

Failure Load Prediction of Structural Adhesive Joints Based on Local Yielding Criterion with Non-linear Material Behaviour

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The support of Anadolu University for providing ASTM- D 1002 testing manual and official ANSYS15 APDL package program, is gratefully acknowledged.

Abstract
In this study, a local yielding failure criterion has been introduced to estimate the static strength of structural single lap adhesive joints under tensile loading. The criterion is based on a simple 2D non-linear elastic-plastic finite element analysis implementing both material and geometrical non-linearity. According to this method, the magnitude of peeling and shear stresses along the adhesive layer are considered as a failure parameter. The criterion suggests that fracture occurs when the failure parameter across the adhesive interface plane reaches a critical value at the edges of adhesive bond-line. The trends of peeling and shear stress concentrations along the bond line of structural single lap joint were given to have an idea about the critical failure distance of adhesive interface planes. It is shown that the predictions based on the proposed criterion have good agreements with the similar studies comparing to the previous works in literature.

Keywords: Single Lap Joint, Failure Criterion, Finite Element Method, Bi-linear Material

1. Introduction

Implementation of bonded joints as an alternative to riveting, welding and other traditional fasteners have been greatly increased in structures and industries such as rail vehicles, aircraft and automobile. In comparison with conventional joining methods, the adhesive joints have specific advantages such as more efficient and uniform stress distribution along the bonding plane, relatively lower weight, enabling joining of thin and dissimilar materials and also improving corrosion resistance and electrically insulating. Moreover, adhesive joints have good damping properties. Their capacity might be beneficial for reducing sound and vibration. They also simplify assembly procedures by replacing several mechanical fasteners with a single bond, or by allowing several components to be joined in only one operation.

Epoxy adhesives, which are widely chosen for bonding process in terms of its applicability to a wide range of material types, become very popular regarding to its higher strength and temperature resistance among the other adhesives. They mainly consist of an epoxy resin plus a hardener. They allow great versatility in formulation since there are many resins and many different hardeners. Epoxy adhesives are

available in one-part or two part form and can be supplied as flowable liquids, as highly thixotropic products with gap-filling capability of up to 25mm [1].
The increased application of adhesive joints was accompanied by the development of mathematical models in order to analyse the fracture behaviour of those joints. Both analytical and numerical models have been developed. Analytical models such as the oldest work proposed by Goland and Reissner [2] usually involve many simplifying assumptions. They introduced equations to predict the shearing and normal stresses in the adhesive layer as well as those in the jointed plates, assuming that the peel and shear stresses were constants across the adhesive thickness. In Cornell's work [3], a variation and extension of Goland and Reissner's method [2] was presented for determining the stresses in adhesive lap-joints. He assumes that the two lap-joint plates act like simple beam and the more elastic adhesive layer is an infinite number of shear and tension springs [4]. Hart-Smith has produced an enormous amount of work on continuum mechanics of adhesive joints, for example [4, 5, and 6].
For practical application of adhesively bonded joints, single lap joints are generally preferred to be analysed due to its ease of operation in many fields and assemblies. However, the peeling stresses generated on the edge of adhesive and adherent interfaces make estimation of failure load and strength difficult accompanied by the geometrical and material non-linearity [7]. In the previous works of literature, there are generally two outstanding methods; one is stress and strain based methods and the other is fracture mechanic approach. Stress and strain method considers some maximum and minimum values depending on the some failure criterion equations. For the estimation of failure loads, many researchers performed some numerical finite element analysis [8-14] considering different material and failure behaviour. In these studies, some failure approaches such as elastic failure mechanism, failure envelope, cohesive zone modelling and some peak stress and strain values were proposed. On the other hand, for practical prediction of static strength of a single lap joint, implementation of fracture mechanics approach requires some information about the toughness, failure mode shape (cohesive, adhesive delamination and stress and strain singularities) that can be obtained early stage of design and manufacture. These methods are only applicable in the case of performing several experiments that increases cost the operation. The failure load of adhesively bonded joints is not only influenced by the geometry of the joints but also by material behaviour.
In this paper, a new model for two dimensional finite element analysis of adhesive joints is presented. The model takes into account peeling and shear stress variation across the adhesive thickness and bond-line as well as the material and geometrical non-linearities. 2D plane strain element for mesh structure of both adherent and adhesive is selected. The most popular single lap joint is chosen for the analyses. The results present the critical failure path and nature of elastic and plastic stresses including the influence of geometrical and material non-linearities.

