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DELAMINATION EFFECT MODELING, SIMULATION AND EXPERIMENTAL VALIDATION OF LAP SHEAR TEST

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ABSTRACT

Single lap joint is among the most widely used adhesively bonded joint type for both non-structural and structural applications. Considering the strength and efficiency of such joint, good understanding of the adhesive behavior and stress analysis of the joint is very important, especially for the overlapped bonded area in the lap joint. Apparent shear strength of adhesively bonded single lap joint is studied and Finite element analysis (FEA) of lap shear test is investigated using ANSYS software. Regarding adhesively bonded structures, the novelty of the present work lies in the study and discussion of the modeling and simulation approaches of interface delamination effect. Finally, an experimental verification of the simulated results is presented and discussed. Here, it is shown that the use of interface elements using cohesive zone model is best suited to predict the failure initiation and delamination pattern of such an adhesive joint.

Keywords: Adhesive bonding, Interface delamination, FEA, Lap shear test, Composite structures.

1. INTRODUCTION

The two general classes of joints are mechanical fasteners and adhesive bonding. Both types of joints receive continuous attention in the scientific community. Additionally welded joints are also widely used and a great amount of research is undertaken for its better understanding (Nachimani, 2012; Sathiya et al., 2012; Kumar et al., 2011). During the last decade, due to extensive research and development efforts, high quality and enhanced strength adhesives are available. This has led to a wider application of adhesive bonded joints over conventional bolted joints, where applicable. In comparison to other fastening mechanisms, adhesively bonded joints exhibit several advantages, such as corrosion resistance, weight reduction, and elimination of stress concentration due to the fastener mounting hole (Hsien and Tandjung, 2005).

Similarly, for performance analysis and strength prediction of adhesively bonded hybrid structures comprising of different substrates, have studied the problem in greater details (Franco et al., 2013; Bella et al., 2013; Konstantinos and Nicholas, 2013a and 2013b).

Adhesive bonded joint failures may be classified as adhesive or cohesive failure. An adhesive failure represents the interfacial bond failure between the adhesive and adherend. This adhesive failure mode is termed here as delamination. However cohesive failure occurs when the adhesive fractures and a layer of the adhesive remains on both the substrates. Figure 1 schematically presents the two different failure modes. Experimental results have shown that the bonded joint failure is a combination of both the adhesive and cohesive failure modes. A good joint design requires the cohesive failure mode that occurs within the adhesive or one of the adherends, this ensures that the maximum strength of the materials in the joint has been reached. Thus it is preferred to avoid delamination in order to have joints with higher strengths.

The present study focuses on the modeling and simulation of delamination failure in adhesive joint between metal plates. For this purpose an FEA model is developed and discussed. Finally the model is validated by comparing the load-displacement characteristics with experimental results. Such a study is more significant in case of composite structures which are prone to interlaminar delamination. Additionally this delamination failure may also occur along the joint interfaces. Therefore it is vital to accurately predict the initiation and propagation of this delamination in composite joints in order to achieve high efficiency joints.

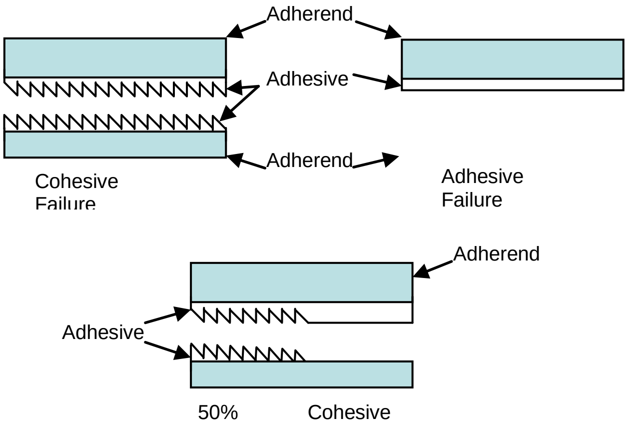


Figure 1 Cohesive and adhesive bond failures.

