Stress Analysis of Tapered Adhesively Bonded Joints with Finite Tip Thickness

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The tapering of adhesively bonded joints has been found to significantly reduce stress concentrations in the adhesive layer. Amongst the initial research on tapering of joint adherends, I.U. Ojalvo’s [1] work on the optimisation of bonded joints provides a solution for outer adherend shape that ensures constant shear stress concentration in the adhesive layer, and his solutions are tapered joints. J.Wang at Defence Science and Technology Organisation (DSTO) expresses interest to understand the effect of finite tip thickness on such joints as provided by Ojalvo, since Wang’s work [2] on tapered joints does not sufficiently account for this limitation. This is the same for Ojalvo’s solution and many other works done for tapered joints. As such, this project addresses the effect of such a limitation on the stress distribution of Ojalvo’s solutions. This is done through linear analysis on an appropriate numerical model with modifications that incorporate the limitation. The results show the stress distribution and stress peaks for the adhesive joints, and also show the stress peak trends with increasing tip thickness. This is useful for joint design considerations when perfect or fine taper cannot be achieved. The results for the analysis on DLJ show that replacing a portion of the curved taper near the adherend tip with another curve produces the lowest stress peaks.

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I. Introduction

A. Aim
The aim of this project is to qualify the effect of finite tip thickness on the stress distribution of joint designs provided by Ojalvo. These are the scarf joint, DSJ, tapered SLJ and DLJ with curved taper. This is done by providing a suitable model with the appropriate modification for numerical analysis. As such, finding an appropriate modification for the joint is also important. This is especially the case for the DLJ with curved taper, where several modifications are done to find out which modification produces the best joint performance. Finally, from the results and conclusions, the project seeks to provide appropriate recommendations to DSTO and industry and for further work in the improvement of the analysis or joint design.

B. Project Scope
As the field of adhesive bonded joint design and analysis is broad and extensive, it is good to provide a focused scope to this project. This project will determine the effect of the finite tip thickness of a tapered adherend on the stress distribution of the joint. As such, other than the tip thickness, the other parameters of joint design will be kept constant. Examples of these parameters are the angle of the adherend taper, the adherend thickness and the adhesive thickness. This is not to mean that the other parameters are not important in joint design, but that the analysis for this project focuses only on the aspect of adherend tip thickness.

Also, as this is an initial study into the effect of finite tip thickness on tapered joints, this project will conduct a linear, two-dimensional, plane strain analysis with isotropic materials. The approach of this project is the determination of peel and shear stress peaks and distributions in the adhesive bond of the modified joints.

C. Goals
This project had the following goals to achieve:
1. To understand adhesively bonded joint design considerations through literature survey.
2. To provide appropriate modification to each joint design provided by Ojalvo.
3. To produce a suitable model for analysis.
4. To conduct numerical analysis with ANSYS Workbench 14.5, a FE software tool.
5. To extract and present data with MATLAB.
6. To draw conclusions to the effect of increasing tip thickness in taper and provide recommendations.

D. Methodology

This project starts with an extensive literature survey to gain an understanding of adhesive joint design considerations, survey existing work on the stress analysis of Ojalvo’s ideal joint solutions, and existing work that specifically incorporates finite tip thicknesses in their analysis. Due to unfamiliarity with ANSYS and FEM, concurrent with the literature survey, time was taken to learn FEM and ANSYS.

After satisfactorily finishing the literature survey and gaining an understanding of joint design and the existing work pertaining to this, appropriate modifications are made for each of the 4 joint types to incorporate finite tip thickness. As the DLJ has a curved taper, several modifications are provided to determine which modification method produces the best results in terms of reduction of stress concentrations. An appropriate model is produced for analysis. The models are then reproduced in ANSYS with appropriate geometry, mesh, loading conditions and boundary conditions. The model is then validated by comparing it with existing work for accuracy. As the data presentation tool in ANSYS is limited, the results are extracted with MATLAB and presented graphically. Appropriate conclusions are drawn followed by recommendations for further work and improvement.

II. Background

A. Joint Design Considerations

This section details the results of the literature survey regarding joint design considerations. More importantly, to make appropriate modifications to the ideal joints, a good understanding of joint design considerations is required.

The shear stress in bonded joints acts in the direction of the bond. Adhesive joints are loaded primarily in shear, since adhesives perform better in shear. The peel stress in bonded joints is defined as the tensile stress acting normal to the bond area. Peel stress concentrations at the edge of the bondline are the main contributing factor to crack initiations in the adhesive and subsequently failure in the adhesive (called cohesive failure). Peel loads are the greatest undesirables in the design of bonded joints [7]. Peel stresses also arise due to the flexing of adherends when loaded. Thus joint configurations with load eccentricity especially worsen this problem [8].

