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Influence of the presence of defects on the stresses shear distribution in the adhesive layer for the single-lap bonded joint

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Abstract. In this study, the finite element method was used to analyze the distribution of the adhesive shear stresses in the single-lap bonded joint of two plates 2024-T3 aluminum with and without defects. The effects of the adhesive properties (shear modulus, the thickness and the length of the adhesive were highlighted. The results prove that the shear stresses are located on the free edges of the adhesively bonding region, and reach maximum values near the defect, because the concentration of high stress occurs near this area.

Keywords: finite element method (FEM); numerical methods; parametric analysis; quasi-static; simulation

1. Introduction

In many practical applications, it is virtually impossible to make a whole structure as a single body. Many structures are therefore manufactured in various parts that are connected through joints later. Therefore, the joining of different parts is an important research field and numerous studies in this area have accordingly been reported Seong *et al.* (2008).

Some of the main advantages of adhesive joints compared to conventional joints are the ability to join dissimilar materials and damage-sensitive materials, better stress distribution, weight reduction, fabrication of complicated shapes, excellent thermal and insulation properties, vibration response and enhanced damping control, smoother aerodynamic surfaces and an improvement in corrosion and fatigue resistance Choupani (2009), Sathiyaseelan and Baskar (2012). The overall strength prediction of adhesively bonded joints is a meaningful concern for the engineering applications. It is expected that the overall strength of the joints can be predicted when the adhesive properties are determined. Consequently, considerable efforts have been made in developing efficient modeling approaches for assessing the load-bearing capacity of the joints Xu *et al.* (2014).

In recent years, the static and dynamic behavior of these joints has been the subject of a considerable amount of numerical studies. Haghani *et al.* (2010) carried out a parametric study to

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investigate the effect of tapering length and the material properties of joint constituents on stress distribution in adhesive joints. The results indicated that the effect of tapering on stress distribution is highly dependent on the stiffness of the laminate and the adhesive used in the joint. Further, Solana *et al.*, Khoramishad *et al.* (2013) predicted the backface strain response using finite element modelling (FEM) of the bonded joint and although they used a different approach to model adhesive damage, good agreement was found between FEM and experimental results in both cases. Wang *et al.* (2009) has extended the work of Crocombe and Bigwood to explain member shear deformation to predict adhesive failure in arbitrary joints has submitted performance large-scale adherent. The non-linear behavior of member brought by the bilinear model. Tape and participant performance have modeled the criterion of Von Mises. Oplinger (2007) provided an alternative analysis to the Hart-Smith modification for the single lap joint by considering large deflections of adherents and the effects of adhesive shear strains and by ignoring the effects of bond thickness deformation. In doing so, adhesive deflections are allowed to decouple the two halves of the joint in both bending deflection analysis and adhesive stress analysis. There exist a good correlation in the edge moment factor k between the Oplinger predictions and those of Goland and Reissner. Therefore the variation in temperature during the process generates voids and cracks on the pultruded parts quoted by Paciornik *et al.* (2010). They pointed out that these defects and cracks are due to improper resin heat transfer during curing that affect the mechanical properties as well as help moisture absorption. However, vinyl ester resin as a matrix with glass fibre performed well to control the heat transfer problem and variation in temperature during pultrusion process. Adams and Peppiatt, Adams and Harris (2011) have used this criterion to predict joint strength with success. However, because of the stress singularity at the re-entrant corners of joints, the stresses depend on the mesh size used and how close to the singular points the stresses are taken. Therefore, the physical insight into the failure process is clear, and it is the maximum principal stress which is most responsible for the failure of joints bonded with brittle adhesives since cracks initiate and propagate normal to these maximum principal stresses. Anderson *et al.* (2010) predicted the failure loads of adhesive joints by using fracture mechanics theory and assuming defects in the adhesive due to small voids. Finite element analysis has also been used to study the interfacial stress distribution of the bond. The debonding of the joint was looked as a phenomenon of stress based failure criterion. However, experiments have shown that the energy release rate controls the debonding propagation. Hence, the use of total energy balance approach to determine the interfacial fracture strength is more appropriate than the stress based approach. To establish consistent results between the energy based approach and the stress based approach, large displacement analysis of the debonded peel arm was introduced by Gent and Hamed (2014).

The objective of this work is to apply numerical study to obtain accurate stress distributions for adhesively bonded joint of aluminum alloys 2024-T3. The analysis considers the stress variation across the adhesive length. The results highlight particular stress concentrations in the adhesive layer and the influence of the adhesive properties such as thickness, length, and shear modulus in the stress distributions. In the second section, we discussed the influence of the presence and the number of defects in adhesive layer on the stress distribution. The effects of the adhesive properties and the presence of defects on the adhesive stress distribution were highlighted.

2. Geometrical model and materials definitions

The geometry and dimensions of the bonded single-lap joints are described in Table 1, with thin layers of aluminum 2024-T3; the layers are bonded with an adhesive Adekit A140 made by AXSON Company as shown in Fig. 1. The structure is subject to uniaxial tensile load for stress level lower than σ=35MPa.