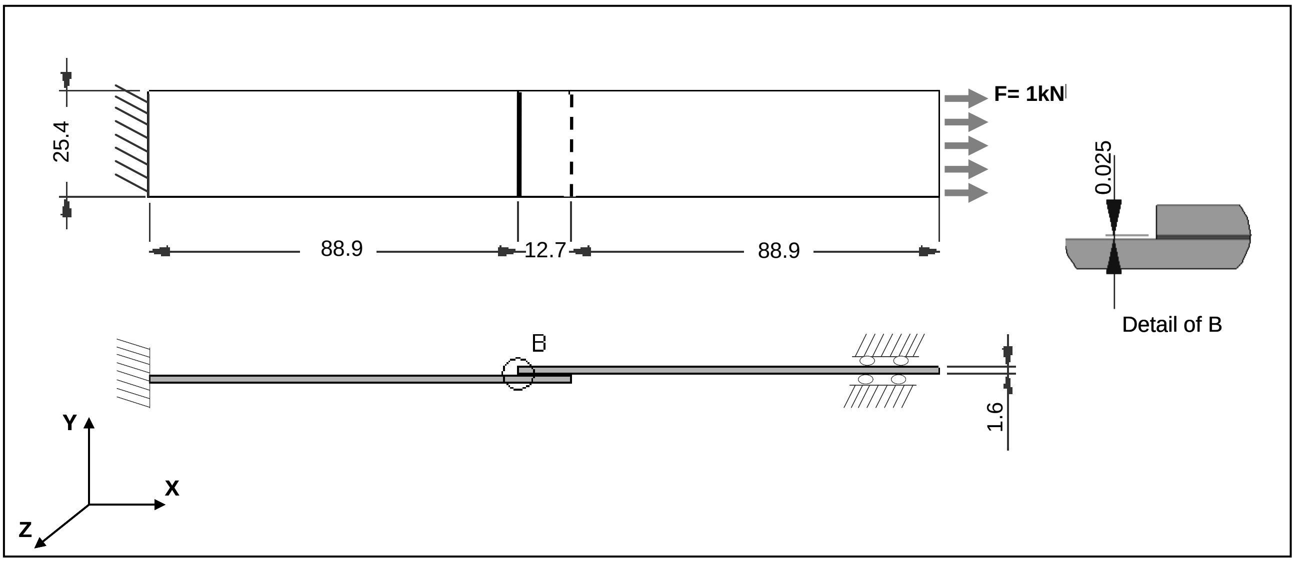


Figure 2 Lap joint specimen (all dimensions are in mm).

In order to study the delamination phenomenon, adhesively bonded single lap joint is used. Adhesive Lap joints are verified using standard test methods. To test the apparent shear strength of an adhesively bonded single lap joint, Lap Shear Test, is one of the most commonly used test method (ASTM D). The present work describes the modeling and simulation of a lap shear joint with special consideration of delamination effect.

2. MODELING AND SIMULATION

Generally a problem is approached either with analytical modeling or through FEA. Compared to analytical approach, FEA of adhesively bonded joints has the advantage of geometric flexibility and the availability of commercial codes (Tsai et al., 1995; Li et al., 1999; Lucas et al., 2009). In the present study, FEA analysis of the lap joint as shown in Figure 2 is performed using ANSYS 10.0. The basic assumptions in modeling of the adhesive lap joint are summarized as follows:

Adherends: In the present study flat mild steel plates with isotropic material properties are used. Plates are assumed to be perfectly straight and no initial bending is considered.

The Adhesive: Typical polymeric structural adhesives exhibit inelastic behavior, due to induced local permanent plastic strains even at low levels of external loading. For more realistic analysis of bonded joints a non-linear adhesive behavior can be considered (Zhang et al., 2006; Markolefas and Papathanassiou, 2009). Ahmad et al. (2010) have also shown the effect of microstructure on to the bond strength. However for simplification purposes, adhesive may be assumed to behave as linear elastic (Cognard et al., 2011). For single-lap joint, the above assumption is found valid for both the shear stress and the out of plane transverse tensile stress resulting from the bending. In reality, especially at the edges of joint, adhesives behave as elastic-plastic. Consideration of adhesive plasticity would decrease the stress concentration thus increasing the predicted joint strength (Hsien and Tandjung, 2005). In the present work of joint strength estimation, elastic adhesive behavior is assumed.

Loading and boundary conditions: General boundary conditions on the joint are applied, with one end fixed and a load of 1 kN is applied on the other end. In order to avoid bending of the free end, it is assumed to have roller supports across the thickness of the plate.

The constitutive mechanical properties of the epoxy resin system (Araldite LY564/ Araldite HY 2954) used in the present study are experimentally evaluated. Standard tensile test specimens as per ASTM standard are machined from a pre-cured larger epoxy plate. In order to obtain a void free cured epoxy plate, the effect of different physical parameters is studied onto the curing of epoxy plates. The voids are due to the presence of entrapped air bubbles. It was finally concluded that before curing the epoxy plates these must be carefully desiccated at -500 ± 50 mm of Hg at room temperature for at least 30 minutes. Table 1 records the mechanical properties of adhesive and adherend.

Table 1 Mechanical properties of lap joint materials.

Joint materials	**Engineering constants**	**Strength,** MPa
Adherend (MS)	E = 207 GPa ν = 0.3	σ_y = 280
Adhesive (Epoxy Resin System, Araldite LY564/ Araldite HY 2954)	E = 2.6 GPa ν = 0.38	σ_t = 69

3. FEA SIMULATION

Two different finite element analysis techniques can be used for the simulation of adhesive lap joints. One of the most common techniques is using merged or identical nodes between adhesive and adherend interfaces. Work of Panigrahi and Pardhan (2007); Joyanto and Jones (1980) are good examples of lap joint analysis with such a technique. This technique produces results with a higher level of accuracy but do not show the interface delamination in joints. However with the help of suitable failure criteria interface separation between the joints can be studied.