In adhesively bonded joint design, care must be taken to ensure that the loading is predominantly in shear and that peel loads are kept to the minimum as most adhesives are much stronger in shear than in peel. The main aim in joint design is the minimisation of loading situations which correspond to poor adhesive performance. Therefore, peel and cleavage type loadings must be avoided or minimised. Several ways to combat peel is by increasing the bond area, increasing stiffness of adherend or reducing stiffness in adherend for the case of tapered adherends [7].

The ultimate goal in adhesive joint design is the ability to predict joint strength. For successful joint strength predictions, knowledge of the distribution of stress or strain within the joint is required together with a suitable failure criterion. Shear and especially peel stress concentrations are important as indicators of joint strength since they are the most likely initiation for failure of the adhesive. Thus for this project, peel stress concentrations will be looked at as the main indicator of joint strength.

B. I. U. Ojalvo’s work on Optimisation of Bonded Joint [1]

Ojalvo’s work on optimisation of bonded joint, aims to reduce the elastic shear stress distribution in the adhesive layer of bonded lap joints through the use of taper. For uniform material and isotropic adhesive, he prescribes a desired shear stress distribution, which is a constant shear stress distribution along the adhesive overlap and derives the expression for outer adherend thickness along the adhesive overlap shown by equation (1).

\[ t_o = \frac{E_t l}{nE_a} \left( \frac{L}{n} \right)^{-1} - 1 \]  \hspace{5cm} (1)

When \( E_t \) and \( E_a \) are the same, load transfer ratio, \( C \), is zero, and \( t_i \) is a linear taper to zero shown by equation (2), equation (1) reduces to equation (3).

\[ t_i = t \left( 1 - \frac{x}{L} \right) \]  \hspace{5cm} (2)

\[ t_o = \frac{t x}{n L} \]  \hspace{5cm} (3)

When load transfer ratio \( C \) is zero, it means that the entire load is transferred from the inner adherend to outer adherend.

Figure 1. Ojalvo’s solutions
Equation (3) shows the expression of adherend thickness reflected by the three joint configurations with linear taper shown in Fig. 1. These are the scarf joint, tapered SLJ and DSJ respectively. The 3 joints have linear taper from \((x=0, t=0)\) maximum adherend thickness to a zero-tip thickness at the end \((x=L, t=0)\), and conversely for the outer adherend. However \(L\) and \(t\) are variables and this means that any angle for a linear taper profile will give a constant shear stress distribution across the adhesive. Ojalvo does not explore the effect of taper angle on the shear stress distribution.

Pertaining to this project, Ojalvo’s solutions are based on the theoretical taper with zero tip-thickness. However, in practice zero tip-thickness in taper is impossible. Therefore, this project will look at Ojalvo’s solutions and apply appropriate modifications to ideal joint configurations for numerical analysis on ANSYS, to qualify the effect of finite tip-thickness on Ojalvo’s solutions.

For the case of the DLJ with curved taper shown in Fig. 1, \(t\) is constant along \(L\). However as the curve is of increasing gradient, for practical reasons the outer adherend thickness is constrained at a certain thickness. This leads to a shear stress distribution that deviates slightly from the constant shear stress distribution. For this project, several methods of modifying the DLJ to incorporate the finite tip thickness will be compared to see which method gives lower stress concentrations and consequently better joint performance.

C. Existing Work on Finite Tip Thickness

While there is plenty of research conducted for each joint configuration named by Ojalvo, most works consider perfectly tapered joints. Only a limited number of works incorporate finite tip thickness into their analysis. Thamm [5] conducts linear analysis for tapered SLJ with finite tip thickness using FDM to solve differential equations for differential elements of the tapered SLJ. His conclusion is that any tip-to-adherend thickness ratio greater than \(1/10\) does little more to improve joint strength.

Lee [6] conducts non-linear analysis for tapered SLJ with finite tip thickness using a Voltera integral equation of the second kind formulated for an arbitrary adherend tapered geometry and adhesive non-linear material properties. He uses successive approximation method to solve for the integral equation. He concludes that non-linear analysis leads to more accurate results for stress distribution as linear analysis tend to be over-conservative.