2. Material and Method

2.1. Failure prediction method

Apart from the classical analytical methods, there is a broad category of failure criteria approaches in literature for bonded structures. Therefore, one of the most outstanding failure method called maximum value criteria is taken account to evaluate yielding loads of bonded joints under axial loading. For determining of yielding loads (local yielding) of single lap joint, a failure criterion based on peak values of peeling and shear stresses on the corners of the adhesive bond-line are considered. In this approach, the equivalent value of those stresses are proposed to be as a yielding parameters. This type of failure criteria is considered to be the most popular and intuitive category for bonded joints [12].
Then, a new distance method mainly called limit state criteria has been proposed in order to estimate failure load (global yielding) of single lap joints. This method is based on a concept termed global yielding, which applies when a path of adhesive along the overlap regions reaches a state in which it can sustain no further significant increase in applied load [12]. The proposed method is based on a specific value of critical stresses along the adhesive mid-plane where failure likely occurs when the resultant stresses reach a critical value at a critical distance. These two failure concepts were already discussed in detail in previous works such as [7, 8 and 14].
Additionally, an elastic-plastic material behaviour for adhesive and elastic-perfectly plastic material behaviour for adherend are considered for these two failure approaches. This is a simple material response for performing progressive failure analysis since only three values of Young's modulus, Poisson's ratio and the ultimate stress are sufficient. In this failure model, plastic regions are initiated at the corners of the overlap region in which the stress concentrations occur. The plastic region propagates along the adhesive layer as the applied load increases. When the overall region of the adhesive layer

becomes plastic region, the final failure occurs without supporting any more load increase [8]. This failure concept has been already used in Ref. [15] and physically consistent with the characteristics of the progressive failure in the adhesive layer.

2.2. Model of a single-lap joint

Single lap joint geometry which exhibits over a range of usage area and popularity among the researchers was selected to be joint geometry. Joint geometry model was designed in accordance with the ‘’ASTM D1002’’ [16] (Standard Test Method for. Apparent Shear Strength of Single-Lap-Joint Adhesively Bonded Metal Specimens by Tension Loading) and thickness of the adherent is chosen to be 1mm and width of the joint is 25mm as stated in the standard. Simulation parameters are overlap lengths of 10, 20 and 30mm, glue layer thicknesses of 0.1, 0.2, 0.3 and 0.4 mm. The schematic illustrations of single lap joint geometry with the dimensions are given in Figure 1.

Table 1. Single lap joint configuration of specimens for numerical study.

Joint Series	Overlap Length L (mm)	Width w (mm)	Adherend Thickness h (mm)	Adhesive Thickness t (mm)
L-10	10	25	1	0.1
				0.2
				0.3
				0.4
L-20	20	25	1	0.1
				0.2
				0.3
				0.4
L-30	30	25	1	0.1
				0.2
				0.3
				0.4

For the numerical study, three different joint series ranging from 10mm to 30mm bond-line length, each includes four glue layer thicknesses are presented as a configuration in Table 1. The strength of bonded joints generally varies linearly proportional to width of joint so that only single value of joint width is sufficient for failure evaluation. In the same way, adherend thickness was confined to 1mm in order to prevent high amount of offset moments creating large peeling stresses at the boundaries of the bond-line.

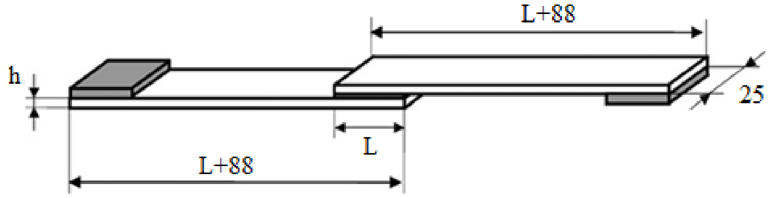


Figure 1. Adhesively bonded single lap joint model according to ASTM D1002 [16].

2.3 Adhesive and Adherend Material

For the numerical failure load prediction S355 medium carbon steel sheet in 1mm thickness was selected as the substrate material emerging ductile material behaviour. Stress versus strain diagram for selected adherent material of S355 steel are presented in Figure 2. It is clearly seen that the material behaviour of S355 is very similar to bilinear or elastic-perfectly plastic material model. So that, bilinear material model can be implemented to S355 sheet metal. Material properties of substrate material is provided from literature [17].