Alshoaibi et al. (2008); Alfano and Crisfield (2001) discussed about a more realistic approach for simulation of delamination in adhesively bonded joints by using interface elements and an interface damage law. This approach uses cohesive zone model (CZM), a tool available in ANSYS software.

Experience with structural failures has shown that most ruptures initiate at joints where stress concentrations are difficult to avoid. Thus, the rational design of a structural joint can often be the most crucial driver in a strength-critical component. In the present study an adhesive interface delamination analysis of the lap joint is performed using both approaches and a comparative study is carried out. In the end the simulated results are compared with the experimental test results.

3.1 Approach 1 (Node Merged Technique):

The FEA model is developed in ANSYS software with the same dimensions as shown in Figure 2 and meshed with 3-D eight-noded solid elements (SOLID45) for both adherend and adhesive. From the results of the previous studies, it is known that the critical sections of the joint are at or near the ends of the overlap where the magnitudes of the stresses and their gradients are high. In contrast, over the middle two-thirds of the overlap, the stress distribution is approximately uniform. Furthermore, the critical regions of the joint are at the adherend-adhesive interfaces. The joint is, therefore, meshed with elements of different sizes: small elements in the overlap region where the stress gradients are high and large elements in regions where the stress distribution is uniform. In addition the adhesive thickness is divided into a finer mesh of elements in order to yield the stress variation through the adhesive thickness. Figure 3 shows the mesh employed for the lap joint and the details of mesh around the overlap region.

Once all the boundary conditions are applied, analysis of the joint is carried out and the results are illustrated in Figure 4, 5, 6. Figure 5 , 6 show that the value of shear and peel stresses along the interface are high at the right free edge of the top and left free edge of the bottom adhesive-adherend interfaces. This observation predicts that the edge separation will initiate from the left free edge of the top and right free edge of the bottom adhesive-adherend interfaces. Considering that the delamination damage between the adhesive and adherend interfaces represent the joint failure. This delamination behavior can be predicted by using the modified TasiWu criteria (Panigrahi and Pardhan, 2007) given in Eq. (1).

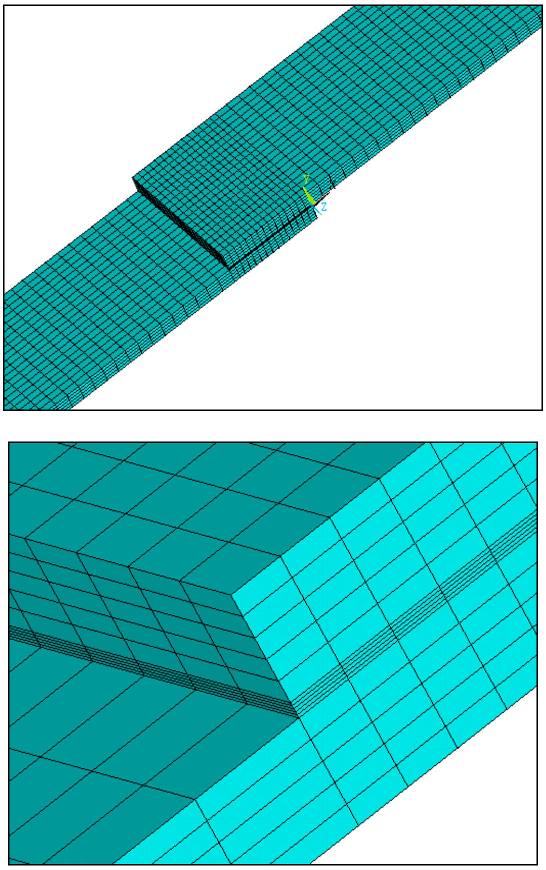


Figure 3 Finite element model of lap joint.

$$\left(\frac{\sigma_y}{Z}\right)^2+\left(\frac{\tau_{xy}}{S}\right)^2+\left(\frac{\tau_{yz}}{S}\right)^2=e^2\begin{cases} e<1, \text{no failure}\\ e\geq 1, \text{failure}\end{cases} \qquad (1)$$

where Z is the normal bond strength, S is the shear strength and e is termed as failure index.

To predict the delamination damage, the criterion is derived considering that only inter-laminar shear stress and through the thickness normal stresses are required. Based on the above criterion and using the maximum values of stresses obtained from Figure 5, 6, it is numerically determined that no edge separation is initiated, as $e < 1$, at the applied load of 1kN. The resulting displacement at the applied load is 0.028 mm (as shown in Figure 4) which is found in agreement with the experimental results. This shows that the FEA model used for simulation of lap shear test is correct. Now in order to have a detailed study of the approach, simulations at different loads are carried out and results are discussed in the following section.

3.2 Approach 2 (Cohesive Zone Model):

Before going into detail of this approach, first the cohesive zone model and its characteristics are discussed.

