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Effect of the geometry in the strength of single-lap adhesive joints of composite laminates under uniaxial tensile load

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ABSTRACT

Adhesively bonded joints are widely used in structures manufactured with composite laminates. Single-lap adhesive joints are the common most used due to their simple geometry and structural efficiency. In this study, a 2D numerical model has been developed in Abaqus/Standard to evaluate the influence of variations in the geometry of the adherends and the adhesive on the mechanical strength of a single-lap joint subjected to uniaxial tensile load, using the Cohesive Zone Model (CZM). Different geometrical configurations of single-lap joints have been studied, such as adherend recessing and chamfering of the adherends and adhesive. The objective is to analyse the effect of these variations with respect to the mechanical strength of the adhesive joint. In this sense, the vertical displacement of the adherends, the peak peel stress, the distribution of peel stress on the overlap length, and the failure load have been studied, identifying the chamfer in the adherends and adhesive as the most influential parameter governing the strength of the adhesive joint.

Keywords

B.- Composites. C.- Finite element stress analysis, joint design. D.- Cohesive zone model.

1. INTRODUCTION

The current significance of reducing environmental impact of the transport industry and the need of saving costs are fundamental issues. The way to achieve these objectives is to reduce

the structural weight in order to decrease the fuel consumption and increase the payload efficiency. For example, it is estimated that a reduction of 1 kg in structural weight of an Airbus A320 translates as a savings of 2900 litres in fuel per year [1]. For such a reduction, two strategies can be followed: 1) using light-density materials such as composite laminates to manufacture airframe structures, or 2) using adhesive joints instead of mechanical joints. [2]

Currently, composite materials are being widely used due to their excellent specific mechanical properties. Boeing B787 and Airbus A380 structures are 50% and 25% composite materials, respectively [3]. In the case of adhesive joints, adhesive bonding has been used in the manufacture of primary aircraft fuselage and wing structures for over 60 years, although this technique is not as predominant as mechanical joints [4].

Adhesive joints present some advantages over mechanical joints. The latter cannot be used for adherends of thicknesses less than 8 mm [5] and the necessary elements, such as bolts or rivets, add weight to the structure [2]. Furthermore, the holes may cause problems in stress concentration, weakening the composite laminate. In this regard, adhesive joints do not increase weight, and the resulting stress distribution is much more uniform [6].

Single-lap adhesive joints are the most commonly used due to their simple geometry and high structural efficiency. However, the main disadvantage of this type of joint is the eccentricity of the load, which causes bending in the adherends and high peel stresses along the edge of the adhesive. Therefore, it is necessary to study this type of joint in order to find a solution for the eccentricity of the load, and to improve the joint strength. Some authors have analysed the unfilleted single-lap configuration [7, 8]; however, the analysis requires a complex combination of rigorous mechanics and mathematics [9]. Adhesive-joint strength depends on a large number of variables, and the design process can be challenging both experimentally and analytically.

The increase in computational power has largely contributed to growing interest in finite-element simulations as a cost- and time-effective method of providing additional information in the study of adhesive joints. In this context, many authors have used numerical modelling to analyse different alternatives for critical parameters affecting the strength of adhesive joints and bonded repairs, such as: overlap length [10, 11], adhesive damage [12], patch dimensions [13],

peel and shear-stress distributions [14], failure mechanisms [6], and influence of cohesive parameters [15]. These studies have dealt with simple geometries and regular flat adherends, but it is for complex configurations that numerical modelling analysis becomes truly advantageous. Of particular interest has been the analysis of different geometric configurations of single-lap joints with the aim of reducing the intensity of the stress peaks and thereby bolstering the strength of the joint. In this regard, various types of joints, local geometrical features such as the spew fillet [16-20], the effect of chamfering [20-23], and adherend recessing [24] have been studied. Chamfering can be applied to the adhesive, adherends, or both components of the joint, and thus it is valuable to undertake a broad analysis, taking into account all these configurations. In addition, no study dealing with the vertical displacement of the adherends in order to evaluate load eccentricity is available in the literature.

In this work, a finite-element model is developed to simulate the influence of different geometrical parameters (adherend recessing and chamfering of the adherends and adhesive) on the behaviour of a composite single-lap joint subjected to uniaxial tensile load, considering only cohesive failure. The objective is to analyse the effect of these variations on the strength of the joint in terms of the vertical displacement of the adherends, peak peel stress in the adhesive, distribution of peel stress along the overlap length, and failure load of the joint.

2. DESCRIPTION OF THE PROBLEM

Five different geometrical configurations of a single-lap joint were studied: single-lap joint of reference, adherend recessing, adherend chamfering, adhesive chamfering, and adherend and adhesive chamfering with the same angle, as detailed in Table 1.

