stiff adhesive was used, while 3M's DP490 soft adhesive was used on the edges that were more likely to experience stress concentrations.

Where, the length L_1, equivalent to the overlap edges, corresponds to the DP490 adhesive, and the length L_2, equivalent to the central region, corresponds to the ESP110 adhesive. The total overlap length is $2L_1 + L_2$.

Table 2.3 Properties of Adhesives [12]

Material	ESP110	DP490
Young's modulus (GPa)	5.1	1.4
Poisson's ratio (GPa)	0.4	0.4
Tensile strength (MPa)	60	33
Coefficient of Thermal expansion (mm/mm/°C)	45×10^{-6}	30×10^{-6}

After the property input of the materials section assignment of the materials was done. The sections were assigned as solid and homogeneous. After the section assignment, the three parts were combined by merging them to make then one part. After the combination, the step was created. As a concentrated force was applied the static, general step was created. The maximum increment was given 10000 where the initial was 0.1. Also, a Constraint was created. Then the Boundary condition was given. One end of the model was encastre as it was fixed. On the other end, a concentrated force was applied.

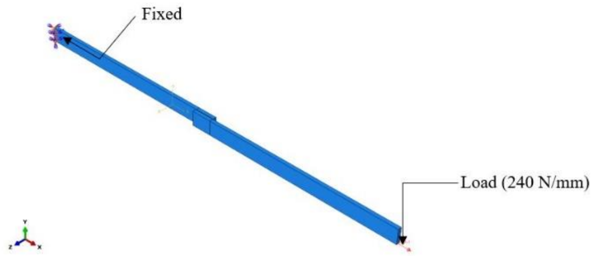

Fig.2 Boundary conditions applied to the model

After applying boundary conditions, the meshing of elements is necessary. The element type of the meshing is C3D8R linear hexahedral i.e; the element is an 8-node linear brick, with reduced integration with an hourglass control element.

The total number of nodes and elements in the bi-adhesive model are 658900 and 613200 respectively.

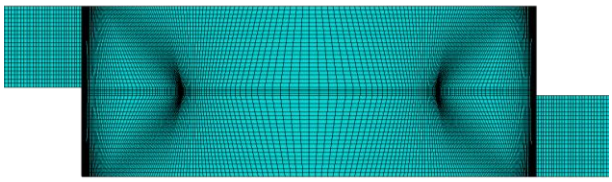

Fig.3 Meshing of the bi-adhesive model

For mesh sensitivity analysis in bi-adhesive, the number of elements is 546375, stress is found 53.61 MPa. After increasing the number of elements to 601456, stress is found 53.75 MPa which does not change much after increasing the element number. So, the mesh size of the model is taken in such a way that the number of nodes is 658900 and the total number of elements is 613200.

2.2 Physical Aspect of Model

The stress and strain distribution of the single lap joint will be determined by using ABAQUS 2017 software with the help of numerical modeling. The project's operations include the creation and application of sophisticated numerical techniques based on the Finite Element Method (FEM). The effect of material constants on the stress singularity will examine using the developed numerical model. At first geometry modeling was done. Then the property was inputted also with the step was created. Meshing was also done after the boundary condition and the load was applied.

3. Result and Discussion

3.1 Model Validation

Mesh sensitivity analysis was performed to make the results independent of the mesh size. Fig. 4 shows the stress against the number of elements. It is observed from this figure that if the number of elements increased beyond 546375, the value of the stress is almost constant. So this mesh size was used for further analysis.

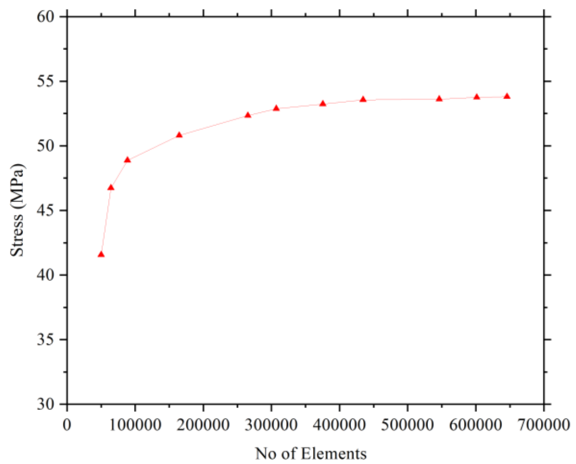

Fig.4 Mesh sensitivity analysis

The bi-adhesive lap joint's assessed shear stress distribution along the overlap length is contrasted with the shear stress from the following paper [12] as shown in Fig. 5.

