PARAMETERS EFFECTS STUDY ON THE MECHANICAL BEHAVIOR OF SINGLE AND DOUBLE LAP BONDED JOINTS

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Abstract. *The use of bonded joints is one of the most efficient ways of transmitting loads between the parts of an aeronautical structure. Showing some different advantages when compared to mechanical joints, it also allows the bonding of dissimilar materials, as metals and composites. In order to design these joints, it is necessary to know the forces, moments, displacements and stress acting in the joint after load application. In order to help the design of bonded joints, a computational tool which is capable to evaluate single and double lap joint is proposed. A commercial program is used to validate the computational tool which is the finite element program ABAQUS^{TM}. After the computational tool validation, the effect of overlap length are studied, showing, mostly for single lap joints, an increase in overlap length decreases the stress intensity in the adhesive layer. It also shows, for the same load, that the stress state in the adhesive layer for a double lap joint is lower than for a single lap joint, so it is desirable using double lap joints every possible time. The adhesive elastic modulus can also be changed, showing a significant stress state decrease in the adhesive layer with lower elastic modulus. For hybrid bonded joints of metal-composite, the differences of adherents stiffness change the displacement field due to materials characteristics, and the stress peaks are moved to less flexible side.*

Keywords: *bonded joints, composite materials, numerical methods, parametric studies, hybrid joints*

1. INTRODUCTION

In the last years, the use of composite materials as a primary structural element has been increasing. Some new aircraft design, for example: Airbus A380 and Boeing 787 use composite materials even in primary structural elements such as wing spars and fuselage skins, achieving lighter structures without loss of airworthiness. One way to assembly, these structures consist on using bonded joints which shows some advantages like a better fatigue endurance, joining dissimilar materials, better insulation, smooth surface and lighter weight. Nevertheless, there is no possibility to disassembly the joints, peeling stress should be minimized and the preparation of the surfaces that will be bonded must be done carefully (Mortensen, 1998).

Many researches have been carried out about bonded joints, trying to predict the behavior, failure, and the strength of bonded joints using finite element models, analytical models or experimental tests. Thomsen (1992) showed that an increase in the overlap length reduces the stress in the adhesive layer, a use of adhesive layer with lower elastic shear and tensile moduli decreases the adhesive stress that is better use identical or nearly identical adherents in bonded joints. Mortensen (1998), in his PhD thesis, presented a development of a computational tool for analysis of bonded joints showing the equations and hypothesis for various type of bonded joints, as well as, the solving process of differential equations using the multi-segment method of integration. Ganesh and Choo (2002) showed the effect of spatial grading of adherent elastic modulus on the peak stress and stress distribution in the single lap joint, which lead to decreasing in the stress peak and a more uniform shear stress distribution.

Belhouari, Bouiadjra, and Kaddouri (2004) showed a comparison between single and double lap joint using a finite element model. In this study, the researchers showed the advantages of using symmetric composite patch for repairing crack, also, that double patch has lower stress when compared with single patch repair. Myeong et. al. (2008) showed that an increase of bonding pressure leads to higher strength bonded joints, an increase in the overlap length also leads to higher strength bonded joints and the major failure mode for single lap hybrid composite/aluminum joints is the delamination of the composite adherent. Agnieszka (2009) showed a numerical method, regarding the sensitivity for hydrostatic stress, for prediction of the delamination initiation, which allows simulating the failure of the joint and composite substrate.

In order to help the design process of bonded joints, it was developed a software called SAJ (System of Analysis for joints), which is capable of analyze a bonded joint behavior in detail, not only for single lap joint, but also, for double lap joint. These joints could be made of composite/composite materials or dissimilar materials (metal/composite). The software developed can calculate the joints stresses, loads and displacements. The results obtained are compared to finite element results in order to validate SAJ.

The present work perform a study of how some joint parameters affects the adhesive stress state, these parameters are:

1. overlap length,
2. adhesive layer thickness,
3. adhesive elastic modulus affects the adhesive stress state.

2. FAILURE MECHANIMS

Bonded joints investigated in this work could be composed by three different types of materials: metallic adherent, composite adherent and adhesive.