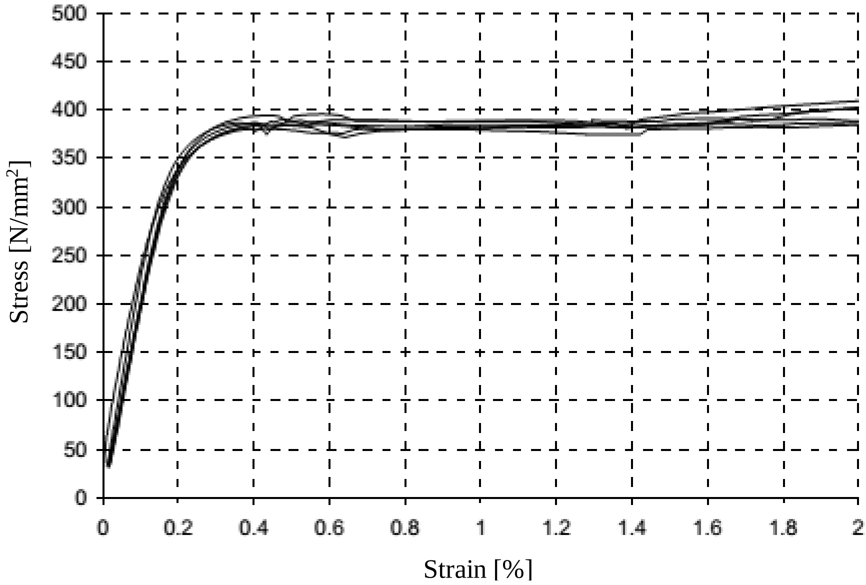


Figure 2. Stress and strain diagram of adherend material for S355 steel plate samples [17].

For the adhesive material, a kind of epoxy adhesive Araldite AV138 having high performance characteristics in structural and engineering joints was used. Epoxy adhesives have mainly brittle material behaviour depending on the curing process and quite suitable for bi-linear material behaviour after effective yielding point. Stress strain diagram for Araldite AV138 epoxy system obtained from supplier is presented in Figure 3 [18].

Table 2. Mechanical properties of Araldite AV38 adhesive and S355 steel adherend [18].

	Material	Yield Strength Sy (MPa)	Modulus of Elasticity E (GPa)	Poisson's Ratio υ	Tangent Modulus K (MPa)
Adhesive	Araldite AV138	36.5	4.9	0.38	**15**
Substrate	S355 Steel	385	200	0.3	**40**

The material properties for both substrate and adhesive material including yield stress, modulus of elasticity, Poisson's ratio and effective tangent modulus which were provided from the reference [19] are depicted in Table 2, respectively.

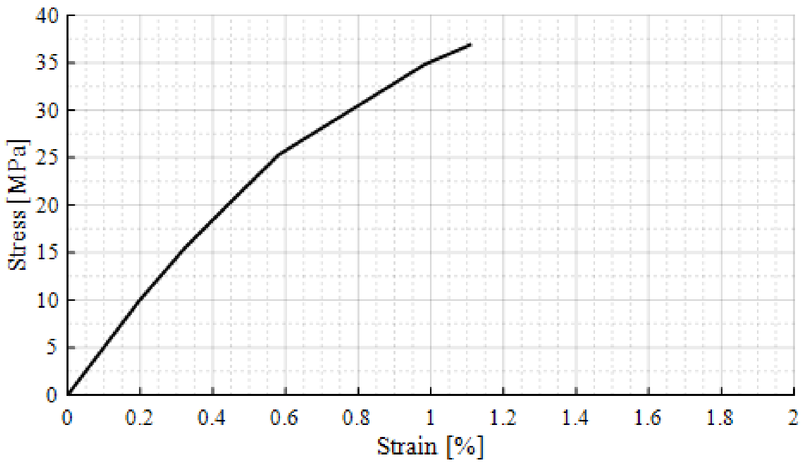


Figure 3. Stress and strain diagrams for epoxy adhesive of Araldite AV38 [19].

2.4. Numerical Study

Numerical analysis of single lap joints were carried out using finite element method regarding to proposed failure prediction criteria. A study schedule was developed in order to understand the influence of geometrical parameters on the performance of single lap joint by implementing a non-linear finite element analysis. A fully non-linear simulation including geometrical and material nonlinearities was performed in order to evaluate yielding load and stress distribution over the glued area of structural single lap joints. All joints were modelled by 2D plane strain elements in a commercial software, ANSYS 15 APDL. Boundary conditions and loading type for the numerical models are shown in Figure 4. For the boundary conditions, one end of the numerical model is fixed up to a grip length of 25mm while an axial tension load applied at the other end with a force step size of 10N. The rotation of the extremities of the model was also fixed in order to prevent rotation considering the boundary conditions stated, which simulate the rigidity of tensile test machine grips.