The properties of the aluminum plate and the adhesive layer are given in Table 2. (Madani *et al.* 2008, Mokhtari *et al.* 2013).

3. Finite elements modeling

A two-dimensional finite element code named Fracture Analysis Code for 2-D Layered structure (FRANC2D/L) was used in the numerical modeling analysis. This code was originally developed at Cornell University and modified for multi-layers at Kansas State University, and is based on the theory of linear and non-linear elastic fracture mechanics (2004). FRANC2D/L uses the following assumptions to obtain the essential structural response features:

- Each layer is considered as an individual two-dimensional structure under a state of plane stress;
- Individual layers can be connected with adhesive bonds;
- It is assumed that the adhesive layer is homogeneous, linear elastic and isotropic;
- The adhesive is assumed to deform only in shear and this deformation is uniform throughout the adhesive thickness;
- The surface shear transmitted through the adhesive is assumed to act as surface traction on the substrates.

Computing code Franc 2D models the adhesive as a spring infinity by introducing just the shear modulus G and the thickness. Modeling the adhesive, does not take into account the plasticity unlike 3D modeling where it’s possible to introduce all the mechanical properties of the adhesive. The numerical model and typical mesh used in FRANC2D/L is given in Fig. 2.

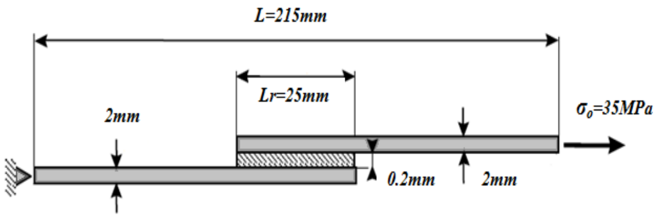


Fig. 1 Boundary conditions and geometric model for the single-lap bonded joint

Table 1 Dimensions of single-lap bonded joint

Adherend length	Overlap length	Sdhesive thickness	Sdherend thickness
120 mm	25 mm	0.2 mm	2 mm

Table 2 Material properties of the single-lap bonded joint.

Material	*E* (MPa)	*υ*	*G* (MPa)
Adherend	68800	0.33	2600
Adhesive	2690	0.30	100

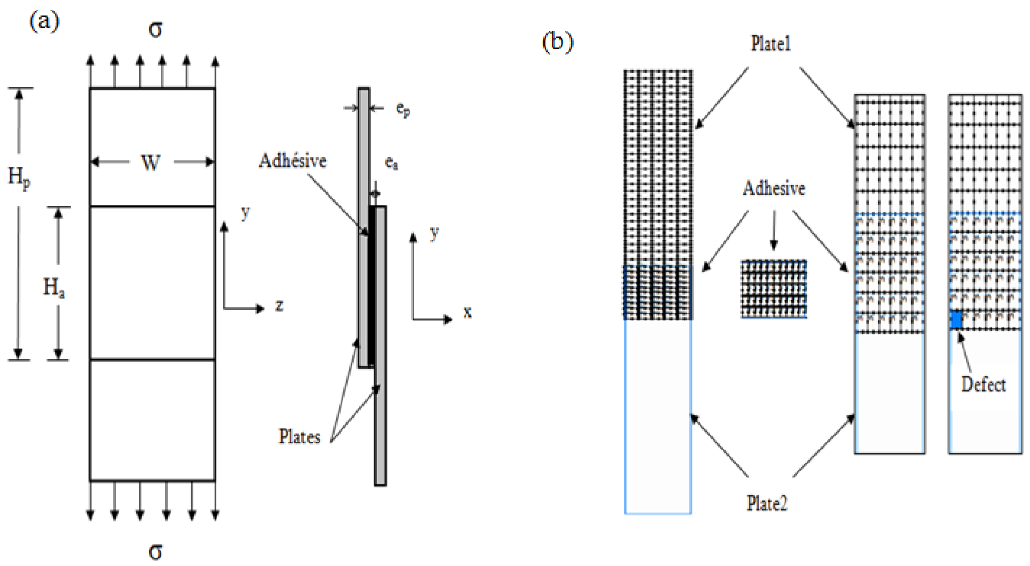


Fig. 2 (a) Numerical model of the single lap joint (SLJ) and (b) finite element mesh of the single lap joint

Where H_p and e_p are respectively the length and thickness of the plates, H_a and e_a are respectively the length and thickness of the adhesive.

The shear stress in the adhesive is given by

$$\tau = \frac{G_a}{e_a}(u_1 - u_2) \tag{1}$$

Where u_1 and u_2 are the displacements in the plates (a) and (b) respectively, G_a and e_a are respectively the shear modulus and the thickness of the adhesive.