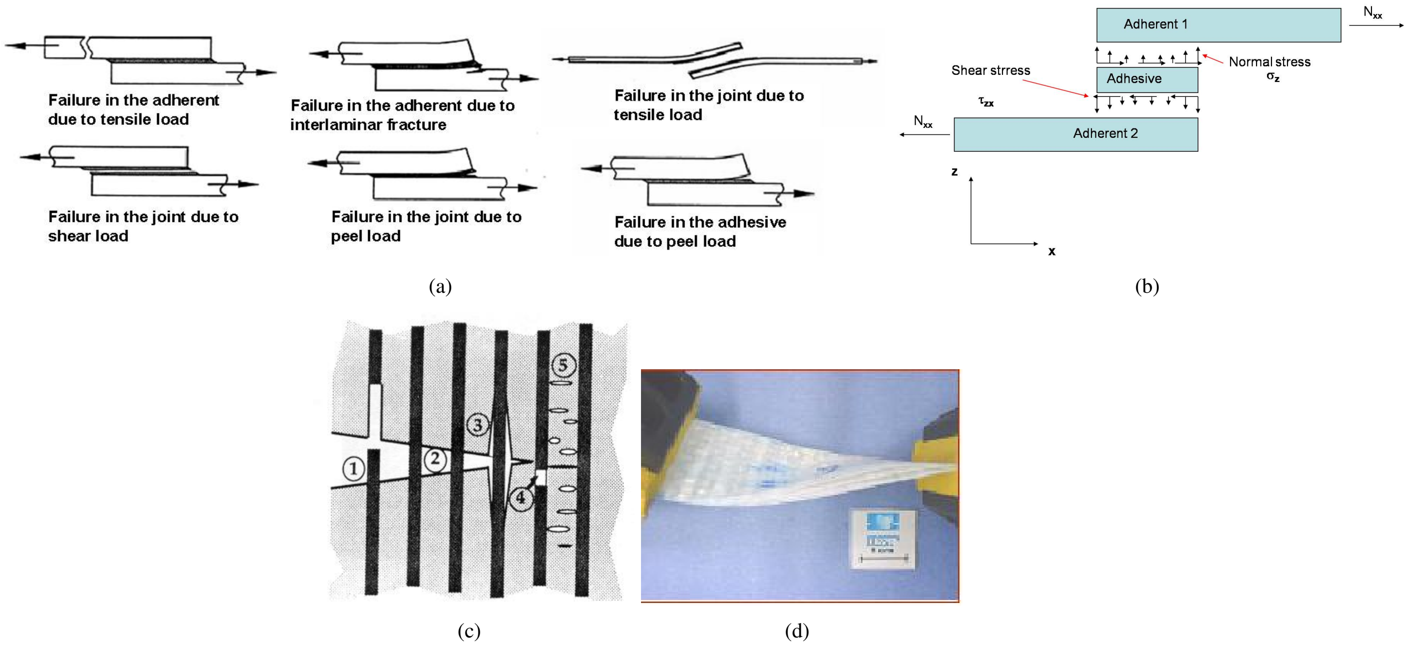


Figure 1. ((a) Failure modes in single lap joint (b) normal and shear stress in lap joint; (c) intra-ply failure of composite (Anderson, 1995) ; (d) inter-ply failure of composite (delamination).

2.1 Adherents

For metal (adherent 1), in specific for aluminum alloy, the yielding phenomenon governs the material behavior. In addition, the type of the surface of the metal plate can influence at the hybrid joint performance, because, the adhesion by the adhesive is improved. This effect was not considered in this work, but it will be studied in the future.

For composite laminate (adherent 2) made from the stacking of plies, which contains a polymeric matrix reinforced by fibers, this material shows two types of failure modes:

1. Intra-ply failure modes: damages at fibers, polymeric matrix and/or interface between fibers and matrix (Fig. 1(c));
2. Inter-ply failure modes: delaminations between plies (Fig. 1(d)).

The intra-ply damage (Fig. 1(c)) at fibers is showed by mechanism 4 that is the fiber rupture. However, the fiber failure mode depends on the type of loading, because, compression loads can induce micro-buckling, but, tensile loads can induce rupture of fibers. The intra-ply damage at the matrix depends on the ductility of the polymer, as well as on the in-service temperature. Thus, the polymeric matrix can present a fragile or a plastic behavior (mechanism 5). Fig. 1 shows other intra-ply failure mechanisms. The mechanism 1 is called "Pull-Out" and occurs when the interface between fiber and matrix is weak. Therefore, the fiber is pulled out of the matrix after the debonding mechanism (mechanism 3) occurred. If the interface between fiber and matrix is strong, the fiber is not pulled out of the matrix and the mechanism 2 called "Fiber Bridging" is activated. The inter-ply failure called delamination (Fig. 1(d)) occurs after intra-ply damages, i.e., the evolution of intra-ply damages propagates the delaminations, because the regions damaged at the ply propagates when the load increases and the cracks at two adjacent plies (with different orientation angle) join for creating a discrete failure between them. At that moment, the interlaminar shear increases strongly and the delamination process initiates. This failure mechanism is very common to occur under flexural and transversal shear stresses due to quasi-static or dynamic loading. In fact, nowadays, the material models for intra-ply damages have been improved, and, the material models for delamination have been developed.

2.2 Adhesive

For adhesive, the material has good strength considering stress in the plane of the joint, i.e., interlaminar shear stress, but the strength values out-of-plane the joint is very poor, for example, strength for peeling load (Fig. 1(a)). This problem can be minimized when the size of over-lap increase and, this influence will be showed at the results. However, the properties of the adhesive can reduce very strongly with the increase of the temperature and humidity, and, this influence has been developed.

3. COMPUTATIONAL TOOL

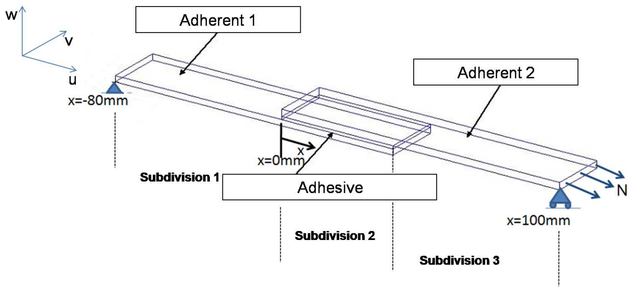
In order to help the assessment of bonded joints was developed a computational tool that are able to calculate the joint loads, displacements, stress and adhesive/adherents stresses. This software was used only for linear elastic analysis.

