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FAILURE ANALYSIS IN ADHESIVELY BONDED COMPOSITE JOINTS

Reyhan Deniz Atay[1]
Turkish Aerospace Industries
Ankara, Turkey

Saeid H. Dashatan[2]
Middle East Technical University
Ankara, Turkey

Levend Parnas[3]
TED University
Ankara, Turkey

ABSTRACT

In this paper, the mechanical performance and failure behavior of adhesively bonded single lap joints are investigated. A mechanical test program is conducted on single lap shear specimens. Without changing composite and adhesive base materials, parameters including the stacking sequence and adherend thickness are considered. Additionally, an analytical finite element analysis program, to perform failure analysis and to determine the load carrying capacity of the selected composite part in an airplane wing structure. For modelling the bond line, the cohesive zone approach is used. Both damage initiation and propagation are performed with the same approach. The effect of geometry on the mechanical performance of the adhesively bonded joints are analyzed. Analytical results are used to determine the stress concentrations within the joint to understand the failure mechanisms.

INTRODUCTION

Adhesive bonding is a joining process in which two neighboring surfaces are connected with the application of a bonding agent. Due to its considerable advantages, adhesive bonding is a frequently used method in aerospace industry; especially for joining laminated composite structures [Bowen et al. 1989].

The conventional mechanical fastening leads to stress concentrations around the fasteners and fiber breakage during the implementation in laminated composites. With the use of adhesive bonding, the drawbacks of the mechanical fastening can be decreased and structural integrity can be increased. In addition, lightweight structures can be obtained with adhesive bonding [Bowen et al. 1989].

In spite of advantages of adhesive bonding, material models and failure criteria are not well developed in contrast to mechanical fastening. For that reason, “overdesigned” structures with high factor of safety are generally obtained to insure safety considerations which leads to creation of expensive and redundantly heavier designs. Therefore, improving the adhesive methodologies, may help to utilize adhesive bonding joints more efficiently [Banea et al. 2009].

[1] Design Engineer in Turkish Aerospace Indutries, Email: reyhandeniz.kalelioglu@tai.com.tr
[2] PhD Student in METU Mechanical Engineering Department, Email: saeid.dashatan@metu.edu.tr
[3] Prof. in TEDU Mechanical Engineering Department, Email: levend.parnas@tedu.edu.tr

Single lap joint (SLJ) is one of the simplest form of the adhesively bonded joints which considerably used in structural joints. SLJ is preferred due to ease of preparation, capability of using substrates with different materials and thicknesses. In addition, combination of uniaxial and shear loading can be investigated with this simple joint model.

In adhesive bonded joints, three different failure modes would take place which are cohesive failure, adhesive failure and adherend failure. Loading conditions, improper surface preparation, curing process are the most important factors which affect the failure modes. Understanding the mechanism of these failure modes is crucial in design and analysis of bonded joints [Noorman 2014].

There are three main methods to perform failure analysis in bonded joints, which are continuum mechanics, fracture mechanics and damage mechanics. Within these methods, continuum mechanics have difficulty to give a solution at singularities and fracture mechanics requires a pre-existing crack. Among these restrictions, damage mechanics has an ability to predict both damage initiation and propagation with a specific method which is Cohesive Zone Modeling (CZM) [Silva et al. 2012]. Through cohesive zone modeling, stress and damage analyses are performed within the same design tool. In this approach, joint strength is determined by using a traction-separation law with appropriate damage initiation and propagation criteria. In the finite element modeling, the negative effects arisen from manufacturing faults are not considered [Guan et al. 2004].

In this study, the failure behavior of adhesively bonded single lap joints with composite adherends are investigated on the contrary to the literature where mostly joints with metal adherends are studied. Besides, unbalanced single lap joints are underline of this study which are quite rare in the literature. Mechanical tests and finite element analyses are performed to determine the crack initiation and propagation behavior on un-balanced bonded lap joints. Effect of stacking sequence and adherend thickness are investigated and the mechanical performance of the adhesive bonded joints are analyzed.