The adhesive forces are obtained by using the adhesive shear stresses as surface tensions on the layer and integrating. Since the surface tensions are proportional to the relative displacement of the two layers, the adhesive force can be expressed in term of nodal displacements of the top and bottom layer. This gives a stiffness matrix for the adhesive elements. The total structure is meshed using standard eight nodded serendipity elements with quadratic shape functions. Fig. 2 shows typical mesh model of one bonded layer.

4. Analysis and results

By examining the failure of adhesively bonding joints, the shear stress and normal stress are the most responsible for the failure. In the following parametric study, we focus on the single-lap joints which are utilized mostly. The parameters that influence the stress distributions in the adhesively bonding region can be classified into two categories. One is called material parameters which includes the adherent material and the shear modulus of the adhesive. The other is called geometric parameter which includes the thickness of the adhesive layer, the thickness of the adherend and the length of overlap.

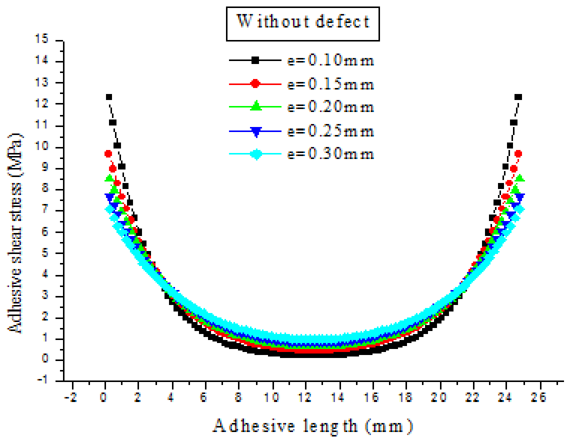


Fig. 3 Distribution of shear adhesive stress for different adhesive thicknesses

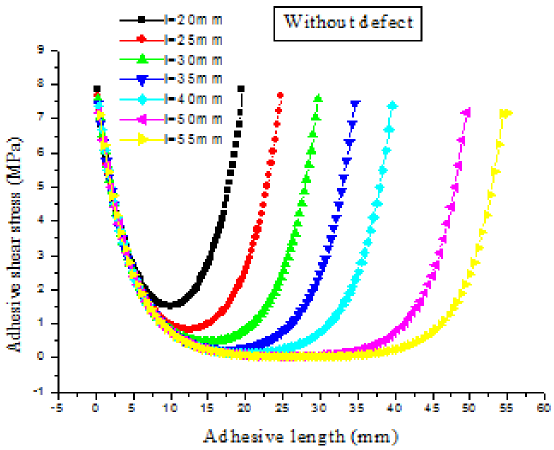


Fig. 4 Distribution of shear adhesive stress for different adhesive length

4.1 Influence of the adhesive thickness

The thickness of the adhesive is an important geometric parameter. Five different thickness values were chosen: 0.10, 0.15, 0.20, 0.25 and 0.30 mm.

Fig. 3 shows the distribution of shear stress in the adhesive for different adhesive thickness. It may be noted that an increase in the adhesive thickness causes a reduction of shear stress. Therefore, membership is best when increasing the thickness of the adhesive. The low thickness leads to poor adhesion. It is preferable to increase the thickness of the adhesive to improve the resistance of the membership but if we indefinitely increase the thickness, the adhesive becomes very resistant and behaves as a third material. In addition, the breakdown becomes more adhesive.

This result leads to the conclusion that the choice of the adhesive thickness must be optimized. Lot of proven research that the influence of the adhesive thickness varies depending on the materials assembled and passage through an optimum cannot always be accentuated. Generally, it locates this optimum thickness between 0.1 and 0.2 mm.

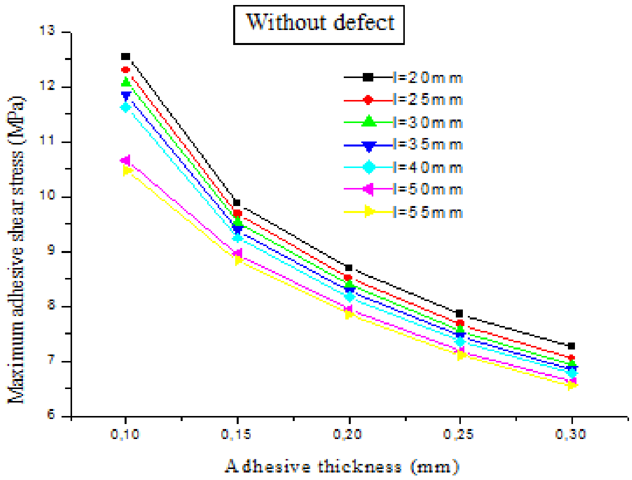


Fig. 5 Distribution of maximum shear stress for different adhesive length and adhesive thicknesses

4.2 Influence of the adhesive length

We studied the effect of the adhesive length on distribution of shear stress in adhesive for the single-lap bonded joint. There are varies the adhesive length, and keeping the same adhesive thickness (e=0.25 mm). Different values of the adhesive length (20, 25, 30, 35, 40, 50, and 55 mm), were examined.