3.1 Software SAJ

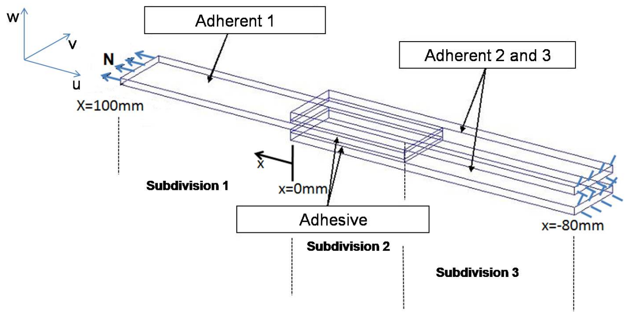
A computational tool was developed in order to help the analysis of single and double lap bonded joints. This software was programmed in Matlab™language. In the case of composite adherents, this software is also capable to obtain the stress and strain for each layer. SAJ is also capable to solve composite/composite and metal/composite bonded joints.

SAJ reads an input file within data of adherents, adhesive and joint characteristics. These file contains information such as layup and layer thickness in case of composite adherents, mechanical properties for adherents and adhesives, joint dimensions of adhesive and adherents and loads. For results, SAJ shows the graphics of forces, displacements and adhesive stresses, also these solutions are given in tabular form.

SAJ solves a set of differential equations of the multi-domain boundary value problem using Matlab™. In order to obtain the set of differential equations, first a subdivision of the joint in three regions were made, one part with only adherents, other part with the bonded region and the last part again only with adherents. These subdivisions are showed for single lap joint in Fig.2(a) and for double lap joint in Fig.2(b). In these figures are also showed the boundary conditions, loads and coordinate system.



(a) Single lap joint



(b) Double lap joint

Figure 2. (a)Single lap joint boundary conditions, loads and coordinate system, (b) Double lap joint boundary conditions, loads and coordinate system.

For each region, using the equilibrium equations of an infinitesimal element are obtained the set of differential equations as showed in Fig.3 for single and double lap joint, in this figure the subscript $_{,x}$ or $_{,y}$ means the derivative relative to x or y. With Classical Laminate Theory, and assuming the hypothesis that all derivatives in y direction are equal zero, plane stress state, Kirchhoff kinematics relations and the equilibrium equations leads to the complete set of differential equations.

For the first subdivision, the set of differential equations are showed in Fig.4(a), these equations are for both joint types out of overlap zone. Figure4(b) shows the equations for adherent 1 only for a double lap case inside the overlap region, and Fig.4(c) shows the equations for adherents 1 and 2 for single lap case and for adherents 2 and 3 for double lap case inside the overlap region.

The adhesive is simulated as tension/compression and shear springs, Eq. (1) to Eq. (3) shows the equations for the adhesive model.

$$\tau_{ax} = \frac{G_a}{t_a}(u_0^i - \frac{t_i(x)}{2}\kappa_x^i - u_0^j - \frac{t_j(x)}{2}\kappa_x^j) \tag{1}$$

$$\tau_{ay} = \frac{G_a}{t_a}(\nu_0^i - \nu_0^j) \tag{2}$$

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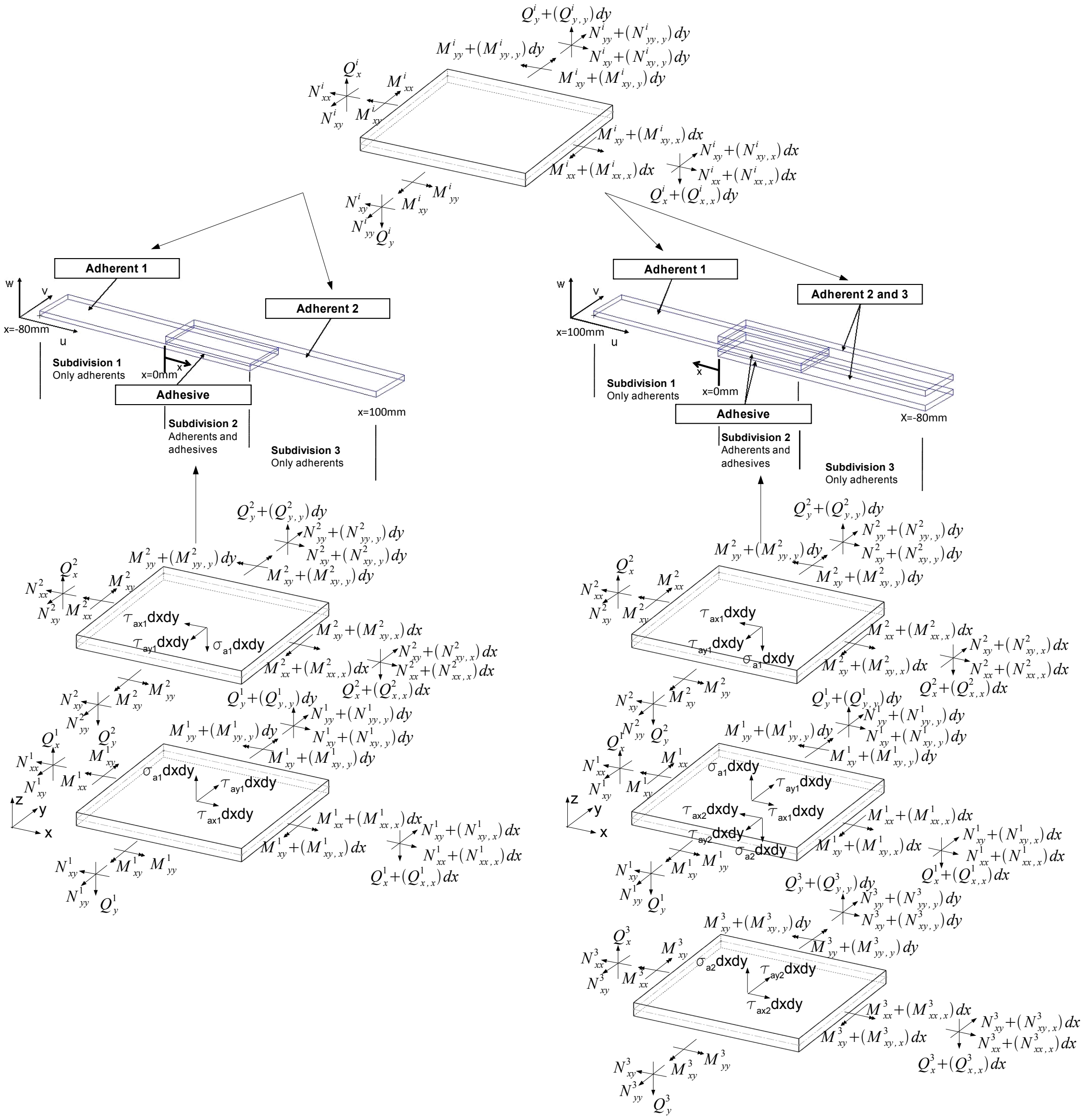