METHOD

Experimental procedure

The test specimens are prepared according to [ASTM D3165, 2007]. In order to minimize the bending caused by the eccentric load path, a plate with the same thickness of the adherends is added on both sides of the specimen. The geometry of the single lap joint test specimen is shown in Figure 2. While t_{plate} values change according to the test specimen, L_{plate}, L_{joint}, L_{trim} and W_{plate} are constant for all specimens and they are given in Table 1.

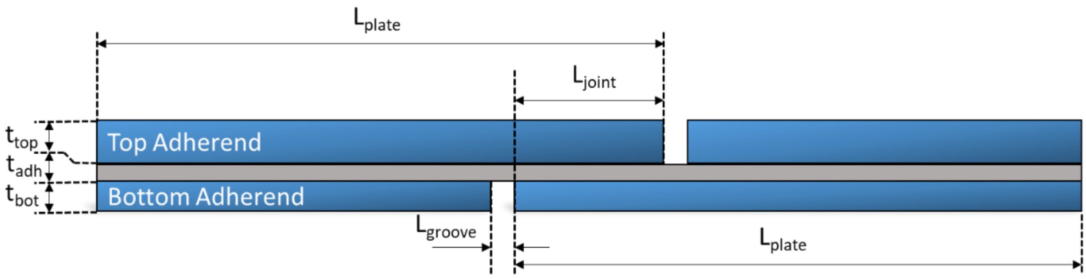

Figure 2: Single Lap Joint Test Specimen

Table 1. Test specimen geometric constants

L_{plate}[mm]	L_{joint}[mm]	L_{Groove} [mm]	W_{Plate} [mm]
123	40	3	25

Paste adhesive Hysol EA9394 is used as a bonding agent between the top and bottom adherends. Adhesive thickness kept constant with 1mm for all configuration. Adherends are created by using fabric plies or both fabric and UD plies. For fabric, HEXPLY 8552S/37% material is selected, while AS4/8552 is selected for UD material. Top and bottom adherends are not identical in a test configuration. Both of them have different thicknesses and different stacking sequences. Top and bottom adherends thicknesses and stacking sequences are defined in Table 2.

Table 2. SLJ Configurations

No	Adherend Bottom	Adherend Top	Joint Length[mm]	Adherend Bottom Thickness [mm]	Adherend Top Thickness [mm]
1	B2	T1	40	**2.44**	**7.76**
				$[45/0/(45)_2/0/45/\mathbf{0/45}]$	$[(45)_2/(\underline{0})_2/\underline{135}/(\underline{0})_2/\underline{45}/\underline{0}/\underline{135}/\underline{0}/0/(\underline{0})_2/\underline{45}/(\underline{0})_2/0/\underline{0}]_s$
2	B1	T2	40	**1.6**	**4.624**
				$[45/0/45/\mathbf{0/45}]$	$[(45)_2/\underline{0}/\underline{135}/\underline{0}/\underline{45}/(\underline{0})_3/0/\underline{0}]_s$
3	B1	T3	40	**1,6**	**3.152**
				$[45/0/45/\mathbf{0/45}]$	$[(45)_2/(\underline{0})_3/0/\underline{0}]_s$
3	B1	T4	40	**1,6**	**2,504**
				$[45/0/45/\mathbf{0/45}]$	$[(45)_2/(\underline{0})_3/0/(\underline{0})_3/(45)_2]$
3	B1	T5	40	**1,6**	**1.488**
				$[45/0/45/\mathbf{0/45]}$	$[(45)_2/\underline{0}]_s$

Finite element model

Finite element model for single lap joint is created to investigate mechanical behavior and failure mode of a single lap joint. Finite element simulations are performed with finite element software ABAQUS/Standard. A three-dimensional model is employed to capture the out of plane stress distribution and bending effects formed in the single lap joint. Instead of modelling full length of the adherends, only the partial volume beyond clamping is modelled as shown in Figure 3. By this way, a considerable reduction in computational time is aimed.