Fig. 4 shows the distribution of the adhesive shear stresses according to the adhesive length (according y axis) for different values of the adhesive length. It can be noticed that the shear stresses decrease if the length of the adhesive increases. This reduction is observed only on the edges of the adhesive. On the other hand, in the center of the adhesive, the reduction of the shear stress value is valid only for length which is close to the width of the plate. If the length becomes significant, the value of the shear stresses tends towards zero. When there is increase of the adhesive length (the increase of contact surface) this creates a decrease of the mean stress and the breaking load increase.

4.3 Influence of the adhesive length and thickness

To see the Influence of the adhesive length and the adhesive thickness on distribution of the shear stress, we then trace the curves of the maximum adhesive shear stress for different adhesive lengths and thicknesses.

This Fig. 5, we can see clearly that the maximum adhesive shear stress decreased considerably with the increase of the adhesive length and adhesive thicknesses. It is also shown that the shear stress gives a relationship linearly proportional to the adhesive length, and adhesive thicknesses.

4.5 Influence of shear modulus of adhesive

In this section we examine the effect of shear modulus G on the shear stresses distribution, for the adhesive length L_r=25 mm. In precedent work of (Madani *et al*. 2012), the authors have

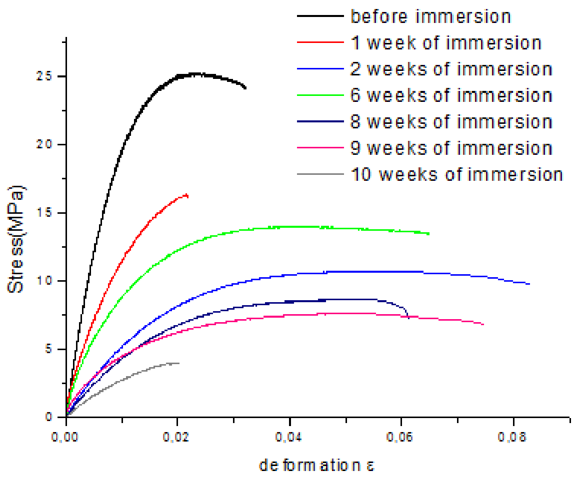


Fig. 6 Stress-strain curve of the adhesive for different weeks of immersion in water

Table 3 The different mechanical property used in the calculations

Young's modulus E (MPa)	2690	1450	1000	750	625	500
Shear modulus G (MPa)	1030.77	557.70	384.61	288.46	240.38	192.31
Water absorbed $\Delta M/M_0$	0.000	0.010	0.0125	0.0175	0.020	0.040

conducted experimental tests using sixty tensile test specimens of aged Adekit A140 adhesive (Fig. 6).

From the tensile curves for different immersion times, we can determine the Young's modulus of the aged adhesive. These specimens were immersed in distilled water inside an enclosure maintained at a constant temperature of 30°C. By applying the equations

$$G = \frac{E}{2(1+\upsilon)} \quad (2)$$

With v the Poisson's ratio, this tends towards 0.5 with ageing.

We determine the adhesive shear modulus for different immersion times Table 3.

The results of the shear modulus were introduced into the calculation code Franc 2D/L to determine the influence the adhesive shear modulus (G) on the distribution of the shear stresses in the bonded joint (Fig. 7).

The rigidity of the adhesive is one of the important factors that may influence the effectiveness of the bonded joint. The adhesive shear modulus (G) is the mechanical property which influences directly on the distribution of the shear stresses in the adhesive layer. Indeed, the shear stresses in the adhesive are related to its shear modulus by the relation (1). The Fig. 7 illustrates the distribution of shear stress in the adhesive for different shear modulus the shear stress increases with the shear modulus increases. Consequently, to improve this stress it is necessary to choose adhesives with lower shear modulus, but this choice can have a harmful effect because a high rigidity of the adhesive produces important shear stresses. On the one hand the aging of the adhesive causes degradation of the shear modulus giving thereafter a good resistance to shear

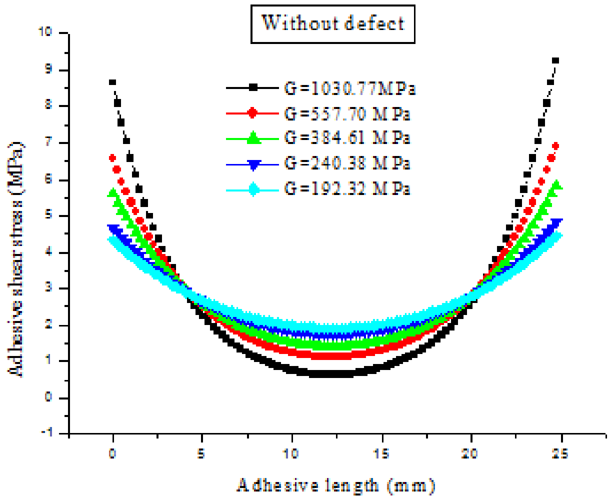


Fig. 7 Shear stresses distribution in the adhesive layer for different shear modulus