Figure 3. Free body equilibrium forces for each subdivision part.

$$
\begin{gathered}
u^{i}_{0,x}-a^{i}_{11}N^{i}_{xx}-a^{i}_{13}N^{i}_{xy}-b^{i}_{11}M^{i}_{xx}=0\\
w^{i}_{,x}+\kappa^{i}_{x}=0\\
K^{i}_{x},x-b^{i}_{11}N^{i}_{xx}-b^{i}_{13}N^{i}_{xy}-d^{i}_{11}M^{i}_{xx}=0\\
v^{i}_{0,x}-a^{i}_{21}N^{i}_{xx}-a^{i}_{23}N^{i}_{xy}-b^{i}_{21}M^{i}_{xx}=0\\
N^{i}_{xx,x}=0\\
N^{i}_{xy,x}=0\\
M^{i}_{xx,x}-Q^{i}_{x}=0\\
Q^{i}_{x,x}=0
\end{gathered}
$$

(a)

$$
\begin{gathered}
u^{1}_{0,x}-a^{1}_{11}N^{1}_{xx}-a^{1}_{13}N^{1}_{xy}-b^{1}_{11}M^{1}_{xx}=0\\
w^{1}_{,x}+\kappa^{1}_{x}=0\\
K^{1}_{x},x-b^{1}_{11}N^{1}_{xx}-b^{1}_{13}N^{1}_{xy}-d^{1}_{11}M^{1}_{xx}=0\\
v^{1}_{0,x}-a^{1}_{21}N^{1}_{xx}-a^{1}_{23}N^{1}_{xy}-b^{1}_{21}M^{1}_{xx}=0\\
N^{1}_{xx,x}+\tau^{1}_{ax}-\tau^{2}_{ax}=0\\
N^{1}_{xy,x}+\tau^{1}_{ay}-\tau^{2}_{ay}=0\\
M^{1}_{xx,x}-Q^{1}_{x}+\tau^{1}_{ax}\frac{(t_1+t_{a1})}{(2)}-\tau^{2}_{ax}\frac{(t_1+t_{a2})}{(2)}=0\\
Q^{1}_{x,x}-\sigma^{1}_{a}+\sigma^{2}_{a}=0
\end{gathered}
$$

(b)

$$
\begin{gathered}
u^{i}_{0,x}-a^{i}_{11}N^{i}_{xx}-a^{i}_{13}N^{i}_{xy}-b^{i}_{11}M^{i}_{xx}=0\\
w^{i}_{,x}+\kappa^{i}_{x}=0\\
K^{i}_{x},x-b^{i}_{11}N^{i}_{xx}-b^{i}_{13}N^{1}_{xy}-d^{i}_{11}M^{i}_{xx}=0\\
v^{i}_{0,x}-a^{i}_{21}N^{i}_{xx}-a^{i}_{23}N^{i}_{xy}-b^{i}_{21}M^{i}_{xx}=0\\
N^{i}_{xx,x}+\tau^{i}_{ax}=0\\
N^{i}_{xy,x}+\tau^{i}_{ay}=0\\
M^{i}_{xx,x}-Q^{i}_{x}+\tau^{i}_{ax}\frac{(t_1+t_{a1})}{(2)}=0\\
Q^{i}_{x,x}-\sigma^{i}_{a}=0
\end{gathered}
$$

(c)

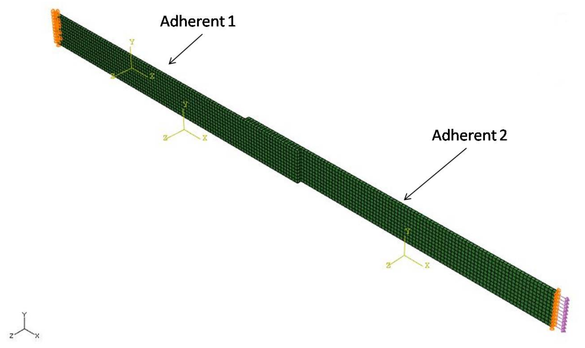
Figure 4. (a)Set of differential equations for bonded joint out of overlap zone for i=1,2,3.; (b) Set of differential equations for double lap joint adherent 1; (c)Set of differential equations for adherents in the overlap joint. For single lap, i=1,2 and for double lap, i=2,3.