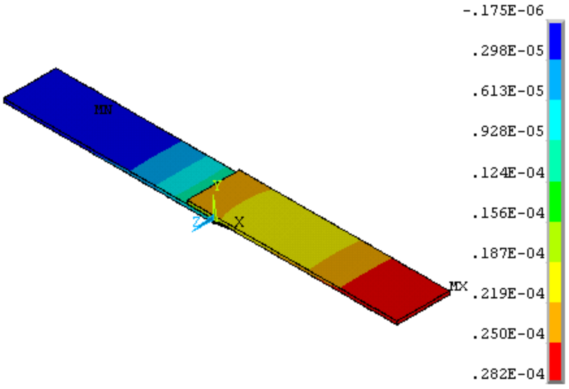
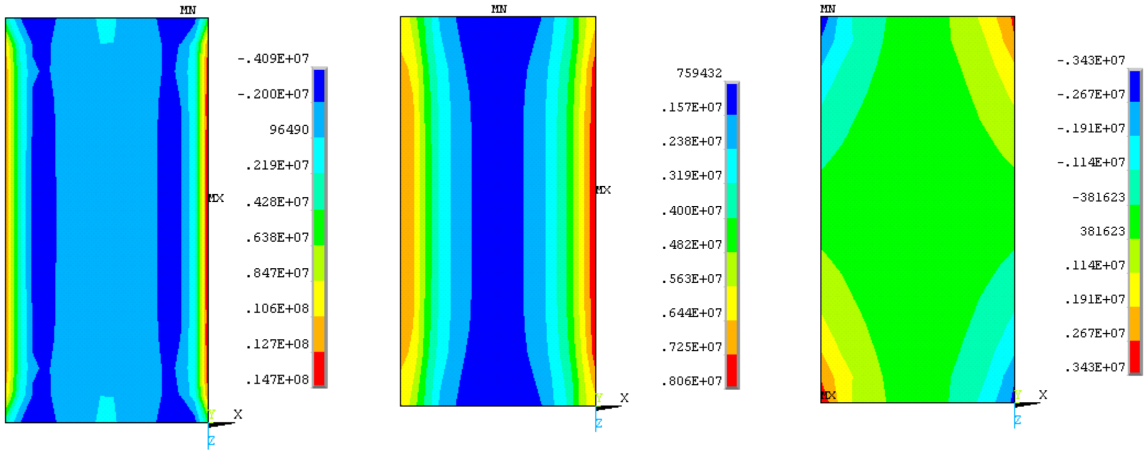
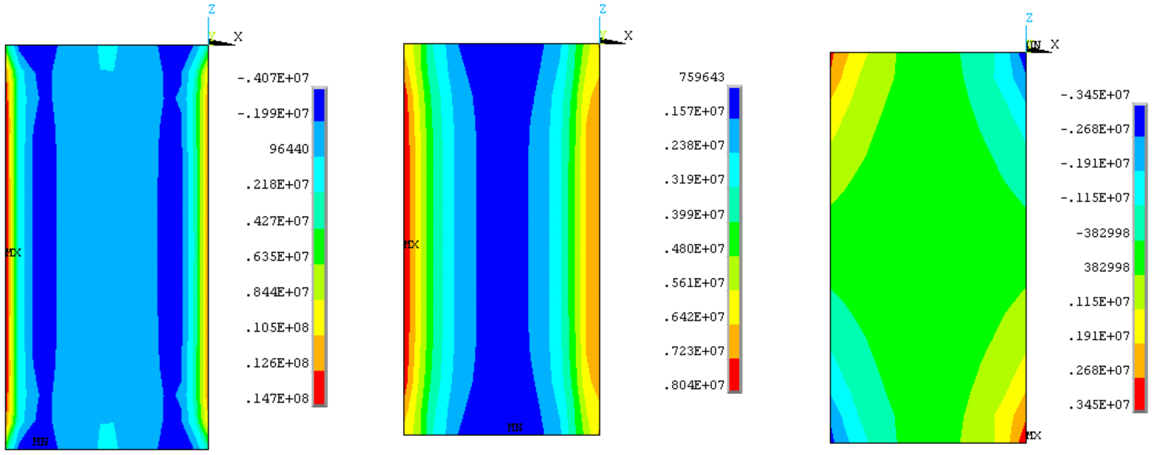


Figure 4 Displacement in X-direction (m).



σ_{yy} (N/m^2) τ_{xy} (N/m^2) τ_{yz} (N/m^2)

Figure 5 Out of plane stress distribution (along the interface of the top adherend and adhesive layer).



σ_{yy} (N/m^2) τ_{xy} (N/m^2) τ_{yz} (N/m^2)

Figure 6 Out of plane stress distribution (along the interface of the bottom adherend and adhesive layer).

Cohesive Zone Model: Toughness and the ductility of the multi-phase materials, such as matrix-matrix composites and laminated composite structure, is largely limited due to fracture or delamination along an interface between phases. This has motivated considerable research on the failure of the interfaces. Traditionally, fracture mechanics methods making use of nodal release technique has been used for modeling and analysis of interface delamination (ANSYS-R10).