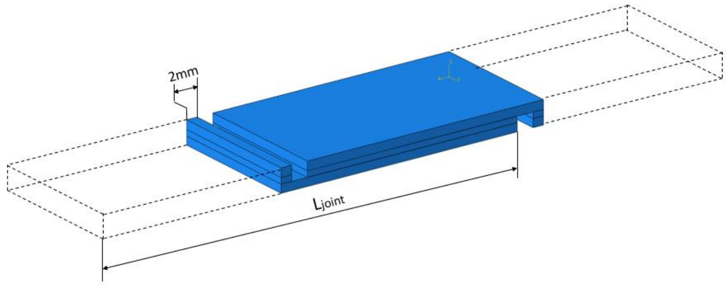

Figure 3: Partial modelling of SLJ

In modelling of adherends and bulk adhesive, 8-node continuum shell elements with reduced integration, S8CR is used. To simulate the interface crack, cohesive elements are placed between interface of the adhesive bulk material and adherends as shown in Figure 4. COH3D8 cohesive element with 8 nodes and 4 integration points are used for interface elements. Tie constraint defined between the interface element and its neighboring elements. By this way, different size of elements can be used between adjacent elements.

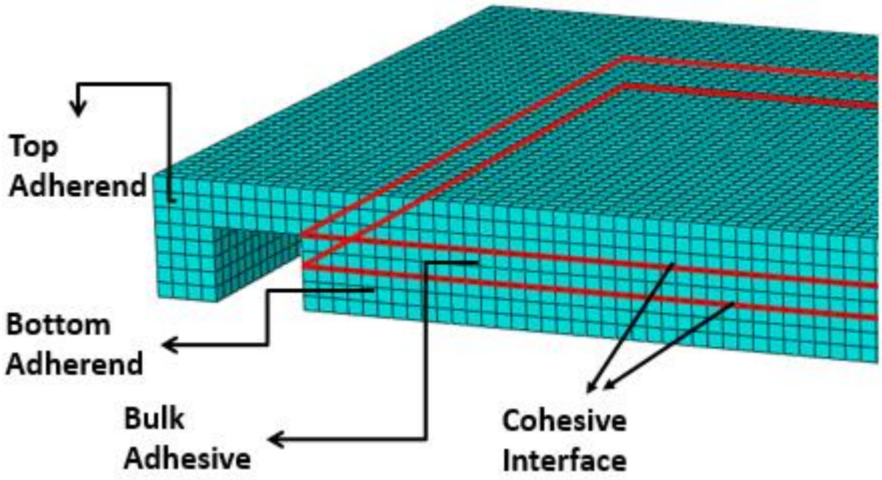

Figure 4: Single Lap Joint Finite Element Model

Exponential behavior for traction-separation law is selected for the adhesive. Interface stiffness is chosen larger than the nominal stiffness as it is suggested in literature [Turon, 2006] to overcome the convergence issues. Quadratic nominal stress criterion (*QUADS*) is selected for damage initiation criteria since it assumes stress relation between different directions. QUADS criterions is defined in the below formula;

$$\left\{\frac{\langle t_n\rangle}{t_n^0}\right\}^2 + \left\{\frac{t_s}{t_s^0}\right\}^2 + \left\{\frac{t_t}{t_t^0}\right\}^2 = 1$$

Where t_n, t_s, t_t, nominal stress pure normal mode, nominal stress in first shear direction, nominal stress in second shear direction respectively.
Critical energy release rate is found with Benzeggagh-Kenane(BK) mixed-mode crack growth criterion. In this criterion, critical energy release rate for Mode I (G_{Ic}), Mode II (G_{IIc}) and Mode III are taking into account.

$$G_c = G_{Ic} + (G_{IIc} - G_{Ic})(\frac{G_{II}}{G_T})^n$$

Surfaces at the end of one adherend is modelled as fixed. From the end of the other adherend, 10mm displacement is defined in x-direction. Translations and rotations in y- and z-directions are prevented along the top and bottom surfaces of the adherend.