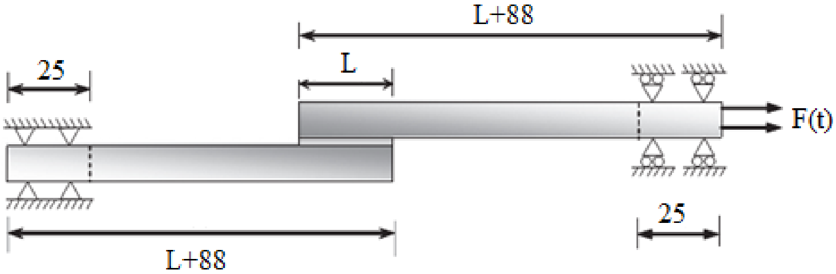


Figure 4. Boundary conditions and loading type of numerical models.

Fig. 5 displays the mesh structure of numerical model with finer mesh intensity over the adhesive layer to capture stress and strain gradients at singularity points precisely. PLANE182, a quadratic four-node element with six degrees of freedom at each node which is capable of analysing large strain and non-linear applications, was selected for the numerical study. The smallest element at the interface, close to extremities, has 10x10μm^2. L-10 joint series corresponding to 0.1mm adhesive thickness, the smallest one in size, is composed of 20600 quadratic elements and 65580 nodes at minimum. Then, a parametric study was accomplished enabling to easily examine the effects of geometrical parameters on the failure estimation and stress variations by changing dimension of the models.

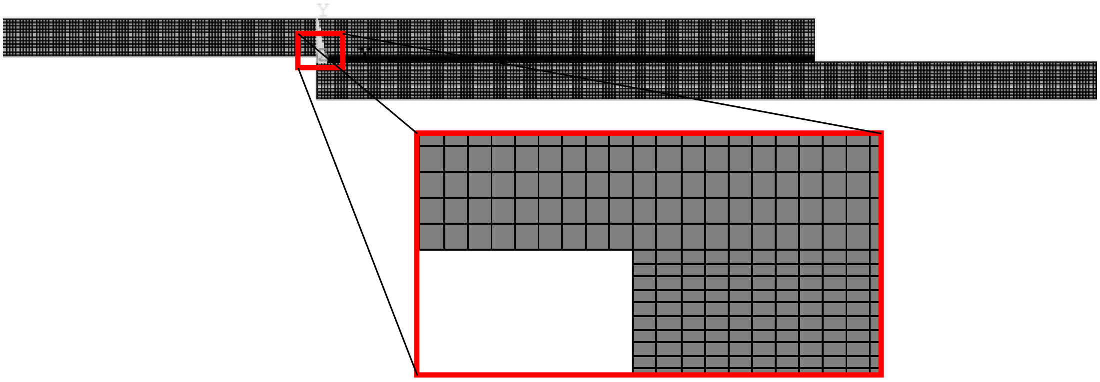


Figure 5. Finite element model of single lap joints with adhesive.

3. Numerical Results and Discussion

3.1. Normalized peeling and shear stress distributions

As a result of non-linear numerical stress analysis of bonded joints, the variation of peeling and shear stresses corresponding to each layer thicknesses are presented in this section. In order to implement failure methodology mentioned in previous part, the critical distances for both normalized peeling and shear stresses were tried to be defined. It is clearly concluded that there is quite high stress concentration on the upper corner as expected. On the bottom corner, the member is subjected to compressive peeling stress. Moreover, through the center region of the adhesive layer, variation of stresses gets more uniform and quasi stable. The failure mechanism in the adhesive layer is caused by the formation of peak shear and peeling stresses on the boundaries. Firstly, the elements at the nearest and furthest regions from the center of glued area reach the yielding point of the material then propagate through the center of the joint from both sides such as progressive failure mechanism. Eventually, the crack reaches a certain value at which the material cannot handle any extra load, which is a sign of failure according to limit state and maximum stress failure methodology.