Alternatively, softening relationships between tractions and the separations may be used to introduce fracture mechanism. This in turn introduces a critical fracture energy required to break apart the interface surfaces. This technique is called the cohesive zone model.

Model Details: With reference to ANSYS – Release 10 documentation, the cohesive zone model consists of a constitutive relation between the traction **T** acting on the interface and the corresponding interfacial separation **δ** (displacement jump across the interface).

The interfacial separation is defined as the displacement jump, **δ**, i.e., the difference of the displacements of the adjacent interface surfaces:

$$\delta = u^{\mathrm{TOP}} - u^{\mathrm{BOTTOM}} = \text{interfacial separation} \tag{2}$$

Note that the definition of the separation is based on local element coordinate system, Figure 7. shows the schematic of an interface element. The normal of the interface is denoted as local direction *n*, and the local tangent direction is denoted as *t*. Thus:

$$\delta_n = n \cdot \delta = \text{normal separation} \tag{3}$$

$$\delta_t = t \cdot \delta = \text{tangential (shear) separation} \tag{4}$$

Procedure: An interface delamination analysis in ANSYS using cohesive zone model involves the same overall steps that are involved in any ANSYS nonlinear analysis. The model is developed with the same dimensions as shown in Figure 2. and meshed with 3-D eight-noded solid elements (SOLID45) for both adherend and adhesive. Furthermore, in order to simulate interface delamination a cohesive zone is defined between the adherend and adhesive layer. A layer of 3-D linear interface elements (INTER205) is used to represent the cohesive zone and to account for the separation across the interfaces. It is important to note that the material properties for cohesive zone characterize the separation behavior at the interface. As defined in ANSYS – Release 10 documentation, the three parameters required for defining cohesive zone are: C_1 = maximum normal traction at the interface

C_2 = normal separation across the interface where maximum normal traction is attained

C_3 = shear separation where maximum shear traction is attained

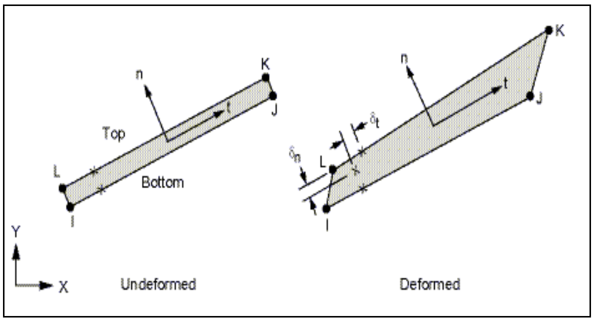


Figure 7 Schematic of interface elements (ANSYS-R10)

In accordance to relevant ASTM standards, experimental values are obtained of these parameters to be used in FEA simulations. After applying all the boundary conditions, a nonlinear analysis of the joint is performed. Figure 8, 9 show the resulting separation along the top and bottom adhesive-adherend interfaces. From the results of previous approach as it is observed that the edge separation will initiate from the left free edge of the top and right free edge of the bottom adhesive-adherend interfaces. The same behavior can be observed from the results as depicted in Figure 8, 9. Here it can be seen that the values of interface separation for all three components are maximum at the respective left and right free edges of the top and bottom adhesive-adherend interfaces. The resulting displacement of 0.037 mm (as shown in Figure 10) is found in close agreement with the experimental results. This similarity in the results shows that approach used models well the behavior of lap joint.

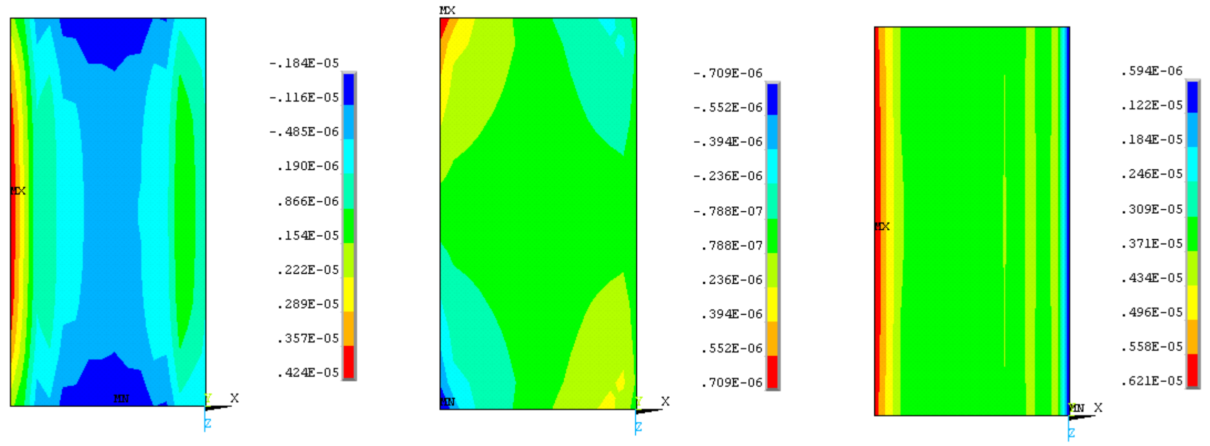
The results of Figure 8, 9 show that XY and XZ components of interface separation are different for both top and bottom adhesive-adherend layers. It is interesting to note in these figures that the interface separation values for XY component of top interface are similar to XZ component of bottom interface, whereas the separation patterns are mirror images of one another. The same behavior is observed for XZ component of top and XY component of bottom interfaces. This observation is in good agreement with the modified TasiWu criteria (Panigrahi and Pardhan, 2007), which says that the delamination damage is due to the combination of inter-laminar shear and through the thickness normal stresses. This validates that the used FEA model is correct.