Table 1. Configurations of single-lap joint.

(1) Single-lap joint		L_t	240 mm
		L_s	10-80 mm
		t_{ad}	0.2 mm
		t_s	2.4 mm

(2) Adherend recessing		L_t	240 mm
		L_s	40 mm
		t_{ad}	0.2 mm
		t_s	2.4 mm
		a	2.5-22.5 mm
		d	1.6, 1.2, 0.8 mm
(3) Adherend chamfering		L_t	240 mm
		L_s	40 mm
		t_{ad}	0.2 mm
		t_s	2.4 mm
		θ_s	90°-15°
(4) Adhesive chamfering		L_t	240 mm
		L_s	40 mm
		t_{ad}	0.2 mm
		t_s	2.4 mm
		θ_{ad}	90°-15°
(5) Adherend and adhesive chamfering		L_t	240 mm
		L_s	40 mm
		t_{ad}	0.2 mm
		t_s	2.4 mm
		θ_s	90°-15°
		θ_{ad}	90°-15°

Configuration (1) was used as single-lap joint with different overlap lengths (from 10 mm to 80 mm). Configuration (2) included three recesses of the adherends (1.6, 1.2 and, 0.8 mm), with recess lengths of between 2.5 mm and 22.5 mm. In configurations (3) and (4) the chamfer of the adherends and adhesive had angles between 15° and 90°. The latter configuration considered the

chamfer of the adherends and adhesive simultaneously, with the same angles as in configurations (3) and (4). All the cases studied show a total length of 240 mm. In configurations (2), (3), (4) and, (5) the overlap length (L_o) is equal to 40 mm.

In this study, certain assumptions were made:

- Each part of the model was considered an individual two-dimensional structure under plane-stress-state conditions.
- Composite adherends were modelled as orthotropic and, showed a linear elastic behaviour.
- The performance of the adhesive was defined using the Cohesive Zone Model (CZM).
- Only cohesive failure was considered
- A small displacement was considered.

In all cases, the vertical displacement of the adherends, peak peel stress in the adhesive, distribution of peel stress along the overlap length, and failure load of the joint were analysed and compared with results given for a single-lap joint of reference, which represents configuration (1) with an overlap length of 40 mm (Table 1).

2.1. Numerical model

To study the influence of several geometric variations on the strength of an adhesive joint, a numerical model using Abaqus/Standard commercial finite-element code was developed. The geometry, configuration (1), considered was taken from the literature in order to validate the numerical model [10, 25]. For the simulation of the experimental conditions, one of the edges was fully clamped, while the opposite end was subjected to a normal traction load by imposing a constant and uniform displacement through the opposite end.

The adherends were made of unidirectional carbon-epoxy pre-preg $[0]_{16}$ lay-up, with a thickness of 0.15 mm each ply, the properties of which are shown in Table 2, and bonded with an epoxy adhesive, Araldite 2015.

Table 2. Mechanical properties of composite adherends [10, 25].

Elastic Modulus	$E_x = 109 \text{ GPa}$	$E_y = 8.8 \text{ GPa}$	$E_z = 8.8 \text{ GPa}$
Shear Modulus	$G_{xy} = 4.3 \text{ GPa}$	$G_{yz} = 4.3 \text{ GPa}$	$G_{xz} = 3.2 \text{ GPa}$
Poisson's ratio	$\nu_{xy} = 0.342$	$\nu_{yz} = 0.342$	$\nu_{xz} = 0.380$

The performance of the adhesive was defined using the Cohesive Zone Model (CZM) implemented in Abaqus/Standard [26]. The CZM approach combines aspects of classical approach: Mechanics of Fracture and Strength of Materials. It is possible to define the entire fracture process with a traction-separation law (in tension and shear). In this work, a triangular-shaped traction-separation law was studied (Fig 1). The first part of the law refers to a linear behaviour that is defined with a stiffness matrix K (Eq 1), which relates stress (t) and strain (ϵ). Uncoupling behaviour ($K_{ns} = 0$) and mixed-mode, loads in normal (n) and shear direction (s), were considered:

$$\begin{Bmatrix} t_n^0 \\ t_s^0 \end{Bmatrix} = \begin{bmatrix} K_{nn} & K_{ns} \\ K_{ns} & K_{ss} \end{bmatrix} \cdot \begin{Bmatrix} \epsilon_n^f \\ \epsilon_s^f \end{Bmatrix} \quad (1)$$