Gleich et al. [3] conducts linear analysis for scarf joints with finite tip thickness. Similar to Thamm’s work, Gleich uses FDM to solve the differential equations for a differential element, but for scarf joint.

Van Tooren & Roza [4] created an adhesive toolbox on MATLAB to determine shear and peel stress distributions in various joint configurations, such as stepped joints, SLJ and tapered SLJ. Their work also uses FDM to solve differential equations. Their work will be used as a means of comparison to validate the model used in this project, this is shown later. No work on DSJ has been found that incorporates finite tip thickness.

III. Modelling

A. Linear Model in Plane Strain

As this is an initial study, we assume isotropic materials that behave linearly. First, we address the modelling of the joint. Considering the use of such joints in the aviation industry and particularly in Wang’s work on bonded repair patches, these joints are employed in industry in the form of sheets in overlap. Another possible use includes skin lap joints. Thus this problem is presented as one in plane strain.

The joint is subject to loading consisting of tension, shear force and bending moments. The material properties of the adhererend and adhesive are considered, so are the thickness of the adherends and adhesive bondline. From Ojalvo’s equation, the inner and outer adherends have the same thickness and are the same material. The boundary condition of the model includes a fixed end on the inner adherend, and a distributed tensile force applied to the outer adherend. The shear stress and peel stresses along the adhesive bond centreline are determined by the local coordinates shown in Fig. 2, where axis 1 is parallel to the bondline and axis 2 is perpendicular.

![Figure 2. Model of modified scarf joint with typical loading and b.c.](image-url)
B. ANSYS Methodology

The problem is presented in plane strain as the strain of the material in the cross-sectional direction of the joint is infinitesimally smaller than the length of the sheet. Therefore, we can model this with 2D analysis in ANSYS. Conducting the analysis in 2D will also save computational cost, as opposed to increased time requirement to process a 3D model with a greater mesh size and number of elements. With the savings in computational cost, it can be assigned to a finer 2D mesh for greater accuracy in numerical results.

For this project, the adherend material used is 2024-T3 Aluminium, which is a mainstay of aviation materials. The adhesive used is FM73, which is a commonly used adhesive in the industry. The material properties used are shown in Table 1.

<table>
<thead>
<tr>
<th>Material</th>
<th>Elastic Modulus, $E$ (GPa)</th>
<th>Poisson's ratio, $v$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2024-T3 Aluminium</td>
<td>72</td>
<td>0.33</td>
</tr>
<tr>
<td>FM73</td>
<td>2.295</td>
<td>0.35</td>
</tr>
</tbody>
</table>

The geometry of the model is modelled in 3 parts: inner adherend (left), outer adherend (right) and adhesive layer. For the analysis of the joint, the parts are connected in bonding. The connection setting chosen on ANSYS is multi-point constraint (MPC). MPC internally adds constraint equations to ‘tie’ the displacements between contacting surfaces. It is a direct, efficient way of relating surfaces of contact regions which are bonded. It is used for bonded and no separation behaviours.

The mesh generated for the model is quadrilaterals dominated. The mesh density of the adhesive and its immediate surrounding adherend is set to be greater than the rest of the model. This will allow for greater resolution and accuracy of the stress distribution in the adhesive, and is especially important when determining stress concentrations.

Results are found using a stress tool to find shear and peel stress along the adhesive centreline. Data is then extracted and read using a MATLAB script (Appendix B) to plot as shear and peel stress distribution.

C. Modified Joints, Loading and Boundary Conditions

It is important to modify the joints appropriately such that the resulting increase in stress concentrations is minimal. Modifications have been made such that the negative impact on joint strength is minimized. Knowledge from the literature survey of joint design considerations has been employed so that the most appropriate modification is used.

For the scarf joint, two modifications were initially considered. The first configuration has the adhesive overlap of the outer adherend start at the beginning of the taper of the inner adherend, shown in Fig. 3(a) just below the ideal scarf. This design is used by Gleich et al. [6] in their analysis of scarf joints. However, this design will lead to load eccentricity, since the load line is not parallel to the horizontal axis. This eccentricity becomes increasingly significant with larger tip-thickness. Load eccentricity increases peel and shear stress concentrations near the tip of the adhesive bond [5], which are undesirable.

The second configuration incorporates adhesive fillet to allow for the joint to be loaded without eccentricity. This geometry is shown before in Fig. 3(a). To decide which modification is more appropriate, a preliminary analysis of the stress distribution in both modifications is conducted for comparison. This is shown later in the analysis part of the report.