$$\sigma_{ax} = \frac{E_a}{t_a}(w^i - w^j) \tag{3}$$

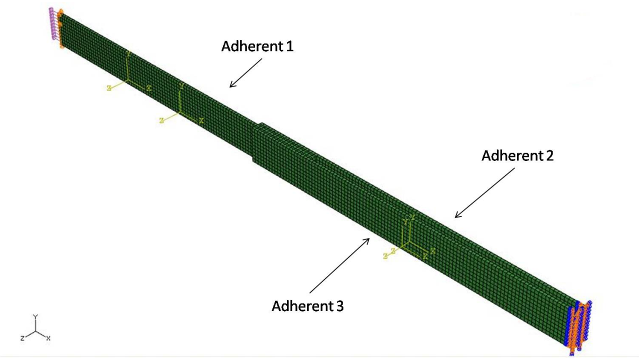
These differential equations system for each subdivision are solved using Matlab^{TM}, which can deal with multi-domain boundary values problem.

3.2 Finite element model

A finite element model for single and double lap joint using commercial software ABAQUS^{TM}were used to compared to the SAJ computational results. The finite element model use a second order element with 20 nodes (C3D20) for adherents and adhesives even for single and double lap joint, C3D20 is used also for modeling composite adherents. Figure 5(a) shows the finite element model for single lap bonded joint and Fig. 5(b) shows the finite element model for double lap bonded joint. Notice that these models are simulating the boundaries conditions and loads for each joint as showed in Fig. 2(a) for single lap and Fig. 2(b) for double lap joint.



(a) Single lap joint



(b) Double lap joint

Figure 5. (a)Single lap joint finite element model, (b) Double lap joint finite element model.

ABAQUS^{TM}constraint function "tie" is used to join the adhesive and adherents. The constraint function tie transfer all degrees of freedom between adherents and adhesive.

3.3 Comparison between SAJ and Finite Element Model

For the comparison a composite/composite joints were used and the adherents and adhesives mechanical properties, as well as, the characteristics given in Tab.1. The boundary conditions in Fig. 5(a) for single lap joint and Fig. 5(b) for double lap joint. The adherents were carbon fiber reinforced plastics and the adhesive was epoxy. A normal load of $0.015kN/mm$ were used for single and double lap joint to proceed with this comparison. It is important to notice that this load is small enough to not cause any plasticity even in adherents or in adhesive.

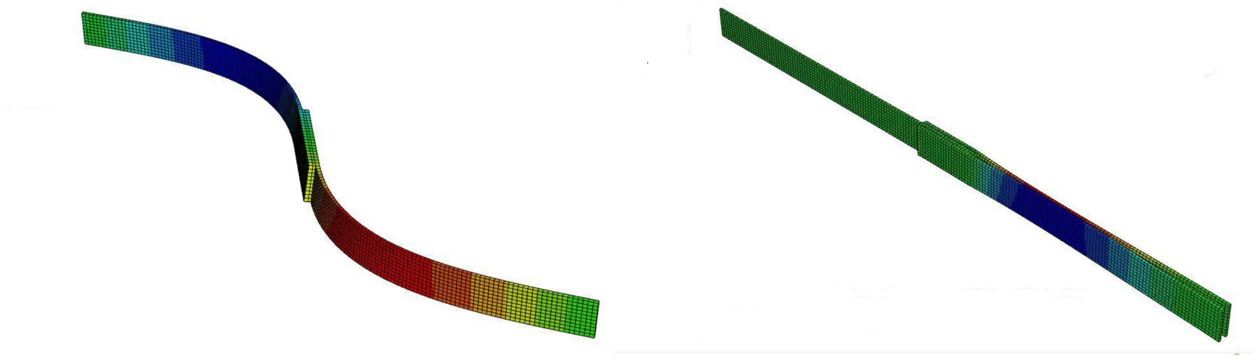
The results in Fig. 6(a) shows the displacement field for single lap joint and in Fig. 6(b) shows the displacement field for double lap joint. Only the results for displacement are shown in this work in order to focus in the parametric studies, more details about SAJ validation in Ribeiro (2009) and Tita, Angelico and Ribeiro (2008).

Table 1. Hexcel T3T-190-F155 carbon fiber reinforced plastic and Hysol EA 9321 epoxy adhesive mechanical properties and characteristics.

	$E_1[kN/mm^2]$	$E_2[kN/mm^2]$	$G_{12}[kN/mm^2]$	ν	$Thickness[mm]$	$Orientation$
Hexcel T3T-190-F155	126.0	7.1	4.0	0.30	$0.8(0.2mm$ per ply)	$[0/45]_s$
Epoxy adhesive	1.485	-	-	0.35	0.5	-