The damage onset was evaluated by the quadratic nominal stress criterion (QUADS):

$$\left(\frac{t_n^0}{t_n^f}\right)^2 + \left(\frac{t_s^0}{t_s^f}\right)^2 = 1 \quad (2)$$

When the damage-initiation criterion is fulfilled, a softening of mechanical properties starts. That part of the law is defined by a damage variable $d_{n,s}$ and the shape of the softening depends on it. Initially, $d_{n,s} = 0$ at the onset of the damage, to displacement $\delta_{n,s}^0$ and $d_{n,s} = 1$, when the failure is complete and the displacement is equal to $\delta_{n,s}^f$.

$$d_{n,s} = \frac{\delta_{n,s}^f \cdot (\delta_{n,s} - \delta_{n,s}^0)}{\delta_{n,s}^f \cdot (\delta_{n,s}^f - \delta_{n,s}^0)} \quad (3)$$

Fig. 1. Traction-separation law.

The mechanical properties needed to define the cohesive behaviour of the adhesive are shown in Table 3.

Table 3. Cohesive properties of adhesive Araldite 2015 [10].

E (GPa)	1.85	t_n (MPa)	21.6	G_n (N/m)	430
G (GPa)	0.56	t_s (MPa)	17.9	G_s (N/m)	4700

The sensitivity of the mesh was evaluated in order to find an equilibrium solution of mesh between computational cost and accurate prediction of load failure (Fig. 3). As a result, for an overlap of 40 mm, the mesh of the adhesive consisted of 200 four-node linear cohesive elements (COH2D4 in Abaqus). The mesh of the adherends consisted of 16,800 four-node linear plane-strain elements CPE4 (Fig. 2).

Fig. 2. Detail of the mesh for numerical models of the different configurations

2.2. Validation of numerical model

The numerical model for configuration (1) was validated by comparing results to experimental data taken from the literature [10]. The variable used in the validation was the failure load to single-lap adhesive joints with different overlap lengths, from 10 mm to 80 mm. Fig. 3 shows the comparison between experimental and numerical results in terms of failure load vs. overlap length

Fig. 3. Validation of the numerical model.

Good correlation can be seen. The greatest difference between experimental and numerical results is given for an overlap length of 20 mm, the value of which is 4.45%. The minimum differences were found for an overlap length of 40 and 50 mm. As a result, the reference model can be considered to be validated.

3. RESULTS

The strength of the single-lap adhesive joints studied are analysed in terms of vertical displacement of the adherends, peak peel stress in the adhesive, distribution of peel stress along the overlap length, and failure load of the joint.

The results of the configurations (2), (3), (4), and, (5) will show a percentage regarding the reference single-lap joint (configuration (1), with overlap length of 40 mm). Therefore, the results of vertical displacement of the adherends, peak peel stress in the adhesive, distribution of peel stress along the overlap length for the reference configuration are presented in Table 4.

Table 4. Results for the reference configuration.

Failure load	P_0 (kN)	9.463
Vertical displacement	δ_0 (mm)	0.6868
Peak peel stress	σ_0 (MPa)	18.10

Vertical displacement of the adherends is measured in the lower adherend, and the peak peel stress of the adhesive is measured at the end of the overlap (Fig. 4).

Fig. 4. Evaluation points of the peak peel stress and vertical displacement.

Fig. 5 shows the peel-stress profile along the overlap in the adhesive, as previous studies [27, 28]. The stress distribution was symmetrical and the maximum peel stresses appeared at the ends of the adhesive, followed by a large gradient and a compressive region. In the centre of the joint, peel stress was not detected.

Fig. 5. Peel stress distribution of the adhesive in the overlap for the reference configuration.

3.1. Vertical displacement of the adherends

One disadvantage of a single-lap joint involves the eccentric loads that cause adherends to bend. This generates high peak peel stresses in the adhesive and therefore reduces adhesive joint strength. In this work the vertical displacement of the adherends was used as variable to evaluate the eccentricity of the load.

Results of the different depths and lengths of recess and chamfer angles, are presented with respect to the results of the reference configuration. All the results of the reference configuration are indicated with a black line in order to make comparisons.

Configuration (2) was studied for three different depths and nine different length recesses. The ratio of vertical displacement of configuration (2) with respect to vertical displacement of the reference configuration (δ_0), as a function of the recess length is shown in Fig. 6. In all cases,

the vertical displacement was reduced; however, the variations of the displacement with respect to the reference case proved negligible, in the best cases, around 3%. Therefore, adherend recessing in this work cannot be considered to be a significant improvement in adhesive-joint design and, no clear trend was identified in the results shown.

Fig. 6. Ratio of vertical displacement of configuration (2) vs. recess length.