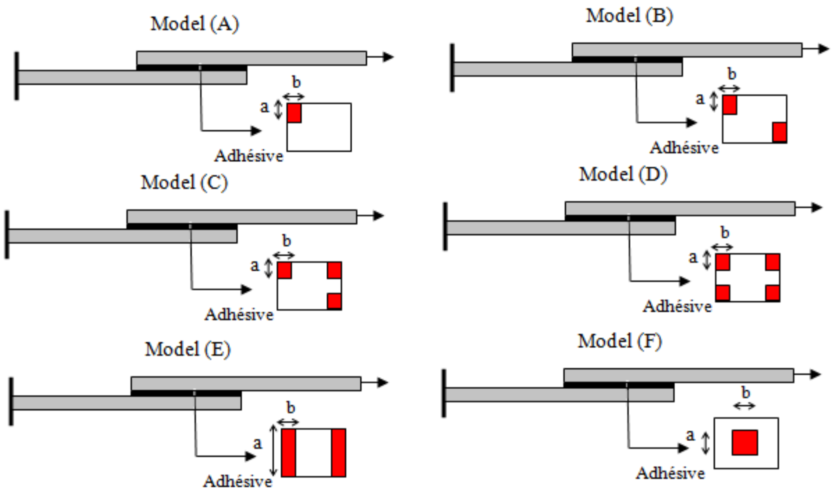


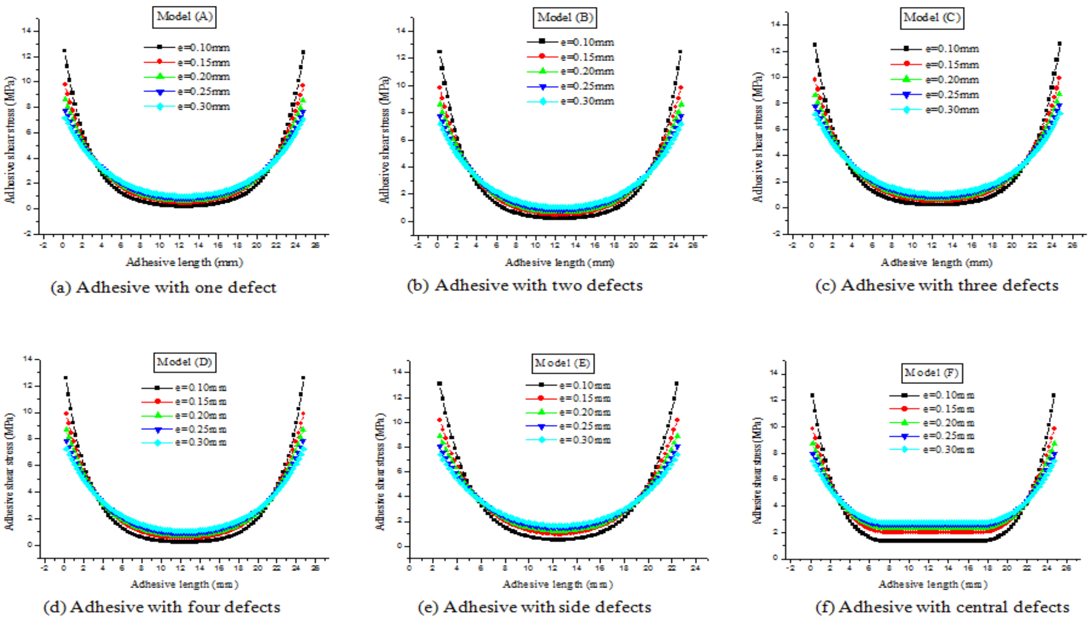
Fig. 8 The geometric models from the single-lap bonded joint and the adhesive with the different defects

against poor peel strength. These high stresses can lead to the failure of the adhesion. One can conclude that the choice of the mechanical property of the adhesive must be optimized.

4.6 The influence of the presence of the defects in adhesive

In this section we have studied the influence of the presence of the defects in adhesive on shear stress distribution along the centre line of the adhesive layer. To illustrate this effect different numbers and position of the defects is considered summer, the geometry and dimensions of the adhesive with defects, are described in Fig. 7. The defect is modeled by the area without adhesive (absence of adhesive). The defect is characterized by the two dimensions *a* and *b* (mm). Regarding the Fig. 8.