The DSJ is modified as shown in Fig. 3(b). Unlike the scarf joint, incorporating a fillet is the only possible modification if the thickness of the outer adherend is to remain the same as the inner adherend.

The SLJ is modified as shown in Fig. 3(c). This modification keeps the adhesive overlap the same, while varying the tip thickness and the consequently the adherend taper angle. This is because decreasing the adhesive overlap length increases the stress distribution and concentrations in the adhesive [7].
The parameters for the 3 joint types are 0.25mm, 10mm, 37.321mm and 15° for the adhesive thickness, adherend thickness, adhesive overlap length and taper angle respectively. The boundary conditions and loading for the 3 joint types are shown in Appendix C. The joint is fixed at the end of the left adherend, and a distributed tensile force of 1000N is applied to the right adherend. For the SLJ, to reduce the effects of bending due to eccentric loading, roller supports are applied to the horizontal surface of the adherend surfaces adjacent to the adhesive layer.

The analysis for the DLJ is conducted for the given parameters: 0.2mm, 6mm, 3mm, 30mm, and 90mm for tip thickness, \( t_i \), \( t_o \), b and L respectively. The analysis for DLJ is a comparative analysis to find out which modification of the ideal DLJ leads to lower stress concentrations and better joint performance. The modifications for DLJ are shown in Fig. 4. Modification 1 cuts the ideal curve at the tip thickness. Modification 2 is to shift the curve left such that the same curve starts at the tip thickness. Modification 3 approximates the curve near the edge of the tip. For this, the curve from \( x=0 \) to \( x=15 \) is approximated by changing the L value in from equation (1) to fit the curve.

The loading and boundary conditions for the DLJ is shown in Appendix C. Half the DLJ is analysed by using a roller support along the line of symmetry. The adherends are fixed at the right end and a displacement load of 0.1mm is applied to the inner adherend in the negative x-direction.

IV. Numerical Analysis

A. Mesh Convergence Study

In finite element modelling, a finer mesh typically results in a more accurate solution. However, as our results involve stress concentrations many order of magnitudes larger than the average stress value, the sensitivity of the stress peaks will likely be dependent on mesh density. Thus, a mesh convergence study is necessary to determine the validity and accuracy of the mesh used.

This is done by first creating a mesh with the fewest, reasonable number of elements and analysing the results. Then the mesh is recreated with a denser element distribution, reanalysed and compared with the results of the previous mesh. This is repeated until the results converge satisfactorily. In this case, the modified scarf joint with 1mm tip thickness is analysed. Fig. 5 shows the increasing mesh density of the adhesive and the adherend immediately around it. The element sizes are of decreasing order 4.8e-4m, 1.68e-4m, 5.6e-5m, and 4.2e-5m.

Fig. 6 shows the plot for peel stress along the adhesive centreline for each of the 4 mesh and the variation in peak peel stresses for the 5 mesh.
densities.

As we can see the shape of the overall stress distribution is preserved. However, the stress peak increases slightly with increasing mesh density. Convergence starts to occur with the element size of 5.6e-5m. The difference in result between 5.6e-5m and 4.2e-5m element size meshes is insignificant at 7% error. Yet when further reduced to element size of 1.45e-5m, the peak stress falls back to the same as that of the 5.6e-5m. Also we notice that the position of the peaks is consistent at x = -7.42e-2m, which is the start of the adhesive overlap.

Concluding this study, we find that in order to obtain accurate results, the remaining mesh modelling will be with element size of 4.2e-5m to 5.6e-5m.

B. FEM vs. FDM – Validation of model

To validate our FEM modelling and accuracy of our results, we compare the results with existing work on stress analysis in tapered joints. The work that is compared with is Van Tooren and Roza’s work on ‘Finite Difference Methods for Stress Analysis of Adhesive Bonded Joints’ [3]. Their work focuses on creating a MATLAB adhesive toolbox that employs FDM to solve differential equations for differential elements in an arbitrary tapered joint, and determine the stress distributions in the adhesive bondline.

The configuration of the joint used for comparison is a tapered SLJ with 10mm adherend thickness, 1mm finite tip thickness, taper angle of 15°, 0.25mm adhesive thickness and 38.637mm adhesive overlap. It is fixed at the left end of the joint and the right end of the joint is subject to a 1000N distributed tensile force. The FE results are extracted from ANSYS and plot against the FD results determined from the MATLAB adhesive toolbox. Fig. 7 shows the shear and peel stress distributions.