Joint chamfering was studied in configurations (3), (4), and (5). The chamfer angle ranges from 90° to 15° , and seven different angles were analysed. Fig 7 shows the ratio of vertical displacement of configuration (3), (4) and, (5) with respect to vertical displacement of the reference configuration as a function of the chamfer angle. In all cases studied, the vertical displacement diminished with respect to the reference configuration. In general, the vertical displacement of the adherend decreased with a more acute chamfer angle. Therefore, a gradual change in the section of the joint reduces the vertical displacement.

For angles between 60° and 20° , the reduction of the vertical displacement is greater when the adherends and adhesive were chamfered at the same time. However, for angles less than or equal to 25° , the vertical displacement in configuration (5) remains almost constant. For angles

between 30° and 15°, the reduction of the vertical displacement was greater in adherend chamfering configuration than in adhesive chamfering.

It can be seen that the greatest variation of vertical displacement of the adherends corresponds to configurations (3) and (5). As the objective is to reduce the eccentricity of the load in order to decrease the value of the bending in the adherends, the best option in joint design is to chamfer the joint, particularly the adherends and the adhesive with a chamfer angle less than or equal to 25°. Nevertheless, if the option selected is to chamfer the adherends, the angle should be as low as possible.

Fig. 7. Ratio of vertical displacement of configuration (3), (4) and (5) vs. chamfer angle.

3.2. Peel stress of the adhesive

Peak peel stress of the adhesive, one of the most determining factors in mechanical strength, should be reduced by decreasing the eccentricity of the load or by changing the geometry of the joint [2]. Peak peel stress of the adhesive was studied at the onset of joint failure.

Variation of peak peel stress of configuration (2) with respect to the reference configuration (σ_0), as a function of the recess length, is shown in Fig. 8. All configurations studied presented smaller peak peel stress, allowing an increment of the mechanical strength of the joint to be

predicted. Variations were greater when the depth of the recess was 1.6 mm. The results for 0.8 mm recess depth were very close to those of the reference case, and thus the effect of recessing was not significant. Differences were more sensitive to the change in depth recess than length, and therefore it can be concluded that the main factor in designing adherend recessing was depth. The cross-section area at the ends of the overlap was smaller when the depth recess was larger; as a result, the peak peel stress in this point decreased in value.

Fig. 8. Ratio of peak peel stress for adherend recessing vs. recess length.

In Fig. 9, the variation in peak peel stress for configurations (3), (4), and (5), with respect to the reference configuration is presented. Great reductions in the peak peel stress were found in the case of adherend and adhesive chamfering, and the variation increased when the chamfer angle became more acute. In this cases, the value of the peak peel stress diminished by some 70% with respect to the reference configuration for a chamfer angle of 15°. This substantial reduction in the peak peel stress can be explained as follows: the change of the cross-section at the end of the overlap is more gradual when chamfering than in the reference configuration, and thus at this point the stress concentration was reduced.

Notably, the reduction in the vertical displacement was greater in the case of adherend chamfering than for adhesive chamfering; however, the reduction of the peak peel stress was greater in the case of adhesive chamfering than for the adherends. Therefore, it can be concluded that the reduction in the peak peel stress is associated not only with the reduction of the bending of the adherends, but with geometrical aspects, too.

Fig. 9. Ratio of peak peel stress for single-lap joint chamfering vs. chamfer angle.

In the case of adherend chamfering, the peak peel stress decreased in value because of the reduction in the eccentricity of the load, but in the case of adhesive chamfering, peak peel stress decreased because of both reduction of the eccentricity and shape of the adhesive ends. The chamfer in the adhesive reduces stress concentration, lowering the value of the peak peel stress. Fig. 10 shows the peel stress distribution along the adhesive overlap for the reference configuration, for the case having the minimum peak peel stress of configuration (2) (depth recess of 1.6 mm and length recess of 12.5 mm), and for the case having the smallest peak peel stress of configuration (5), with a chamfer angle of 15° in the adherends and the adhesive.

In all the cases studied, the peel-stress distribution was symmetric, showing a peak peel stress at the free ends of the adhesive and a zone of little compression [2]. A great reduction in the peak peel stress for configuration (5) was evident.

In configuration (2), peak peel stresses near the end of the overlap appeared because of the change in the cross-section at the location where the recess was made; however, this peel stress was not decisive for the strength of adhesive joint, which depended on the maximum peel stress at the free ends of the adhesive. In addition, between the recesses there was a compression zone, which did not appear in the reference single-lap joint, and configuration (5).

Fig. 10. Peel-stress distribution for the reference single-lap joint, and configurations (2) and (5).