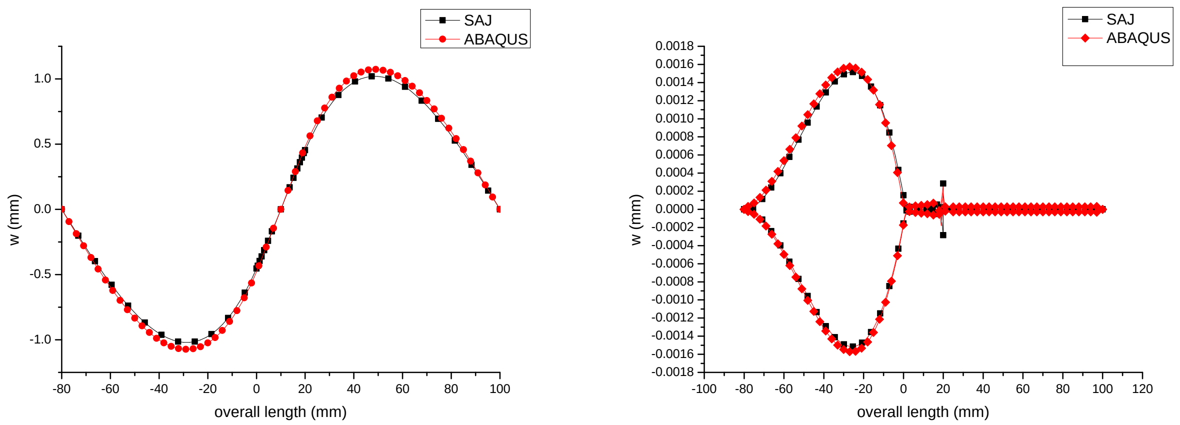
Figure 7(a) shows the displacement in w direction comparison between SAJ and ABAQUS^{TM}for a single lap joint and Fig. 7(b) for double lap joint. For single lap joint, the joint is considered simple supported in both sides with load in u direction (Fig. 2(a)), for double lap joint, the side with two adherents are clamped and the other side is free with a load in u direction (Fig. 2(b)).

Once the comparison between SAJ and ABAQUS^{TM}shows a good fit, SAJ can be used more easily in parametric studies since only few changes in the input data file are necessary. Otherwise to perform parametric studies using finite element software demands huge modifications in the model which can become time expansive.



(a) Single lap joint (b) Double lap joint

Figure 6. (a)Single lap joint displacement field; (b) Double lap joint displacement field.



(a) Single lap joint (b) Double lap joint

Figure 7. (a) Single lap joint displacement in w direction; (b) Double lap joint displacement field in w direction.

4. PARAMETRIC STUDY

One of the most important part of the joint is the adhesive layer, where the interactions between adherents and adhesive occur and the load transfer. For these reasons, this work focus in the adhesive layer stress distribution. For all parametric studies, the boundary conditions and load are showed in the Fig. 2(a) for single lap joint and in Fig. 2(b) for double lap joint.

For double lap joint, due to use of symmetric laminates, only σ_z and τ_{zx} are shown for one of the two adhesive layer in order to improve the visualization of results. The same procedure is used for the case of hybrid joints, because the aluminum are only used as adherent 1 (see Fig. 2(b)) and adherents 2 and 3 are symmetric composites, keeping the joint symmetry.

4.1 Effect of the overlap length

Some important parameters for bonded joints were studied, which presents a significant impact in the adhesive stress distribution. In this case, a hybrid joint composite/metal is used, the mechanical properties and other important characteristics for adhesive and adherents are showed in the Tab.2 for both type of joints, a load of $0.020kN/mm$ was used also for both type of joints. Aluminum 2024-T3 was used in single lap joint as adherent 1, and for adherent 2, a carbon fiber composite (Hexcel T3T-190-F155) and a epoxy adhesive were used. For a double lap joint, aluminum 2024-T3 was used for adherent 1, and composite material was used for other adherents and epoxy adhesive.

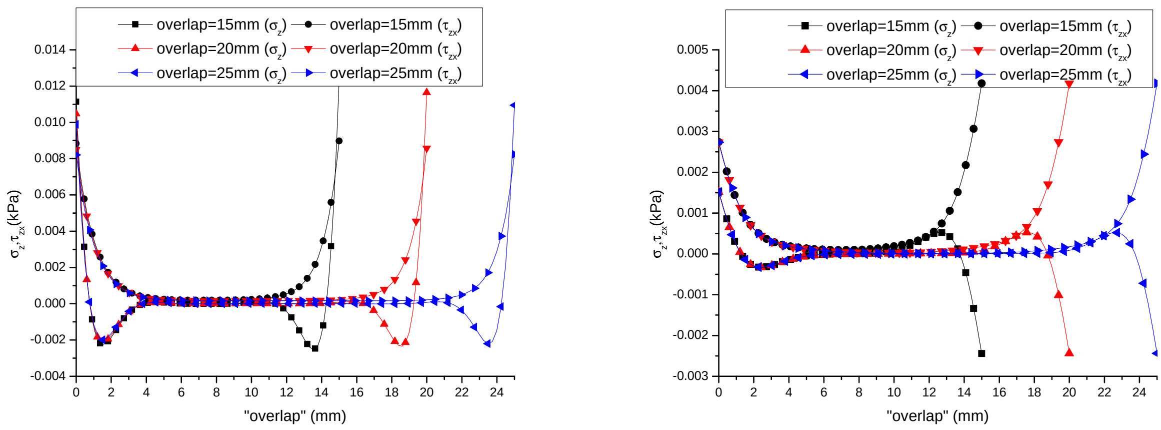
Figure 8(a) shows the effect of the overlap length in the adhesive layer stress distribution for a single lap joint and Fig. 8(b) shows the results for double lap joint.

Table 3 shows the σ_z and τ_{zx} values obtained in the left edge of the adhesive layer for single and double lap joint. From the results, it is clear that an increase in the overlap length results in lower stress state in the adhesive edge, mainly for single lap joints, considering the lengths studied in this paper.