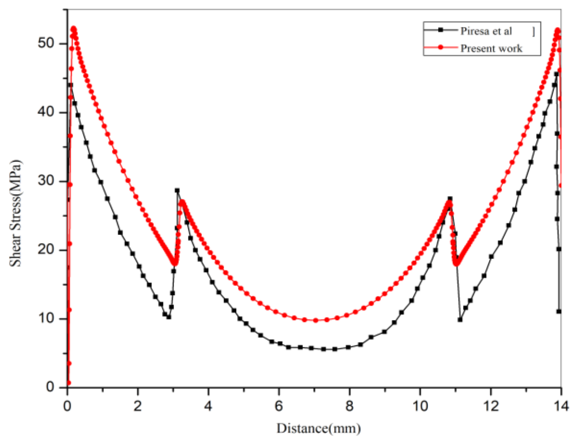

Fig.5 Comparison of shear stress with pires et al.

The bi-adhesive model has an average inaccuracy of roughly 19.7%. This analysis examines the shear stress distribution over the length of the overlap for connections created using adhesive (DP490 and ESP110) as well as joints created using a graded bond line with a geometry ratio of $L_1/L_2 = 0.4$ and a load of 240 N/mm.

In addition to the shear stresses mentioned above that can lead to failure, there are additional stress factors that must be taken into account. Normal and von Mises equivalent stresses were both considered for this. The inquiry uses Peel and other popular stress analyses to evaluate the adhesive failure in various joints.

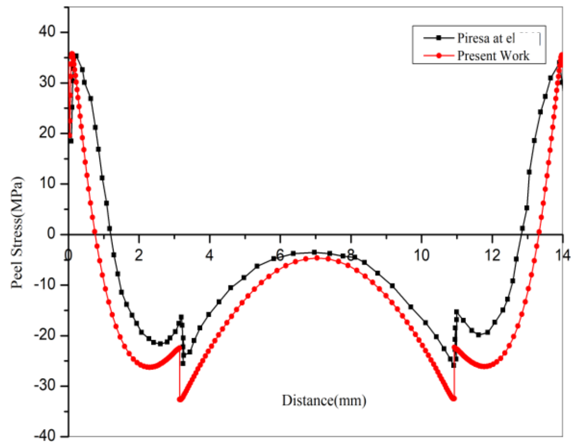

Fig.6 Comparison of peel stress with pires et al.

The bi-adhesive lap joint's peel stress distributions along the overlap length are depicted in Fig. 6. It is evident that the joint formed by the bi-adhesive (DP490 and ESP110) bond line produces relatively little peak stress roughly 36MPa for a load of 240 N/mm and a geometry ratio of L_1/L_2=0.4.

3.2 Stress distribution comparison for carbon fiber adherend

To analyze the parametric study on bi-adhesive lap joint, A4S carbon fiber is taken as adherend where the positions and the properties of the adhesives remain the same, which has Young's modulus 225GPa and Poisson's ratio 0.2 [13].

Shear stress along the length of the overlap for adherends made of carbon fiber and aluminum is shown in Fig. 7. As can be shown, compared to aluminum adherend, carbon fiber adherend produces relatively low peak stresses, increasing the strength of the bi-adhesive lap joint. From Fig.7 it can also be obtained that, in aluminum adherend, peak stress occurs at the bond line whereas in carbon fiber adherend peak stress occurs and the inner end of the adhesive.