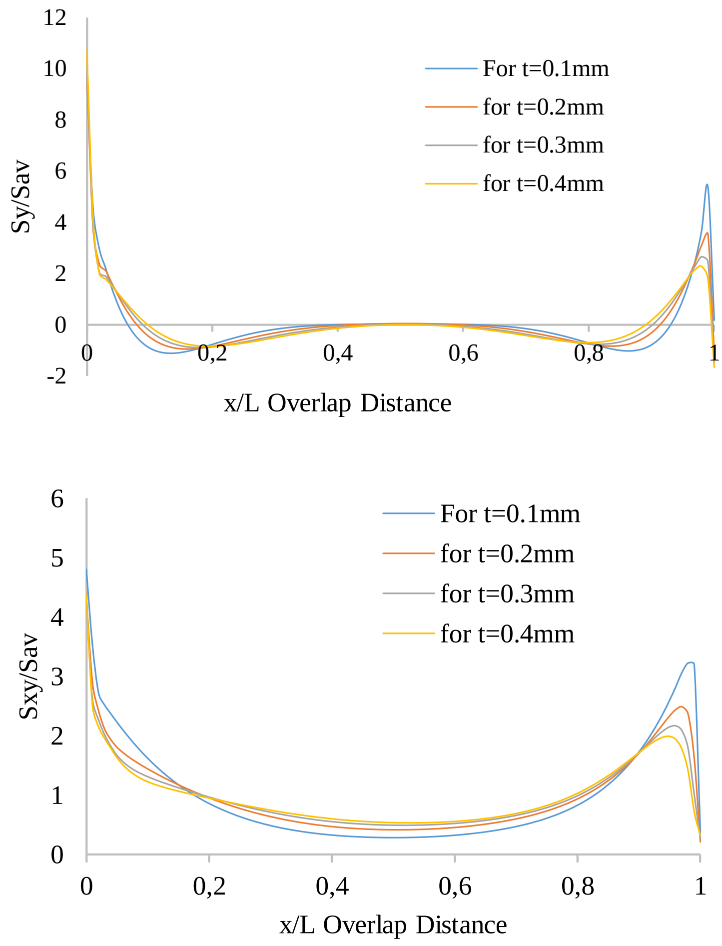
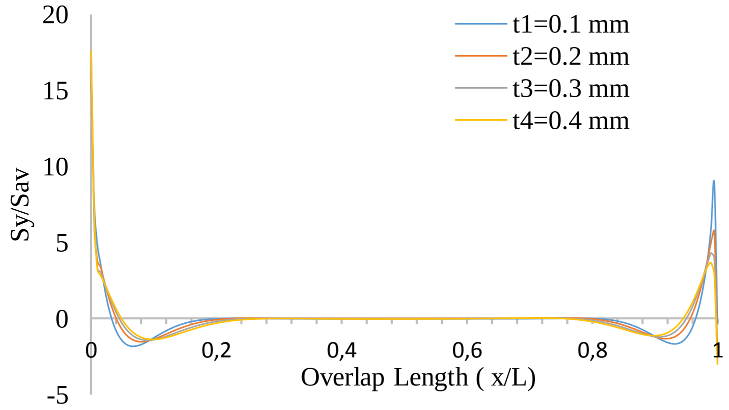


Figure 6. Normalized peeling and shear stress variations across the bond-line for L=10mm.



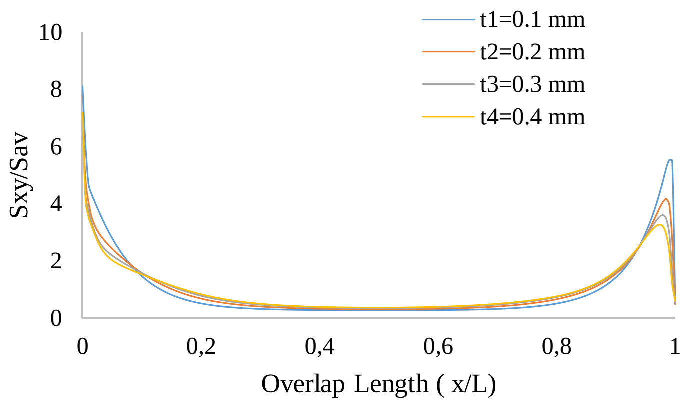


Figure 7. Normalized peeling and shear stress variations across the bond-line for L=20mm.