RESULTS

Test Results

Effects of Bending Stiffness

Stiffness increase in composite specimens is shown to provide a higher joint efficiency. When bending stiffness of the adherend increase, the bending curvature in specimens decreases in return. Thus, resulting peel stress decreases for stiff laminates and this leads to an increase in joint strength [Kupski et al. 2019]. The classical lamination theory (CLT) is used to calculate the bending stiffness in longitudinal direction. The effective flexural longitudinal modulus for symmetric laminates is determined based on CLT as follows;

$$E_x^f = \frac{12M_x}{\kappa_x h^3} = \frac{12}{h^3 D_{11}^*}$$

Table 3. Longitudinal Bending Stiffness Effect on Shear Strength

	Bottom adherend thickness [mm]/ Sequence	Top adherend thickness [mm]/ Sequence	*D11**	Longitudinal bending stiffness [GPa] Ex=12/(D11*.t^3)	Shear Strength [MPa]
B1_T2_40	1.6 [45/0/45/0/45]	4.624 $[(45)_2/\underline{0}/\underline{135}/\underline{0}/\underline{45}/(\underline{0})_3/0/\underline{0}]_s$	0.002	48.94	13.02
B1_T3_40	1.6 [45/0/45/0/45]	3.152 $[(45)_2/(\underline{0})_3/0/\underline{0}]_s$	0.008	46.34	10.67
B1_T4_40	1.6 [45/0/45/0/45]	2,504 $[(45)_2/(\underline{0})_3/0/(\underline{0})_3/(45)_2]$	0.022	35.39	8.33
B1_T5_40	1.6 [45/0/45/0/45]	1.488 $[(45)_2/\underline{0}]_s$	0.220	16.56	7.87

On the selected configurations that are given in Table 3, results showed that higher shear strength obtained with the increase in bending stiffness. In Kupksi study, it is explained that the increase in bending stiffness leads to a decrease in peel stresses which in turn increases the joint strength.

Effects of Adhesive Joint Length and Thickness

As it is mentioned in literature [Kutscha et al. 1969], adhesive bond length and adherend thickness ratio (L/t) have an important effect on shear strength of joints. The results given in Table 4 and showed graphically in Figure 5 indicate that the increase in adhesive bond length to adhesive thickness ratio results in an increase in the shear strength of the joint.

Table 4. Longitudinal Bending Stiffness Effect on Shear Strength

	Bottom adherend thickness [mm]	Top adherend thickness [mm]	Joint Length [mm]	L/t	Max load [kN]	Shear Strength [MPa]
B1_T2_40	1.6	4.624	40	8.65	12.66	12.57
B1_T3_40	1.6	3.152	40	12.69	10.64	10.67
B1_T4_40	1.6	2.504	40	15.97	8.38	8.33
B1_T5_40	1.6	1.488	40	26.88	7.37	7.29

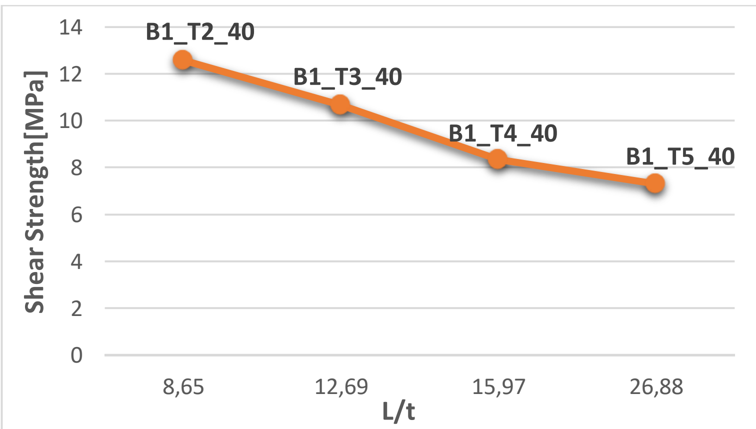

Figure 5: L/t effect on Shear Strength of the joint

FEM Results

Investigation of Stress Distributions

Stress distributions in the SLJ specimens are investigated through the overlap length. The analyses for the stress distribution in SLJ specimens with different configurations can help better understanding of failure behavior in such structures.