Overall, we see that both methods produce almost identical stress distributions with only slight deviation in values. The results show that the model and FE settings applied is valid and can be used for further analysis.

C. Validation of joint modification

The preliminary analysis for the modified scarf joints was conducted for 1mm tip thickness. Fig. 8 shows the shear and peel stress distributions of the two different modifications to the scarf joint. The results show that the stress concentrations for the modified scarf joint with fillet have significantly lower stress concentrations. Also, the stress distributions are symmetrical. The asymmetric stress distributions of the modified scarf joint with load eccentricity show the effects of the load eccentricity on stress concentrations. It leads to bending of the joint and induces shear and peel stresses at the adhesive edges.

Thus the modification with adhesive fillet is used for analysis since its stress concentrations are lower, leading to better joint performance.

D. Validation of Ojalvo’s solution

Ojalvo’s solutions are a result of an imposed constant shear stress distribution in the adhesive. Fig. 9 shows the comparison of each joint’s shear stress distribution obtained from analysis. We see that the shear stress distribution for the scarf and DSJ is approximately constant over the adhesive overlap, except at the ends where it decreases to zero. This concurs with Ojalvo’s working.
However, this is not the case for the tapered SLJ, even with the frictionless roller supports on the adherend to reduce bending and induced peel and shear stresses. The non-uniformity in distribution arises from what is called ‘differential straining’. It is the primary means of transferring load in the joint.

They are introduced in the single lap joint by the eccentricity of the load path. This separation of the load path produces a bending moment which acts on the joint, causing rotation of the bond line to remove the eccentricity from the load path. This bond-line rotation then produces a peel stress that acts across the thickness of the adhesive. Similar to the shear stress, peel is concentrated at the ends of the overlap.

Thus we conclude that Ojalvo’s solution only applies to scarf and DSJ, and not for SLJ.

E. Results for Scarf Joint

FE analysis is conducted for scarf joint with perfect taper and subsequent finite tip thicknesses of 1mm, 2mm, 3mm and 4mm. The shear and peel stress distributions are determined and plot in Fig. 10.

The black dashed lines demarcate the start and end of the respective adherend overlaps. Since increasing the tip thickness effectively cuts off more of the tapered adherend, it results in a longer adhesive fillet and shorter adhesive overlap. We note that the shear stress peaks are located slightly aft of the beginning and before the end of the overlap, whereas the peel stress peak is located at the beginning and end of the overlap.

The formulas for shear and peel stress distribution for scarf joints [9] are shown in equation (4) and (5) (for 1m sheet length). The values obtained from analysis are for 2D analysis of 0.001m sheet length. The values obtained concur well with the numerical results for the perfectly tapered scarf joint.

\[
\tau = \frac{P}{\ell} \sin \theta \cos \theta = 25000 \text{ Pa} \tag{4}
\]

\[
\sigma = \frac{P}{\ell} \sin^2 \theta = 66987 \text{ Pa} \tag{5}
\]

We see that increasing the tip thickness of the adherend increases the shear stress concentration at the ends of the overlap. Also, the mean shear stress across the overlap increases. This can be attributed to the reduction in overlap length, resulting in increasing the mean stress applied to achieve the same load transfer.
The peel stress distribution can be characterised by sharp peaks at the ends of the adhesive overlap. Like the shear stress distribution, increasing the tip thickness increases the peel stress concentrations. The peel stress concentrations are generally lower than the shear stress concentrations.

From Fig. 11, we notice that the peel stress peak for the 4mm case is lower than the 3mm case, however we note that the peel stress than dips into negative peel stress in Fig. 11. This is because peel stress failure is characterised by the stress gradient, rather than solely on its absolute value. The peak stresses for both shear and peel increase linearly up to tip thickness of 3mm before it diverges. This is likely due to the effective overlap being too small, and the effect of the large softer fillet causing the joint to flex more, inducing higher shear and peel stresses.

F. Results for DSJ

![Figure 12. Shear and peel stress distribution for DSJ with various tip thicknesses](image)

Fig. 12 shows the shear and peel stress distribution for the DSJ. The asymmetry of stress distribution is because the pointy tip of the scarf joint is kept constant at 1mm. Like the scarf joint, the stress peaks for both shear and peel stress can be observed to increase approximately linearly with increasing tip thickness as shown in Fig. 13.

From Fig. 12 we observe that when the tip thicknesses of the pointy end and at the fork ends are not the same or similar, it results in an asymmetrical stress distribution in the adhesive.