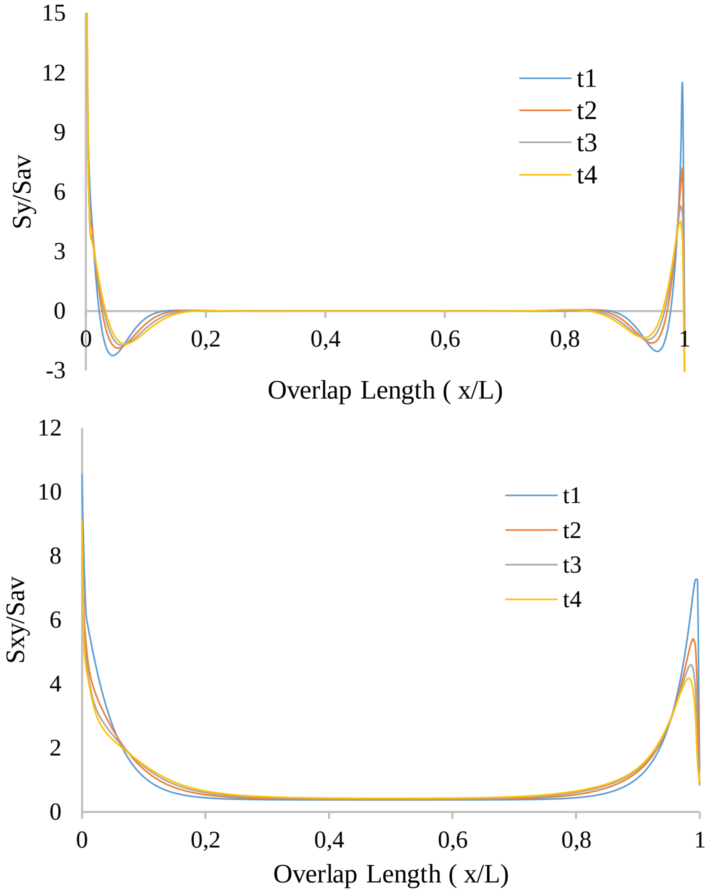


Figure 8. Normalized peeling and shear stress variations across the bond-line for L=30mm.

The finite element stress analysis was performed for bonded joints and normalized peeling and shear stresses for upper interface of adhesive layer for each joint configuration of L-10, L-20 and L-30 series corresponding to all adhesive bond-line thicknesses of t1=0.1, t2=0.2, t3=0.3 and t=0.4mm are displayed in Fig. 6., 7 and 8, respectively. Normalized stress factors were calculated by dividing the local stress component to mean stress which is the ratio of applied axial force over the glued area in z direction. The distributions were captured when a local point in the bond-line reaches the yielding state, which simulate the initiation of plastic deformation. It was clearly observed that the normalized stress values of peeling and shear at yielding point decreases when the adhesive layer becomes thicker for all joint series. Besides, the stress extremities accumulate on the corners of the upper mid-plane and getting smooth through the middle of bond-lines, which was also stated in Ref. [4]. The optimum adhesive thickness was obtained in the joint configurations having a thickness of 0.4mm in terms of normalized stress factor, but at higher layer thicknesses cohesive failure mechanism should be considered which requires fracture mechanics approaches. For this reason, relatively lower thicknesses are recommended for brittle adhesives to acquire accurate failure estimation based on limit state and maximum stress failure criteria to figure out debonding mode of yielding mechanism at the interfaces. Similar distributions for peeling and shear stress levels were also represented for elasto-plastic material behaviour in Ref. [6], considering different planes at the adhesive zone. The critical distance from both ends of adhesive bond-line, where no stress oscillation take place approaching almost uniform stress distribution, was determined between 10 and 20 percent of total overlap length roughly for L-10, L-20 and L-30 joint series. Obviously, this critical length is of importance to evaluate failure parameter over the plastic region. Likewise, peeling stresses nearly become zero over a large portion of overlap length with increasing bond-line length through the comparison among the Fig. 6, Fig. 7 and Fig. 8. It is also a positive impact on shear stress attaining more stable trends with relatively sharp inflection points.

3.2. Local Yielding Loads and Progressive Failure Mechanism

A combined failure mechanism has been introduced to single lap bonded joints including both maximum stress theory and limit state criteria to simulate progressive plastic zone propagation. A critical distance of about 20 percent of total bond-line length has been focused to capture resultant stress history after first yielding is reached. This critical regions also explain why the interfaces are important regarding to adhesive failure. Relying on this plasticization zone, the points at which yielding initiates are arranged for each joint series of L-10, L-20 and L-30 corresponding to each bond-line thickness (see Fig. 9). Based on the proposed method, the yielding starts at nearly 1kN and for t=0.1mm considerably increases up to t=0.4mm corresponding to 1.35kN for L-10 joint series. It was certainly concluded that the optimum adhesive layer thickness lays between 0.2mm and 0.3mm as it was stated in Ref. [19].

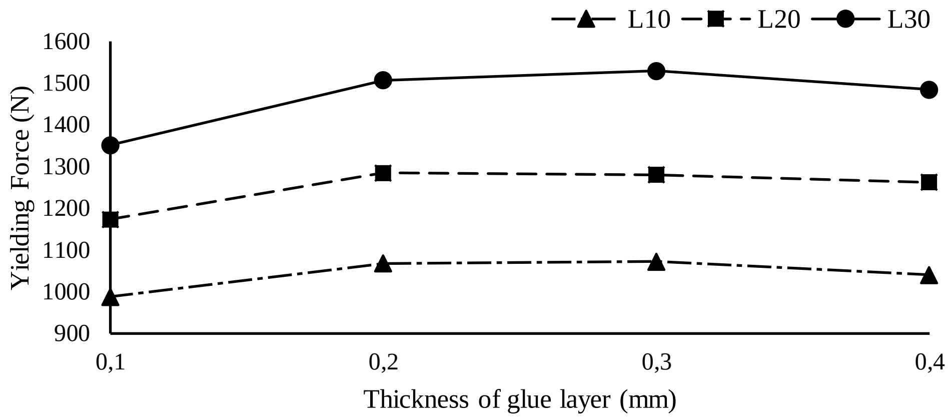


Figure 9. Local yielding loads of samples at which first plasticisation appears.