Shear and peel stresses in SLJ specimens are investigated with a 3D finite element analysis at the mid-width of the adhesive across the bond-line of the bonded joint. With the increase of the thickness of the top adherend, the stiffness difference between top and bottom adherend increases that leads to a higher bending moment. Different from the symmetric joints, it can be seen that (Figure 6) peel and shear stress distributions on the right and left overlap edges are quite different. The right side of the overlap, shows higher peel and shear stresses which gives a conclusion about the crack initiation side in asymmetric SLJs. With the increase of asymmetry, the peel and shear stress that joint experiences increase significantly.

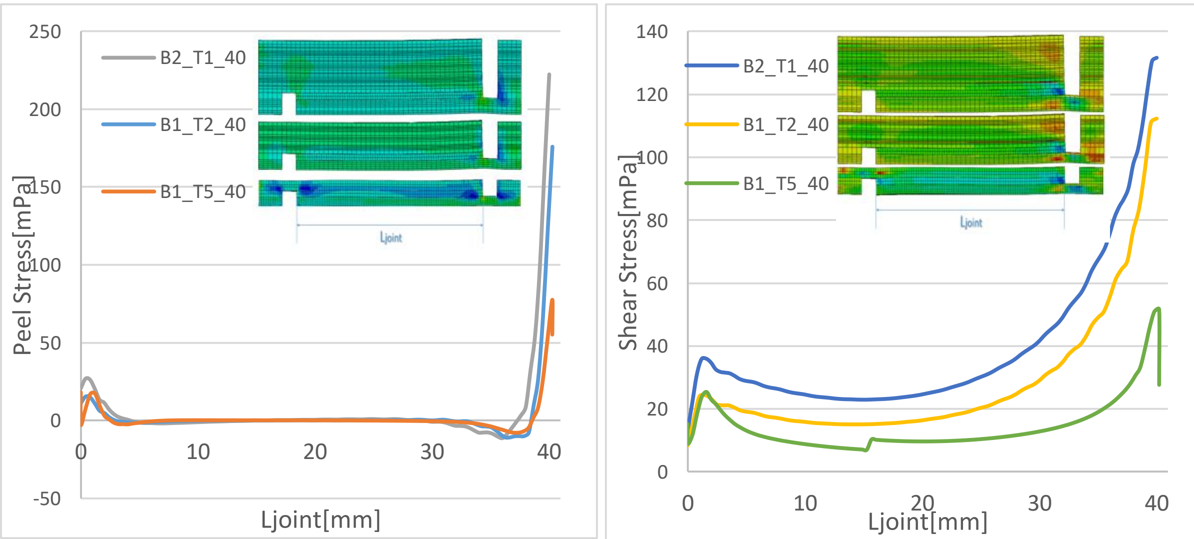

Figure 6: Comparison of Peel and Shear Stresses Distributions

Results in Cohesive Zone Model

To investigate the crack initiation and propagation the cohesive zone method is used to simulate the crack at the interface between adhesive and adherends. Cohesive zone modelling and finite element analyses are performed in ABAQUS.

In contrast to the real life applications, a discrete adhesive is modelled, in other words, adhesive and interface models are only crated at the overlap as it can be seen in Figure 7. In consequence, stress singularities that take place at the point of the junction of the adherend and adhesive, translate to the opposite side of the interface. Even if crack initiation points are different in FEM and real life application, the crack propagation can be simulated properly with FEM.