4.6.1 Influence of the adhesive thickness with defects

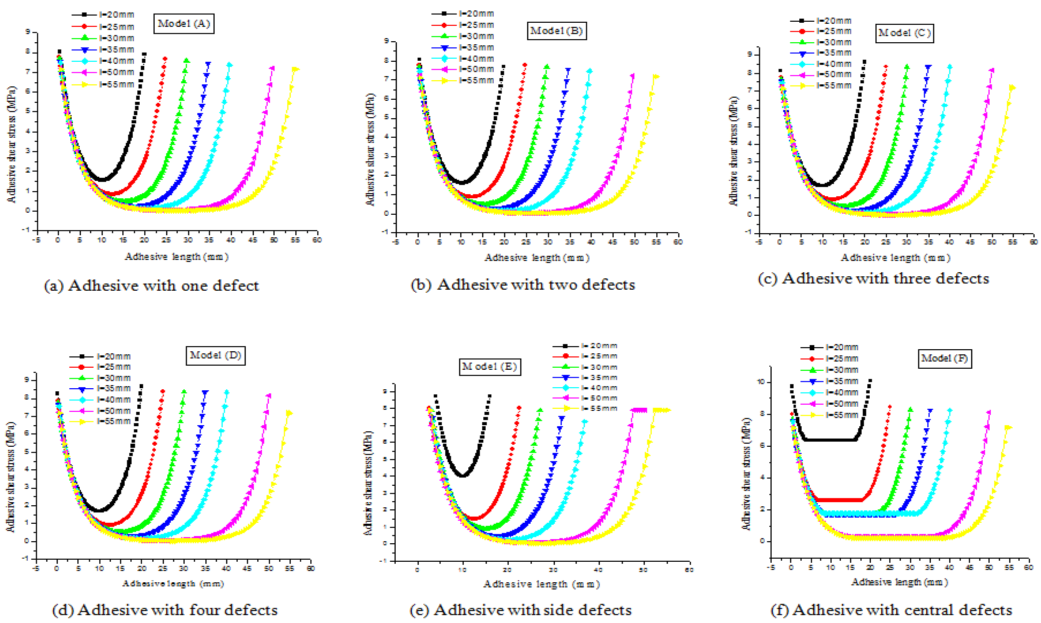


(a) Adhesive with one defect (b) Adhesive with two defects (c) Adhesive with three defects

(d) Adhesive with four defects (e) Adhesive with side defects (f) Adhesive with central defects

Fig. 9 Distribution of adhesive shear stress according to the adhesive length for different adhesive thicknesses

4.6.2 Influence of the adhesive length with defects

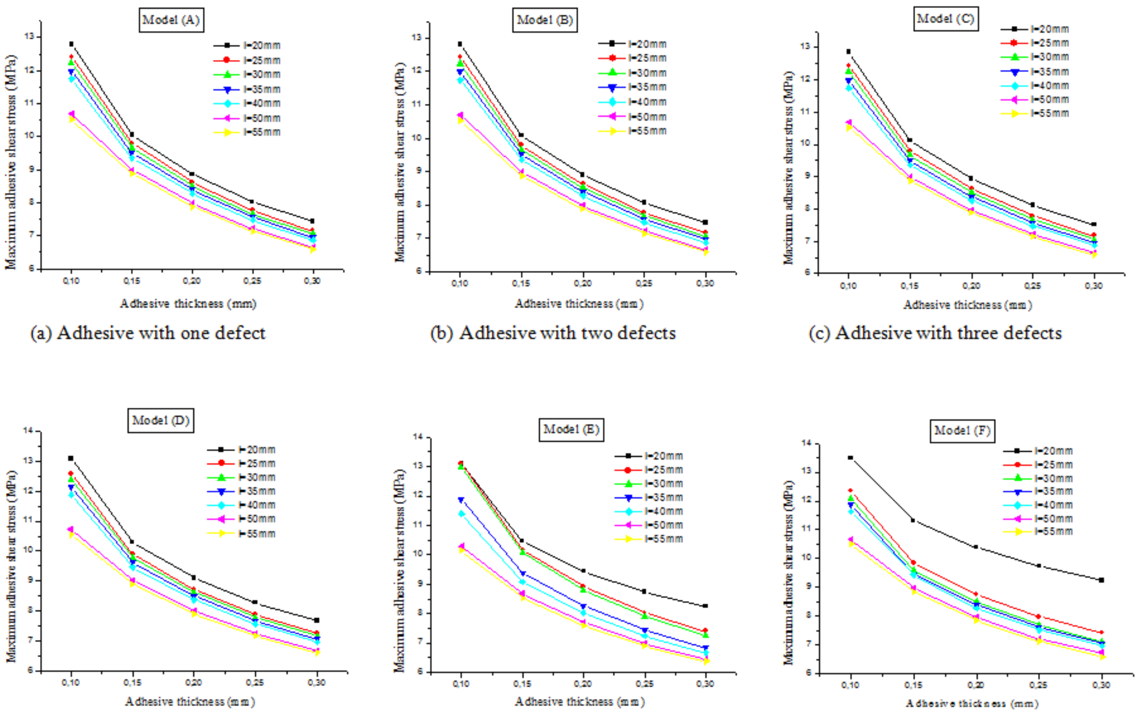


(a) Adhesive with one defect (b) Adhesive with two defects (c) Adhesive with three defects

(d) Adhesive with four defects (e) Adhesive with side defects (f) Adhesive with central defects

Fig. 10 Distribution of adhesive shear stress for different adhesive length

4.6.3 Influence of the adhesive length and thickness with defects



(a) Adhesive with one defect (b) Adhesive with two defects (c) Adhesive with three defects