Now in order to determine delamination damage, a failure criterion denoted by *e** is developed in the present work based upon the normal interface separation.

$$e^* = (\text{Normal component of interface separation} / C_2) \times 100 \tag{5}$$

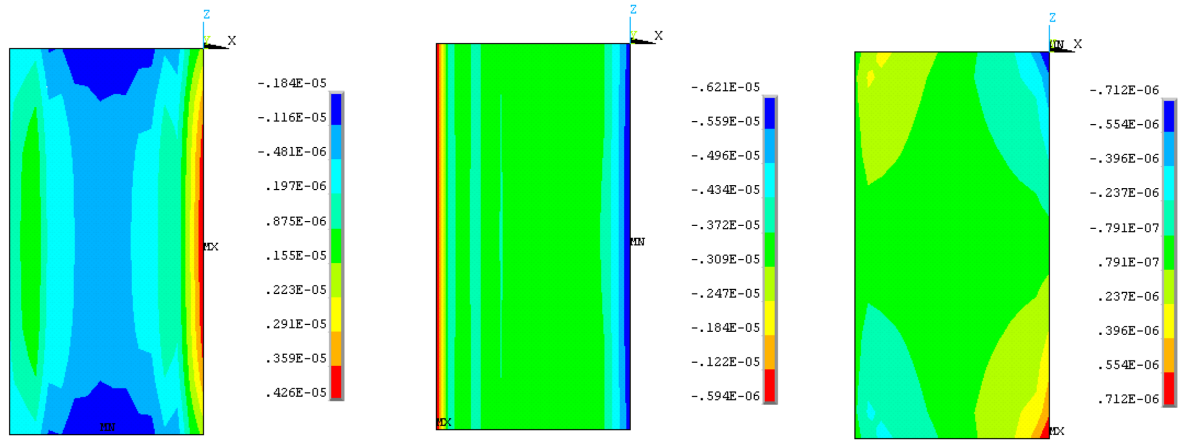
Now, **If** $e^* < 5$, no failure
If $e^* \geq 5$, failure

The criterion is established considering that the normal component of interface separation plays major role in delamination.



Normal component of Interface Separation XY component of Interface Separation XZ component of Interface Separation

Figure 8 Interface separation along top adherend and adhesive layer (m).



Normal component of Interface Separation XY component of Interface Separation XZ component of Interface Separation

Figure 9 Interface separation along bottom adherend and adhesive layer (m).

Based on the criterion, given in Eq. (5) and using the values presented in Figure 8, 9, it is observed that no edge separation is initiated at the load of 1kN (as $e^* < 5$). This observation is in relation with approach I that no edge separation is initiated at the applied load.

Comparing displacement results obtained from both approaches (as depicted in Figure 4, 10) with experimental results, we observe that the second approach using cohesive zone model produces results with much accuracy. Also the stress patterns for this approach, shown in Figure 11, 12, seem more realistic because in practice the joint failure is a combination of adhesive and cohesive bond failure. Using same procedure and model, various simulations are run at different loads and results are recorded. These results will be discussed later in Section 5 of this paper.

4. EXPERIMENTAL PROCEDURE

For the lap shear test as per ASTM standard, specimen is made out of steel with same dimensions as shown in Figure 2. The specimens are bonded with the adhesive (Epoxy Resin System) and cured. After curing, specimen is pulled to failure on tensile testing machine using uniform crosshead speed of 5 mm/min ±25%. The loading data is recorded and the obtained values of breaking load, elongation, and shear strength are used to verify the finite element simulations. In order to have accurate results multiple experiments are performed, Figure 13. shows failure modes of lap shear test samples. The resulting average values of the experiments are as follows:

Breaking Load = 4.7 kN
Elongation = 0.19 mm
Shear Strength = 19 MPa

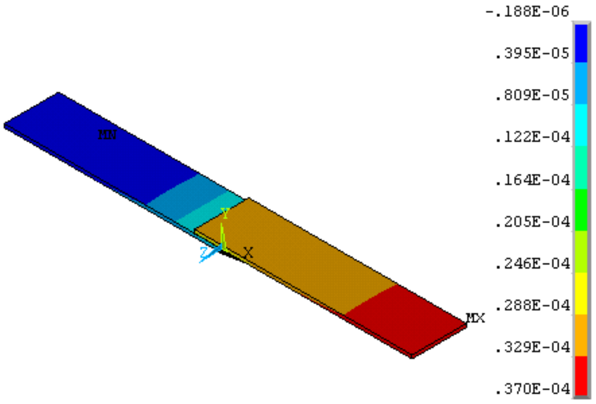
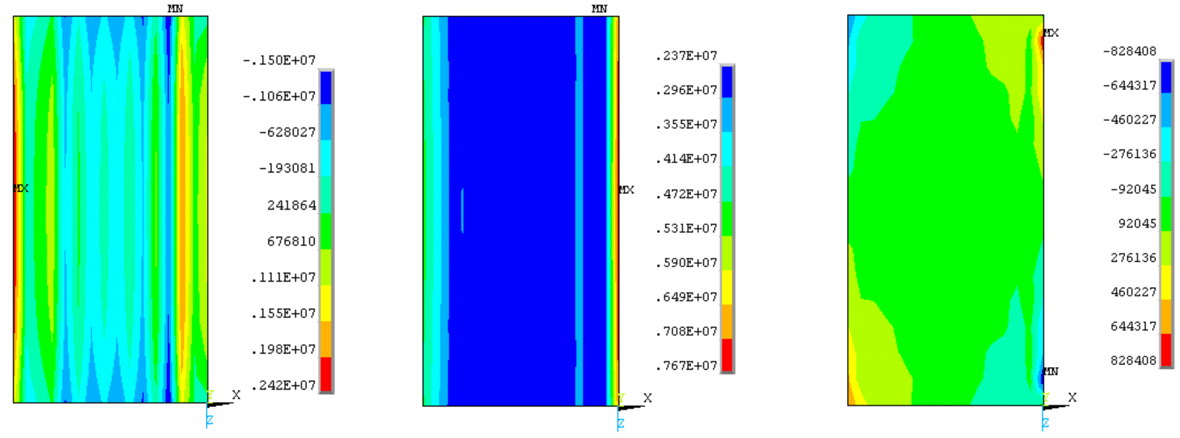


Figure 10 Displacement in X-direction (m).

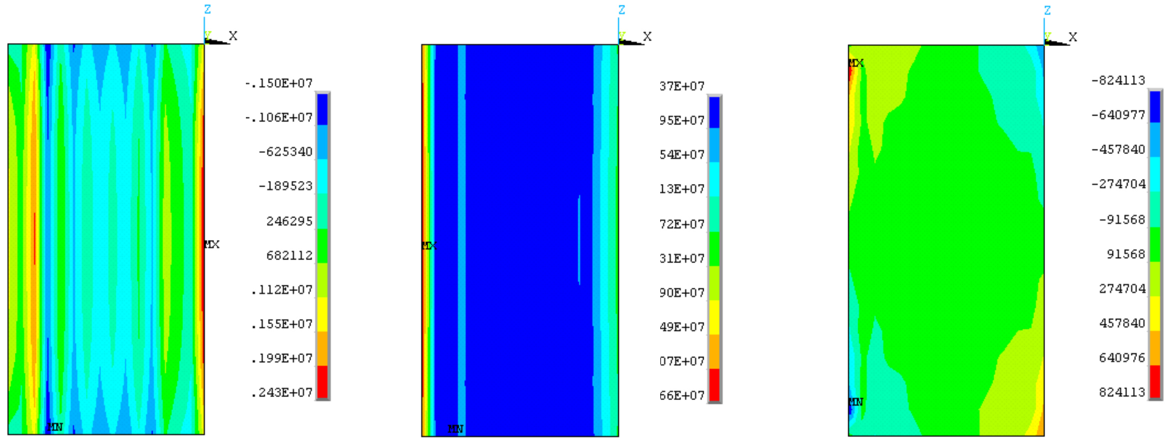


σ_{yy} (N/m^{2})

τ_{xy} (N/m^{2})

τ_{yz} (N/m^{2})

Figure 11 Out of plane stress distribution (along the interface of the top adherend and adhesive layer).



σ_{yy} (N/m^{2})

τ_{xy} (N/m^{2})

τ_{yz} (N/m^{2})

Figure 12 Out of plane stress distribution (along the interface of the bottom adherend and adhesive layer).

From the experimental results, it may be concluded that the failure is a result of the combination of peel stresses and shear stresses, as part of adhesive is found on both the adherend plates.

Figure 13 shows that the damage in the form of delamination is initiated at the free edge of upper plate (at which force was applied). The same behavior is observed in the simulated results obtained from both the approaches. For example from Figure 5, 6 (node merged technique) and Figure 11, 12 (cohesive zone model) stress concentration is obtained at the free edges which will result in initialization of delamination. It is also important to note that the surface roughness plays an important role in the resulting values and due care must be given for preparation of the surfaces to be bonded.