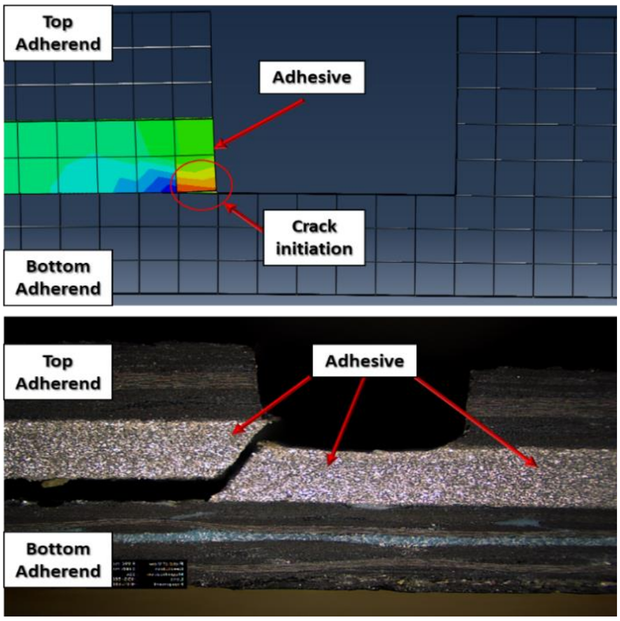

Figure 7: Discrete adhesive model

According to the analyses performed on Specimen B1_T5_40, the initial crack is observed on the left side of the overlap as shown in Figure 8, where the joint experiences the maximum shear and peel stresses (Figure 9).

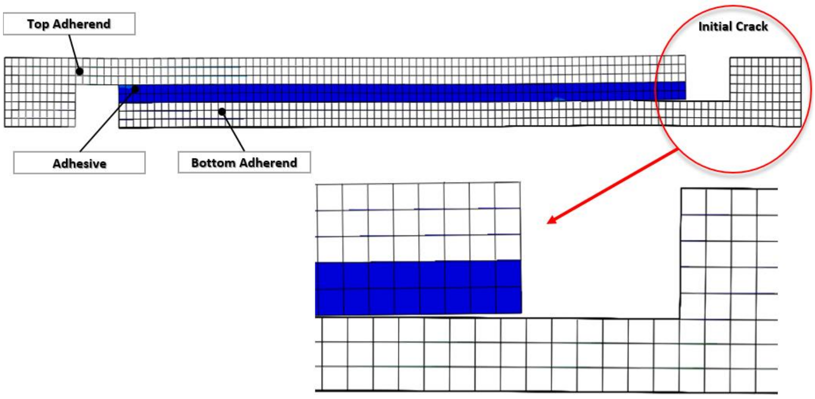

Figure 8: Interface crack initiation in Specimen B1_T5_40

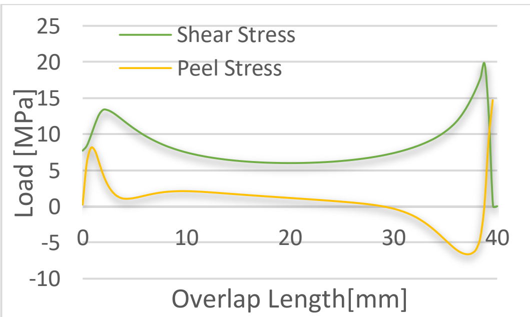

Figure 9: Specimen B1_T5_40: Stress distribution along overlap

Similar results are obtained with the previous estimations according to the results in stress distribution analyses. The crack initiation is observed at the thicker adherend side of the overlap. It is shown that the finite element results are in good correlation with the real life applications.

CONCLUSION

The failure mechanism of adhesively bonded joints are investigated with single lap joint specimens. Adherends which are created from composite plies with various thicknesses and stacking sequences has been used in the study to analyze the effect of thickness and stiffness of the adherends to the failure behavior of the adhesively bonded joints. Results showed that, a higher shear strength is obtained with the increase in bending stiffness and higher shear strength results are obtained with the decrease in L/t ratio.

Stress distribution created along the overlap is used to explain the failure behavior in SLJ joints. Higher peel and shear stress concentrations obtained at the thicker side of the overlap end where lower stresses obtained on the opposite side due to the eccentricity in the joint. With the increase in the difference between adherend stiffness, higher peel and shear stresses are observed. With the aim of modelling the interface crack in SLJ specimens a finite element model of the single lap joint with discrete adhesive modelling is created by using cohesive zone approach. By means of cohesive zone model, crack initiation and propagation are represented which shows good correlation with interferences that are made according to test results and stress distributions.

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