(d) Adhesive with four defects (e) Adhesive with side defects (f) Adhesive with central defects

Fig. 11 Distribution of maximum adhesive shear stress for different adhesive length and different adhesive thicknesses

Table 4 Detailed dimension of defects

Models	A One defect	B Tow defects	C Three defects	D Four defects	E Side defects	F Central defects
a (mm)	5	5	5	5	25	15
b (mm)	2.5	2.5	2.5	2.5	2.5	10

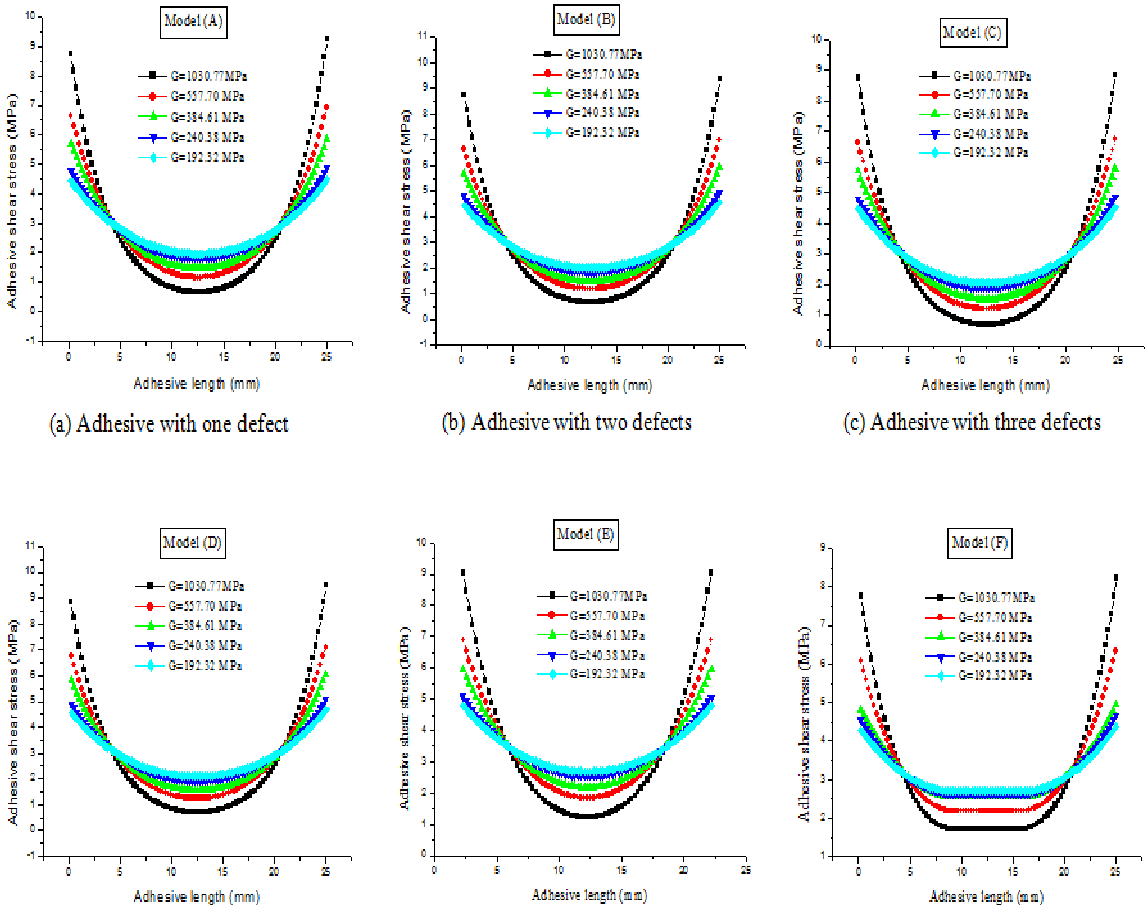
In the presence of the defects in adhesive layer (Fig. 9, 10, 11) the stress distribution is almost the same as for the case without defects. As the defect size is smaller compared to the length of the adhesive, the stress value is constant.

If the defect is located far from the adhesive edge, it has no effect on the value of the stress at one point or one can even eliminate a large part of the adhesive of the central area, since in most cases in the bonded assemblies only the edges of the adhesive the load to resist, while the central of the adhesive remains inactive.

Note also that the increase of the thickness of the adhesive minimizes the effect of the presence of the defect, one must avoid taking a thicker adhesive, in this case the adhesive behaves as a rigid material and in this case the defect become like a notch.

The overlapping length can also minimize the effect of defect on the stress distribution for minimum overlap lengths failure can affect the value of the stress at a point where the central of the adhesive becomes active. For the defect lengths presence influence is negligible except for major defects.