5. DISCUSSION

Design, simulation and experimental procedures of lap shear test have been described. The simulations are carried out using two different techniques (node merged and cohesive zone model). The results from both the approaches can be summarized as follows:

For the approach using node merged technique, based on the failure criterion given in Eq. (1) it is known that the edge separation will only start at $e \geq 1$. Now at the time of joint failure as their will be complete separation between the adherend and adhesive layer, the value of failure index e for all points across the interface will be greater or equal to 1. Figure 14 predicts that the interface delamination at the edges starts at a load of 1.5 kN for which value of e is equal to 1. However the graph is not predicting the joint breaking load, because the value of failure index e at the middle of interface is less than 0.5 even at a load of 4.5 kN. Thus it is evident that this approach has some major limitations in predicting the behavior of adhesive joints. This observation is true because the effect of interface delamination is not accounted for this technique. Comparing the same with experimental results shows that the joint failure is due to a combination of interface shear and peel stresses. Thus it is important to perform FEA of an adhesive joint with delamination effect.

For the second approach, cohesive zone model, based on the failure criteria given in Eq. (5) it is known that edge separation will only start at $e^* \geq 5$. Figure 15 predicts that the interface delamination at the edges starts at a load of 1.7kN for which value of e^* is equal to 5. This obtained value of edge separation load is in agreement with the value of 1.5 kN obtained from Figure 14. This similarity in results show that the FEA model used is correct. Another parameter to verify the FEA model is the resulting elongation (displacement) at the breaking load. Figure 16 compares the experimental elongation results with the two approaches. It is evident that the approach using cohesive zone model is closer with the experimental results and thus is more representative of the actual physical test.

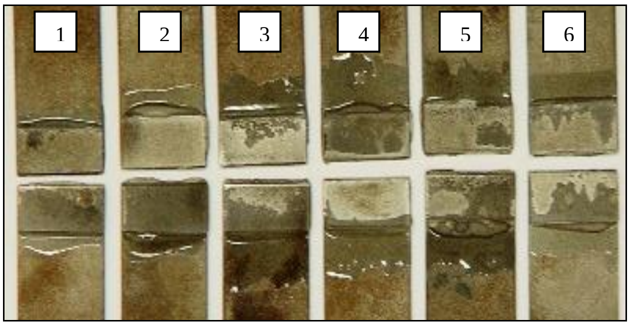


Figure 13 Failure modes of lap shear test samples.

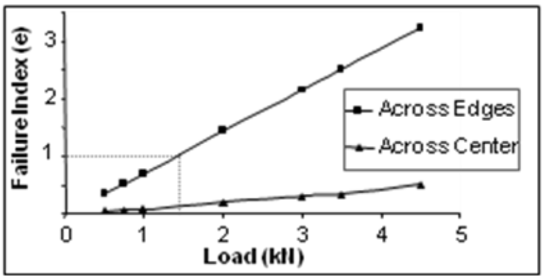


Figure 14 Load vs. Failure Index (using node merged).

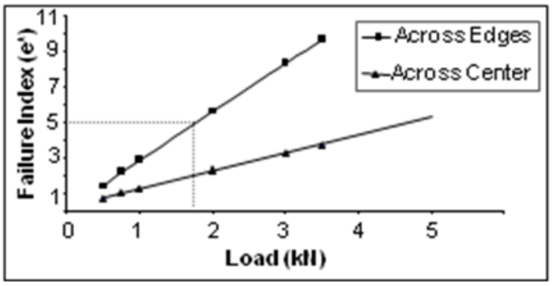


Figure 15 Load vs. Failure Index (using Cohesive Zone Model).

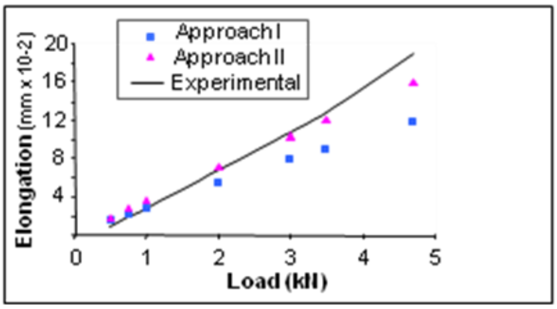


Figure 16 Load vs. Elongation.

6. Conclusion

Design and analysis of a single adhesive lap joint is carried out in detail to demonstrate the modeling, simulation and experimental validation procedure. The results of the study have shown that a more accurate technique for simulating the adhesive joints is using cohesive zone model. In case of adhesive joints, interface delamination plays an important role in the joint failure and it is important that the FEA model must account for this effect. Such a type of validated technique would be very useful in predicting the strength of a bonded joint or in case of composite structures to predict delamination.

The experimental and finite element results are in good agreement for the simulation approach using cohesive zone model. Thus, the finite element model chosen to analyze the adhesive-bonded joint is found valid and may be used in future works involving adhesively bonded composite joints.

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