Also it can be observed that the stress decreasing trends with an increase in the overlap length. So, it is possible to

Table 2. Adherents and adhesive mechanical properties and characteristics

	$E_1[kN/mm^2]$	$E_2[kN/mm^2]$	$G_{12}[kN/mm^2]$	ν	$Thickness[mm]$	$Orientation$
Hexcel T3T-190-F155	126.0	7.1	4.0	0.30	1.2(0.2mm per ply)	$[0/45/-45]_s$
Aluminum 2024-T3	72.0	-	-	0.30	1.2	-
Epoxy adhesive	1.485	-	-	0.35	0.5	-



(a) Single lap joint (b) Double lap joint

Figure 8. Overlap parametric study - (a)Single lap joint; (b) Double lap joint.

Table 3. Stress values for overlap length

Single lap joint			
Overlap length [mm]	15	20	25
σ_z [MPa]	0.012	0.011	0.010
τ_{zx} [MPa]	0.0090	0.0086	0.0082
Double lap joint			
Overlap length [mm]	15	20	25
σ_z [MPa]	0.00152	0.00151	0.00151
τ_{zx} [MPa]	0.00274	0.00273	0.00273

conclude that exist a length in which any further increase in the overlap length do not decrease the stress state in the adhesive layer edge. This trend is clearer to observe in the double lap joint results.

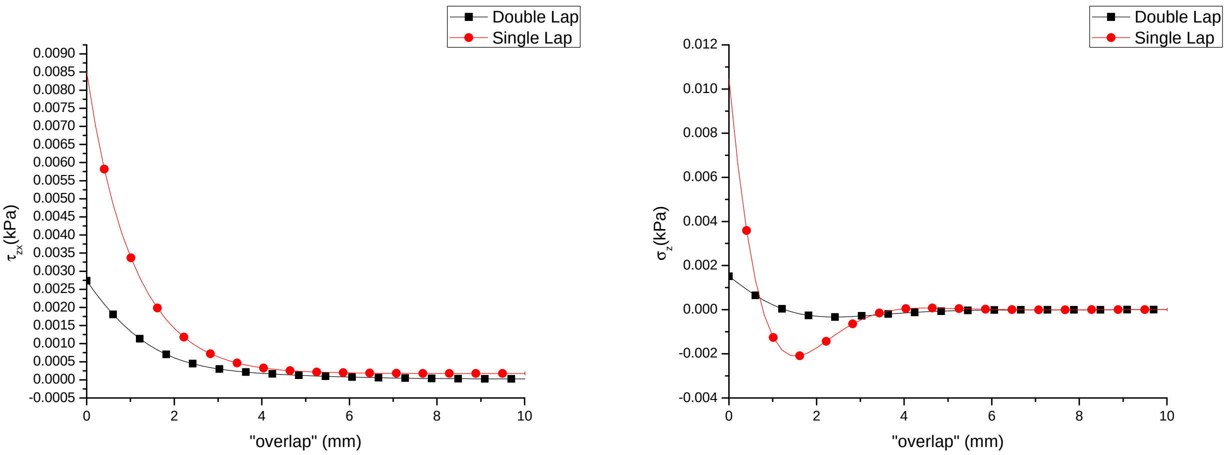
4.2 Comparison between single and double lap joints

In this study, all the joint parameters for single and double lap joint were kept the same as used for the overlap effect analysis. It is important to note that the overlap length is equal $20mm$. The results are showed for half of the overlap length in the region with greater differences between these two types of joints. Figure 9 shows the difference between double and single lap joint stress distribution in the adhesive layer for the same load conditions and same joint characteristics. Fig. 9(a) show the difference between these two types of bonded joints for shear stress in the plane zx (τ_{zx}) and Fig. 9(b) show for the normal stress (σ_z).

Table 3 shows the difference between these single lap and double lap bonded joints. The values for σ_z and τ_{zx} are significantly greater for single lap joints.

4.3 Effect of the adhesive elastic modulus

Another important parameter is the adhesive elastic modulus, keeping other parameters constants and using three different values for the adhesive elastic modulus ($1.5GPa$, $2.0GPa$, $3.0GPa$). Analysis of the effect of this parameter in the stress distribution in the adhesive layer was performed. These values for adhesive elastic modulus could be found in



(a) Single lap joint

(b) Double lap joint

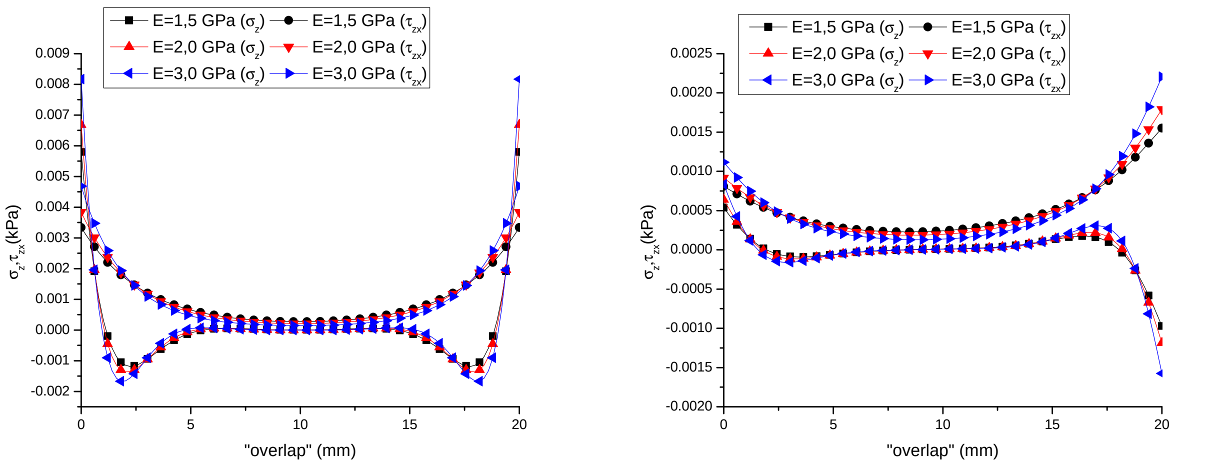
Figure 9. Comparison between single and double lap joint (half of the overlap length)(a)Shear stress; (b) Normal stress.

the literature as presented in San Román (2005).