Likewise, overlap length has an effective influence on yielding load which was observed to be 1068, 1284 and 1506N for each thickness value of 100, 200, 300 and 400 µm respectively. However, the rate of increase in yielding load for overlap length and bond-line thickness were predicted to slightly go down according to observation in Fig.10, that implies no considerable effect of those design parameters beyond a certain level.

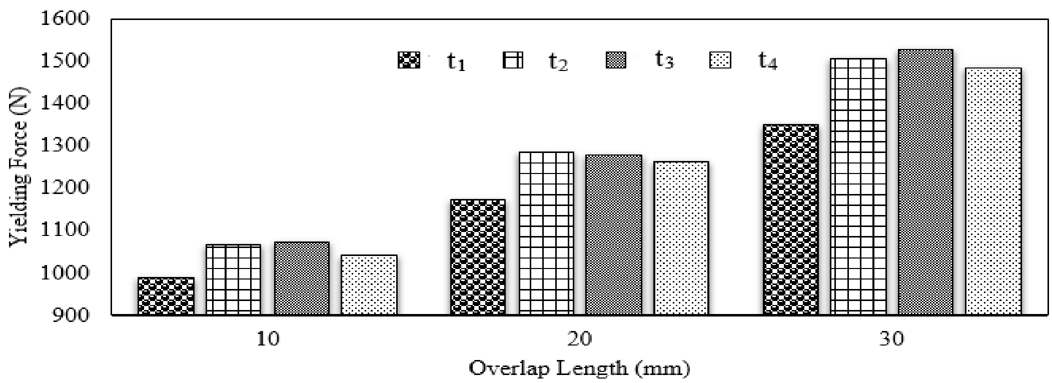


Figure 10. Diagram for local yielding loads of samples at which first plasticisation appears.

The interface of adhesive structure undergoes progressive plasticisation process until the failure at which no more force can be sustained by the joint. Four consecutive stages of plastic zone formation for L-20 joint series with a thickness of 0.2mm were captured in Fig. 11, each represents the initiation of plastic stress and growth of progressive failure mechanism at four separate instants. In addition, it was proposed that failure occurs when the red zone reaches the critical distance, and the amount of axial load at this instant was assumed to be failure load for single lap joints. For example, in (Fig. 11.a) yielding started with a load of about 1300N, followed the path toward the middle of bond-line (Fig. 11.b and 11.c) then a global failure occurred in Figure 11.d corresponding to 8.73kN.