G. Results for SLJ

![Figure 13. Peak stresses / Peak stress of ideal DSJ](image)

![Figure 14. Shear and peel stress distribution for SLJ with various tip thicknesses](image)
Fig. 14 shows the shear and peel stress distribution for the tapered SLJ. The peak shear stress for the SLJ with perfect taper is distinct from the peak shear stress for the SLJ with 1mm tip thickness. The shear stress distribution also converges for any finite tip thickness from 1mm upwards. The result for shear stress concurs with Thamm [5], where he suggests that for any tip to adherend thickness ratio larger than 1/10, decreasing the tip thickness would do close to nothing in the improvement of joint strength. This is reflected in Fig. 15 as the peak shear stress curves towards an asymptote of approximately 1.4 times the peak shear stress in an ideal tapered SLJ. The dip is observed at tip thickness of 1mm and smaller.

However, we also observe an increase in peak peel stresses for increasing tip thickness. This was not accounted for by Thamm. From Fig. 15 we see that the peak peel stress increases linearly up to 2mm tip thickness before it starts to deviate from linearity.

**H. Results for DLJ**

Fig. 16 shows the results for the shear and peel stress distribution for the DLJ and its modifications. Fig. 16 also shows the peak stresses for the various modifications.

The performance of each joint configuration is characterised by the peak peel stress, since it is the main contributor to joint failure. Thus, each modified configuration will be compared according to its peak peel stress. Modification 3 has the lowest peak peel stress at 1.47 times the peak stress of Ojalvo’s solution, followed by modification 2 at 1.67 and then modification 1 at 1.80.

The results show that replacing a portion of the original curve near the tip with a modified curve gives the lowest peak stress. The question that follows is whether a shorter modification will yield better results, since modification 3 replaces half the curve from x=0 to x=15.

At the time of conclusion of this research summary, there is still work being done on the analysis of the DLJ. Mainly, it is to conduct analysis on several more modifications to see which achieves better joint performance. Also, different parameters will be used to provide sensitivity analysis on the effect of changing certain parameters. This will be presented in the final deliverable.

**V. Conclusions**

From this project, we observe that increasing the tip thickness increases the shear and peel stress peaks of each joint type. More importantly, this analysis shows the trend of stress peaks when the tip thickness is increased. This trend can be used in practical joint design when perfect or fine taper cannot be achieved, and other factors such as cost of fabrication and availability of tools limit the ability to taper down to a fine tip.
thickness. With these results, compromises can be made to achieve joint strength requirements with full knowledge of the consequences when choosing a certain tip thickness.

For the scarf joint and DSJ, the stress peak increases linearly up to the point of 3mm tip thickness, where the peaks diverge from the linear trend, increasing its curvature.

For the tapered SLJ, the shear stress peaks increases linearly to 1mm, before it curves towards an asymptote at 1.4 times of the ideal, the peel stress peaks increases linearly to 2mm before it decreases its curvature. Thus for tapered SLJ, for any tip-to-adherend thickness ratio greater than 1/5 (2mm/10mm for this project), decreasing the tip thickness yields marginal reduction in peak stresses. This supplements Thamm’s conclusions, since he does not consider peel stresses in the adhesive.

For the DLJ, replacing a portion of the original curve near the tip with another curve produces the best results in terms of reduction of stress peaks. More work is being done at the moment, and more results will be available at the final deliverable.

VI. Recommendations

As the analysis for this project only varied tip thickness and involved a fixed set of parameters, i.e. taper angle, adhesive thickness etc. were fixed. Further work can be done such as conducting a sensitivity type analysis to analyse the change in peak stress trends when changing parameters such as taper angle and adhesive bondline thickness. This will supplement the results obtained from this analysis and either confirms the assumption of the conclusion that the peak stress trends can be applied parametrically, or improves upon it.

For the scarf and DSJ, either experimental or numerical work can be done to explore the effect and feasibility of incorporating a stiffer resin for the adhesive fillets in such joints. Since a stiffer fillet should reduce flexing of the joint, it may lead to reduced peak peel stresses induced by the flexing of the adherends.

Lee’s work on non-linear analysis of tapered SLJ shows that linear analyses tend to be over-conservative, leading to over-conservative joint designs. Therefore, further analyses that incorporate the non-linear characteristics of the adhesive may be conducted to compare with the linear results.

Also, as composite matrix materials are increasingly being used in the aviation industry, the same analysis can be conducted for composite matrix materials with orthotropic material properties to determine the performance of composites in such joints compared to isotropic materials.

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References

Periodicals

Books