The mechanical properties and other characteristics are showed in Tab. 4. In this case, a normal load of $0.015kN/mm$ was imposed for both type of joint. Figure 10(a) shows the results for single lap joint and Fig. 10(b), for double lap joint.

Table 4. Graphite/Epoxy adherent (Mortensen, 1998) and adhesive mechanical properties and characteristics.

	$E_1[kN/mm^2]$	$E_2[kN/mm^2]$	$G_{12}[kN/mm^2]$	ν	$Thickness[mm]$	$Orientation$
Graphite/Epoxy	164.0	8.3	2.1	0.34	0.8(0.2mm per ply)	$[0/45]_s$
Epoxy adhesive	–	-	-	0.35	0.5	-



(a) Single lap joint

(b) Double lap joint

Figure 10. Young modulus parametric study - (a)Single lap joint; (b) Double lap joint.

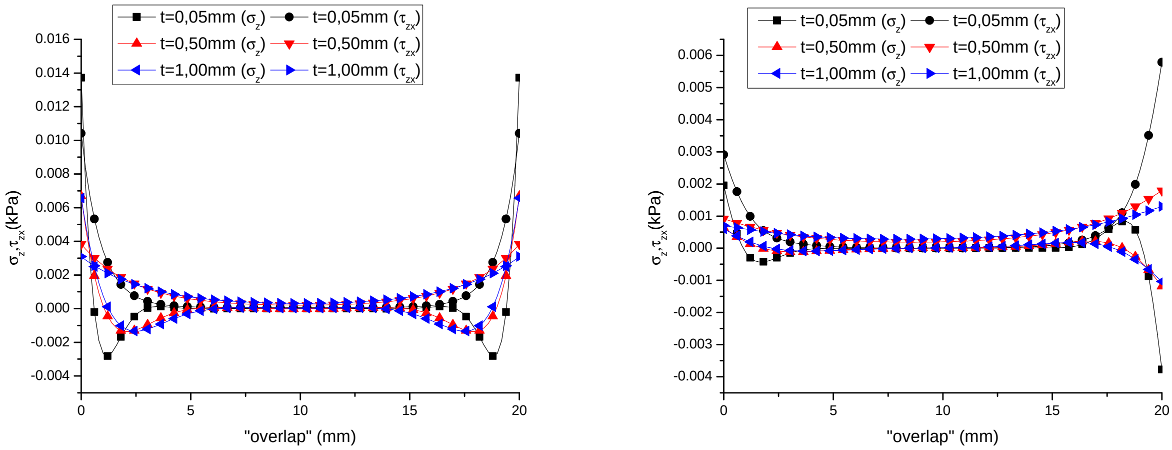
It can be observed that an adhesive with lower values of elastic modulus results in a lower stress state in the adhesive layer for single and double lap bonded joints, but it is desirable that the adhesive has a satisfactory strength.

4.4 Effect of the adhesive layer thickness

The adhesive layer thickness (keeping the other parameters constant), also affects the stress distribution in the adhesive layer. Regarding three different adhesive layer thickness ($0.05mm$, $0.5mm$, $1.0mm$) and mechanical properties, as well as, for adherents and adhesive characteristics as showed in Tab. 4. The analyses were made using a normal load of

$0.015kN/mm$. Note that these adhesive thicknesses could be found in some papers as Qian and Sun (2008).

Figure 11(a) shows a single lap joint adhesive layer stress distribution for three different thickness and Fig. 11(b) for double lap joint.



(a) Single lap joint

(b) Double lap joint

Figure 11. Adhesive thickness parametric study - (a)Single lap joint; (b) Double lap joint.

These results show that these parameters could affect the adhesive layer stress distribution significantly.

5. CONCLUSIONS

The SAJ (System Analysis for Joints) leads some conclusions regarding the joint parameters and type of joint which can be observed as a guide during the design process. Understanding the behavior of the stress state with variations in the joint parameters can help the joint design process. SAJ also perform parametric studies faster than finite element programs.

According to results, it can be concluded:

1. A thicker adhesive layer (keeping other parameters constant), could reduce the adhesive edge stress state increasing the joint resistance;

2. The adhesive stiffness affects the stress state, which a more flexible adhesive reduce the stress peak in the edges of the adhesive layer, so if the resistance criteria is accomplished, it is more recommendable use adhesives more flexible than a stiffener adhesives;

3. A short overlap length will increase the stress peak in the adhesive layer edges so, it is reasonable to increase of the overlap length, but the joint weight could increase.

The use of double lap joints, due to lower stress, is more recommendable to use instead of single lap joints, although the double lap joint lower stress a more complex manufacturing process could increase the costs and double lap joints could increase the part weight, so the designer must consider in the time to manufacture the joint type.

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8. Responsibility notice

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