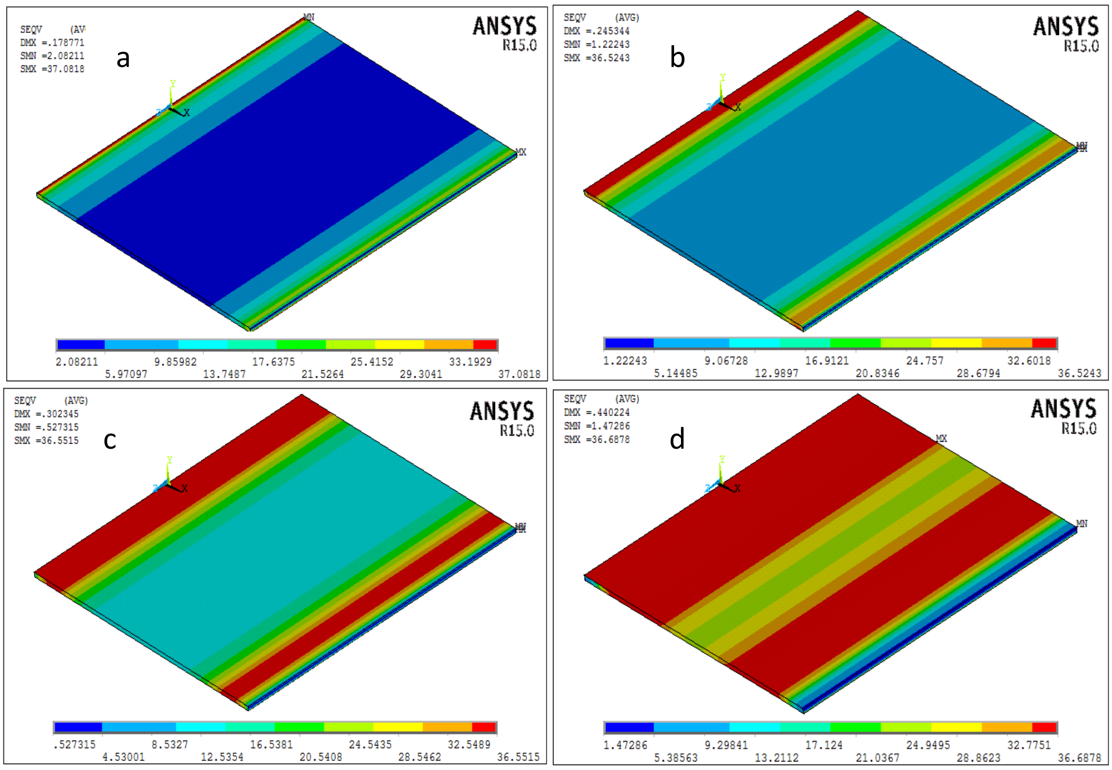


Figure 11. 3-D representation of adhesive at L=20mm and t=0.2mm simulating progressive plasticisation process under axial loading at four different instants when; a) Axial force is 1.3kN at x=0, b) Axial force 2.3kN at x/L=0.06, c) Axial force is 5.3kN at x/L=0.13 and d) Axial force is 8.3kN at x/L=0.29 (The reader referred to the online version of this figure for clear observation.)

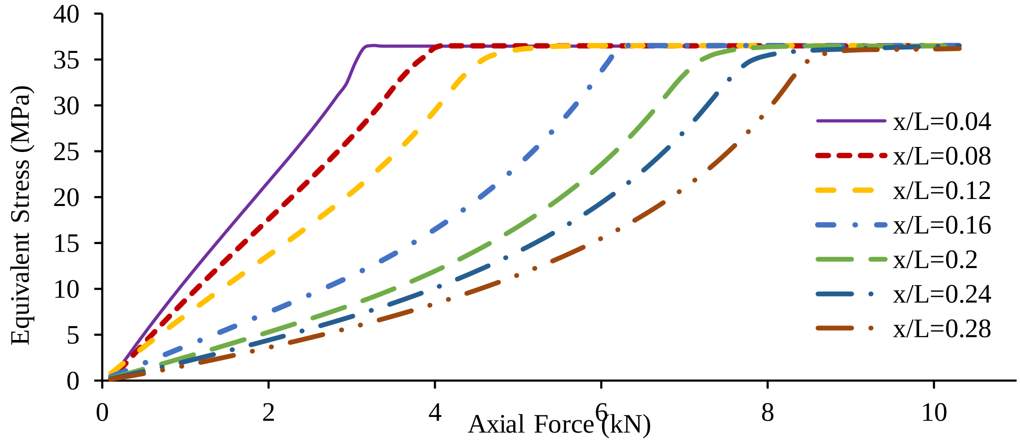


Figure 12. Stress spectrum of local points on the upper interface of adhesive against applied tensile load for L=20mm and t=0.2mm at various x/L ratios.

To develop more clear examination of equivalent stress gradients and critical distances for the estimation of critical distances, Fig. 12 was arranged at random points at the upper interface of L-20 joint series. Each point on the curves exhibits perfectly plastic material response after reaching limit maximum stress value.

4. Concluding Remarks

There are various studies published by researchers in literature considering different failure estimation approaches. These failure methods are based on different critical parameters such as maximum peeling stress and strain, fracture mechanics approaches requiring extensive tests prior to design stage, limit state criteria, energy approaches and etc. In this paper, a new yielding load estimation criterion was introduced based on combined maximum equivalent stress and local yielding theory assuming that only adhesive failure at the interfaces occurs. Then 2-D finite element analysis was accomplished to achieve yielding loads including elastic-plastic material behaviour and geometrical non-linearity. Consequently, following results were obtained from the progressive failure analysis.

- Peeling stress distribution plays an important role for predicting critical distance where failure likely occurs in this interval. It may be used as a tool to optimize overlap length of adhesively bonded structures instead of shear lag model.
- Although normalized stress in the critical zones has been improved at higher adhesive thickness, the optimum value was found out to be in the range of 0.2mm and 0.3mm in terms of static strength aspects. For further optimization, Taguchi method may be implemented to FEM results by adding some extensive analysis, which was proposed by the work in Ref. [20].
- The yielding load at a local region was roughly evaluated as the 25 percent of whole failure load of the joint for L-20 series. Definition of a local yielding load has a significant effort to evaluate crack propagation for possible fatigue and impact failure even if the joint does not completely fracture.

Acknowledgement

The support of Anadolu University for providing ASTM- D 1002 testing manual and official ANSYS15 APDL package program, is gratefully acknowledged.

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