In general, in the reference single-lap joint and configuration (2), peak peel stress was much greater than the one given in the rest of the overlap. This means that the value of the stress distribution along the overlap was negligible with respect to the value of the peak peel stress at the end of the overlap.

3.3. Failure load of the joint

In the same way as the vertical displacement and the peak stress peel, the results of failure load are presented with respect to the reference configuration (P_0). Fig. 11 shows the failure-load

results in the case of the recessing of the adherends. In all cases, the failure load increased with respect to the reference configuration. The greatest depth recess, 1.6 mm, caused the most marked variations of failure load. When the depth recess decreased, the variation in the failure load diminished, because configuration (2) was geometrically more similar to the reference configuration. Although there was no definite trend, the depth-recess results presented a local maximum. It was calculated that the best relation depth to length (d/a) of recess in order to increase the failure load, was between 0.064 and 0.32.

Fig. 11. Ratio of failure-load for adherend recessing vs. recess length.

Fig. 12 shows the failure load for chamfering as a function of the chamfer angle. An increase in the failure load occurs in all configurations studied with respect to the reference configuration. A clear trend can be discerned: the failure load increases when the chamfer angle narrows. The failure load significantly increases for angles of less than 45° and when chamfering the adherends as well as the adhesive. The highest failure load results in the case of adherend and adhesive chamfering at chamfer angle of 15° . In this case, minor peel stress was previously found. The results of adherend chamfering are more notable than are those for adhesive chamfering. The increase in the failure load was associated with the observed reduction in the

vertical displacement, which reduced the eccentricity and lowered the peak peel stress in the adhesive.

Stress concentration occurred at the ends of the overlap for configuration (1), which had a square end. Any change in the end geometry of the joint by chamfering, as in configuration (5), spread the load transfer over a larger area and gave a more uniform peel-stress distribution, improving the performance of the joint.

Fig. 12. Ratio of failure-load for single-lap joint chamfering vs. chamfer angle.

From a comparison of the results obtained with adherend recessing and with chamfering of the adherends and adhesive, it can be concluded that the failure load in the best case of joint chamfering (adherend and adhesive chamfering at 15° at the same time) is slightly higher than in the best case of joint recessing.

In configuration (2), the case with the minimum peak peel stress corresponded to a depth and length of recess of 1.6 mm and 12.5 mm, respectively, which did not coincide with the case with the greatest failure load (depth recess of 1.6 mm and length recess of 5 mm); however, differences between the two cases were minor. In the case of chamfering, the configuration with

less peak peel stress coincided with the one with the greatest failure load: chamfering both the adherends and the adhesive at 15° .

Finally, for all the studied configurations the best design is chamfering the adherends as well as the adhesive, with a chamfer angle of 15° . In this case, the failure load increased, and the vertical displacement and peak peel stress reduced their values.

4. CONCLUSIONS

In this work, different geometrical configurations of single-lap adhesive joints were analysed. A finite-element model was developed in Abaqus/Standard. The joint was subjected to a uniaxial tensile load, considering only cohesive failure. The main goal of this work was to analyse the influence of geometric variations on the mechanical strength of the joint in terms of failure load, eccentricity of the load, and the peak peel stress.

In the case of the recess of the adherends, some conclusions were drawn. In all the study cases, the best depth/length relation to increase the mechanical strength was between 0.064 and 0.32. The greatest variations appeared in the case of the biggest depth of the recess, 1.6 mm in this case, as it was geometrically the most different from the reference configuration. The recess caused a peak of the peel stress in the adhesive at the point where the recess was made, but this peak did not limit the strength of the joint, as the peak peel stress at the end of the adhesive was much greater. It can be concluded that the most important parameter in the strength of the joint, in the case of adherend recessing, is the value of the depth recess, and not its length. The depth recess was found to be the responsible for reducing peak peel stress because of the decrease in the cross-section at the end of the overlap.

The best option of all the configurations studied is chamfering the adherends as well as the adhesive, with a chamfer angle of 15° . When the chamfer angle decreased, the failure load increased, and the vertical displacement and peak peel stress reduced their values.

The effects of chamfering the adherends or chamfering the adhesive on the failure load were appreciated from chamfer angles of 30°, and the greatest contribution to increase the failure load was because of adherend chamfering.

The reduction of peak peel stress in the case of chamfering the adherends and the adhesive was a result of a reducing the eccentricity of the load, and the gradual change of cross-section at the end of the overlap, which avoided the stress concentration at that point. Also, the strength of the joint increases because of a better load transfer through the adhesive in the case of chamfering with respect to single-lap joint configuration.

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