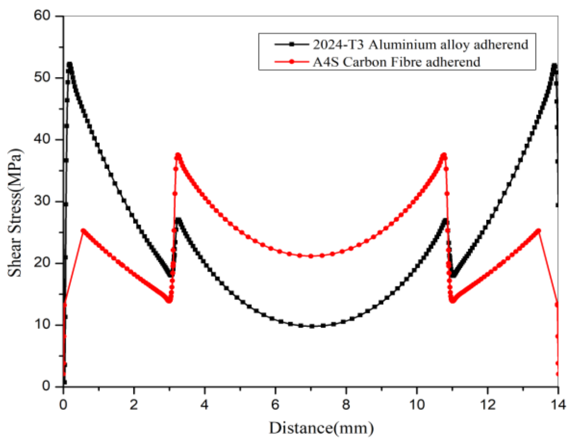

Fig.7 Shear stress for carbon fiber adherend and aluminum adherend.

Similar to that, Fig. 8 compares the peel stresses for adherends made of aluminum and carbon fiber along the length of overlap. As can be shown, compared to aluminum adherend, carbon fiber adherend produces relatively low peak stresses, increasing the strength of the bi-adhesive lap junction.

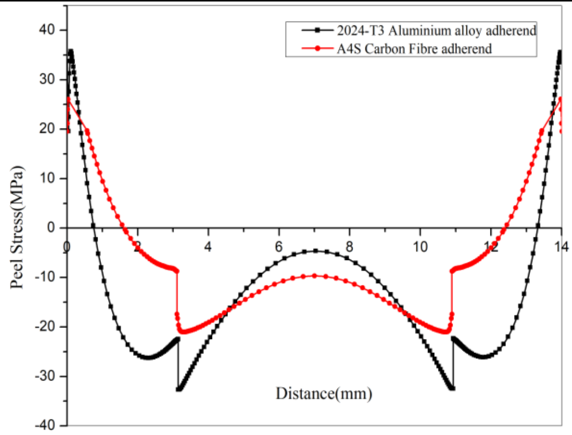

Fig.8 Peel stress for carbon fiber adherend and aluminum adherend.

3.3 Stress distribution for various L_1/L_2 length ratios

The various L_1/L_2 length ratios are 0.4, 0.8, and 2.0 respectively as shown in Fig. 9. The peak stresses of adhesives DP490 and ESP110 with the same Young's modulus and Poisson's ratio dropped as the L_1/L_2 ratio raised, strengthening the bi-adhesive lap junction. The peak value does, however, slightly increase when the ratio increases over 0.8, which is not desired. In the bond line, a lower L_1/L_2 ratio gives lower stress. The peel stress along the span length for different L_1/L_2 length ratios of the adhesive and carbon fiber adherend is shown in Fig. 10.

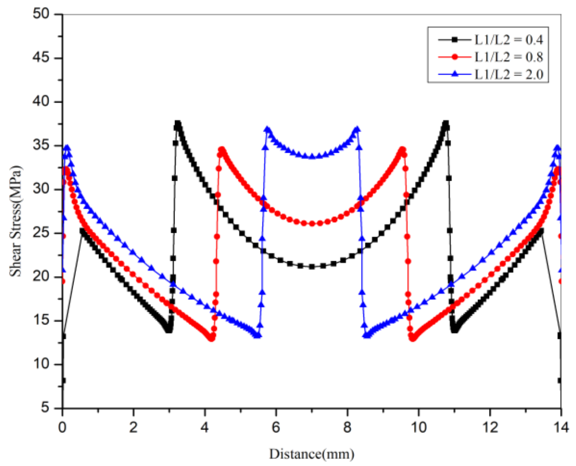

Fig.9 Shear Stress for various L_1/L_2 ratios of adhesive with carbon fiber adherend

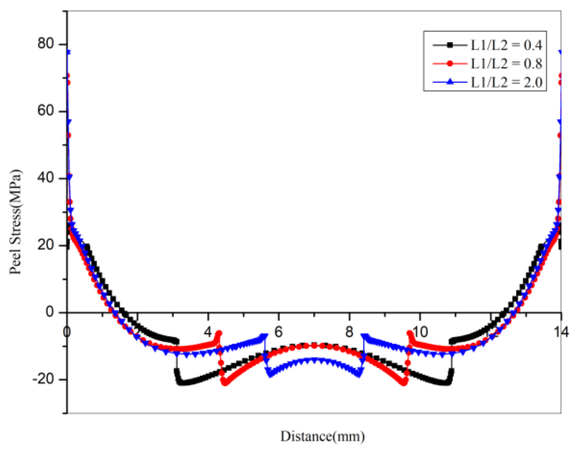

Fig.10 Peel Stress for different L_1/L_2 length ratios of adhesive and carbon fiber adherend