4.6.4 Influence of shear modulus of adhesive with defects



(a) Adhesive with one defect (b) Adhesive with two defects (c) Adhesive with three defects

(d) Adhesive with four defects (e) Adhesive with side defects (f) Adhesive with central defects

Fig. 12 Distribution of the adhesive shear stress for different shear modulus

Figs. 13-14, were drawn to see clearly and easily compare the results of the influence of different parameters on distribution of shear stress

4.6.5 Comparison of the distribution of the maximum adhesive shear stresses for the adhesive length L_r=25 mm with and without defects

From this Fig. 13, we note that the presence of retinal detachment causes an increase of stress shear maximum i.e., the constraints are highest for various cases of retinal detachment and are

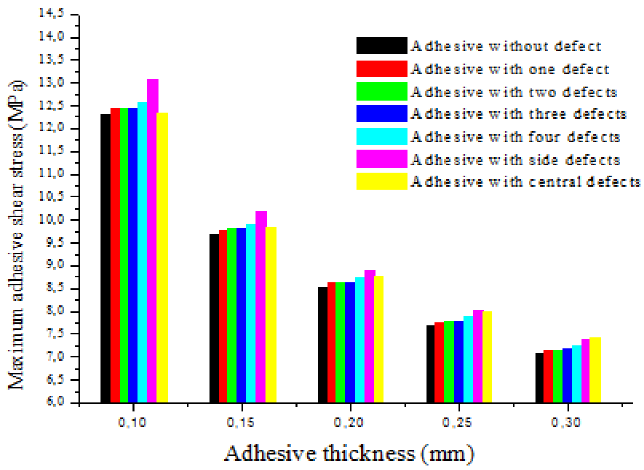


Fig. 13 Distribution of maximum adhesive shear stress for different adhesive thicknesses with and without defects

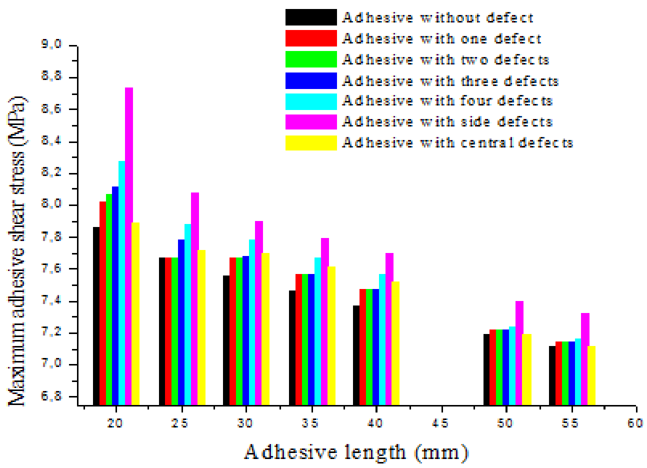


Fig. 14 Distribution of maximum adhesive shear stress for different adhesive lengths with and without defects

located on the ends of the region of collage, and the central area of the adhesive always with values less than those on the ends, because the concentration of high stress occurs on the free edges of the fixing by gluing area.

4.6.6 Comparison of the distribution of maximum adhesive shear stress for a thickness e=0.25 mm with and without defects

Comparing the effect of the length of recovery for different models with and without defects, one can see that the models or the position of the defect in the corner of the recovery zone constraints are more raised by report other models or the position of the defect in the media zone, ago only small difference with a without defect, accordingly, constraints maximum shear still happen at the end of the bending and reach maximum values at the end of the defect. This position at the ends of the recovery remains unchanged when the settings vary i.e., for length and the thickness of the adhesive different to the presence of defects.

5. Conclusions

The results obtained in this study have enabled us to deduct the following conclusions:

• The single lap joints has a symmetry relative to the center of the adhesive in the distribution of shear stresses in all cases with and without defect;

• The increase in the thickness of the adhesive reduces a shear stress, but the choice of this thickness must be optimized in order to avoid the emergence of a third material with a low mechanical properties;

• The increases of the length of recovery leads to a decrease a shear stresses in the adhesive layer, if the adhesive length becomes significant, the values of shear stress tends to zero in the middle of the length of the adhesive, but, only the edges of the adhesive supported the load;

• The central area of the adhesive remains inactive for the lengths of adhesive larger or equal to the width of the plate;

• When the defect is located near the free edges of the adhesive, the value of the shear stress reaches a maximum, near the defect. The effect of the presence of a defect in the adhesive layer, results in an increase in the value of the shear stress when the defect is located on the banks of the adhesive, however, presents no effect on value of shear stress when it is locate in the middle of the adhesive layer.

• In the presence of adhesive defects on the edges of the adhesive, the shear stress can reach a maximum, which subsequently can cause the creation of a crack at this level and thus causes the joint failure.

• The stress concentration on the free edges of the layer of adhesive can be reduced by increasing the thickness or the length of the adhesive.

• A slightly stiffer adhesive would lead to lower significantly the stress in the adhesive layer.

• The increase in shear modulus of adhesive decreases the resistance of the accession.

• Degradation of the adhesive mechanical proportions is causes a reduction of maximum shear stresses.

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