The peak stresses marginally increased with the rising L_1/L_2 ratio for the same Young's modulus and Poisson's ratio for both adhesives, reducing the strength of the bi-adhesive lap junction. However, as the ratio rises above 0.8, the peak value somewhat falls, which is preferable.

3.4 Stress distribution for interchanging adhesives

The shear stress comparison for bi-adhesive obtained along the overlap length when adhesives are interchanged as L_1=ESP110 and L_2=DP490 are as shown in Fig. 11, where the adherend is carbon fiber. As can be observed, the strength of the bi-adhesive lap joint is reduced as a result of the modified bi-adhesive bond line producing significantly higher peak stresses than before. Fig. 11 also shows the separately used of both of the adhesives DP490 and ESP110 as a single adhesive which gives higher peak stresses than the ideal bi-adhesive formation. The peel stress comparison for bi-adhesive obtained along the overlap length when adhesives are interchanged for carbon fiber adherend are shown in Fig. 12.

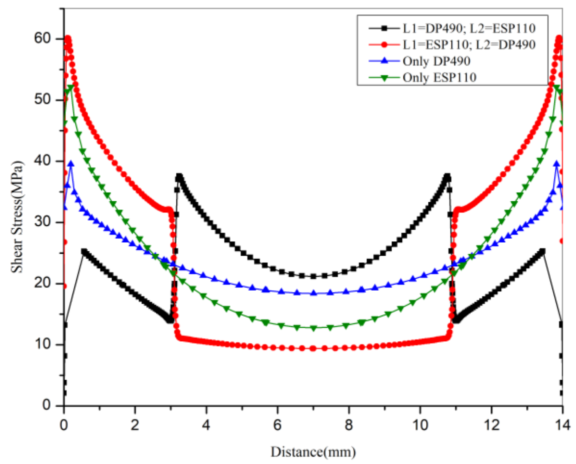

Fig.11 Shear Stress for different L_1/L_2 length ratios of adhesive and carbon fiber adherend

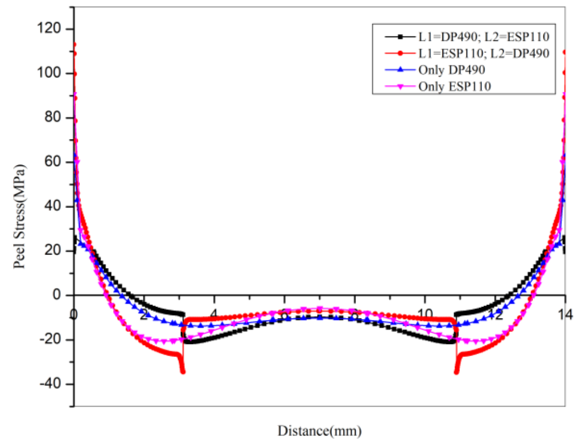

Fig.12 Peel Stress for interchanging the adhesives for carbon fiber adherend

As a result, it is clear that the bi-adhesive bond line exchange results in significantly higher peak stresses than it did previously, which reduces the bi-adhesive lap joint's strength.

4. Conclusion

In this paper, a finite element method was applied to analyze the strength of an adhesive bond single lap joint. In the bi-adhesive model, the edges that were more likely to experience stress concentrations received a low modulus glue whereas the middle of the overlap received a stiff adhesive. The entire portion had one side that was cast as it was fixed, while the other side had a focused force applied to it. The comparison shows that when the two adhesives are applied separately, the bi-adhesive joint exhibits a consistent distribution of stress. The strength is highest when the separately used single adhesive is brittle adhesive but slightly higher when the separately used single adhesive is softer adhesive. According to the parametric analysis, joints with carbon fiber adherends have stronger joint strength, increasing by 30% in comparison to joints with aluminum adherend.

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