INVESTIGATION OF FAILURE ANALYSIS ON SINGLE AND DOUBLE LAP BONDED JOINTS

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Abstract. *The use of bonded joints is one of the most efficient ways to transfer loads between parts of an aeronautical structure. Showing some different advantages when compared to mechanical joints, it also allows bonding dissimilar materials, as metals and composites. In order to design these joints, it is necessary to know the membrane and shear forces, moments, displacements and stress acting in the joint after load application. In order to help the design of bonded joints, a computational tool, called SAJ, which is capable to evaluate single and double lap joint is developed. A commercial program is used to validate the computational tool which is the finite element program ABAQUS^{TM}. First ply failure analysis were performed using Hashin damage criteria for plane stress state with SAJ and ABAQUS^{TM}. For tridimensional stress state, it is implemented Hashin 3D damage criteria using an UMAT (User Material Subroutine) by Fortran language, and this subroutine is linked to ABAQUS^{TM}. SAJ and Finite Element results for first ply failure were compared. SAJ results were closer to Finite Element results for plane stress state hyphothesis. However, for tridimensional stress state, finite element model and SAJ shows relevant differences for single lap joints with symmetric laminate.*

Keywords: *failure analysis, bonded joints, composite materials, numerical methods.*

1. INTRODUCTION

In the last years, the uses of composite materials as a primary structural element have 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 consists on using bonded joints which show some advantages like a better fatigue endurance, possibility of joining dissimilar materials, better insulation, smooth surface and light 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).

One advantage of using composite materials is the possibility to design the material changing the plies orientation. Considering that aircrafts are subjected to various load cases during a normal flight, and that the structure must stand for all loads case, it might happen that for one load case some ply fibers be perpendicular to the load which is the most critical orientation for a laminate material.

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 the multi-directional adhesive state of stress could be related to a unidirectional state of stress through a function similar that presented by von Mises. 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 types 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 decrease 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 a symmetric composite patch for repairing crack. Also, that double patch has lower stress when compared with single patch repair. 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 analyzing a bonded joint behavior in detail, not only for single lap joint, but also, for double lap joint. 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.

Due to joint geometry, mostly for single lap joints, a normal load can cause moments and shear loads in the joint, which results in a complex load case that is variable along the joint. The present work performs a joint adherent failure study using first ply failure as stop criteria. The analysis stopped when the adherent first ply fail, which is a conservative approach because the whole laminate is considered failed. Nevertheless, it is a good first approach for a composite structural analysis. Progressive damage analyses are not performed in this work. Phenomenological failure criteria were used for identify the failure, also is possible to indicate which play fail and the failure mode as:

1) fiber rupture in tension;
2) fiber buckling and kinking in compression;
3) matrix cracking under transverse tension and shearing;
4) matrix crushing under transverse compression and shearing.

First ply failure analysis were performed using Hashin damage criteria for plane stress state with SAJ and ABAQUS™. For tridimensional stress state, it is implemented Hashin 3D damage criteria using an UMAT (User Material Subroutine) by Fortran language, and this subroutine is linked to ABAQUS™. SAJ and Finite Element results for first ply failure were compared. SAJ results were closer to Finite Element results for plane stress state hypothesis. However, for tridimensional stress state, finite element model and SAJ shows relevant differences for single and double lap joints.

2. FAILURE MECHANIMS

Bonded joints investigated in this work were composed by two different types of materials: composite adherent and adhesive.

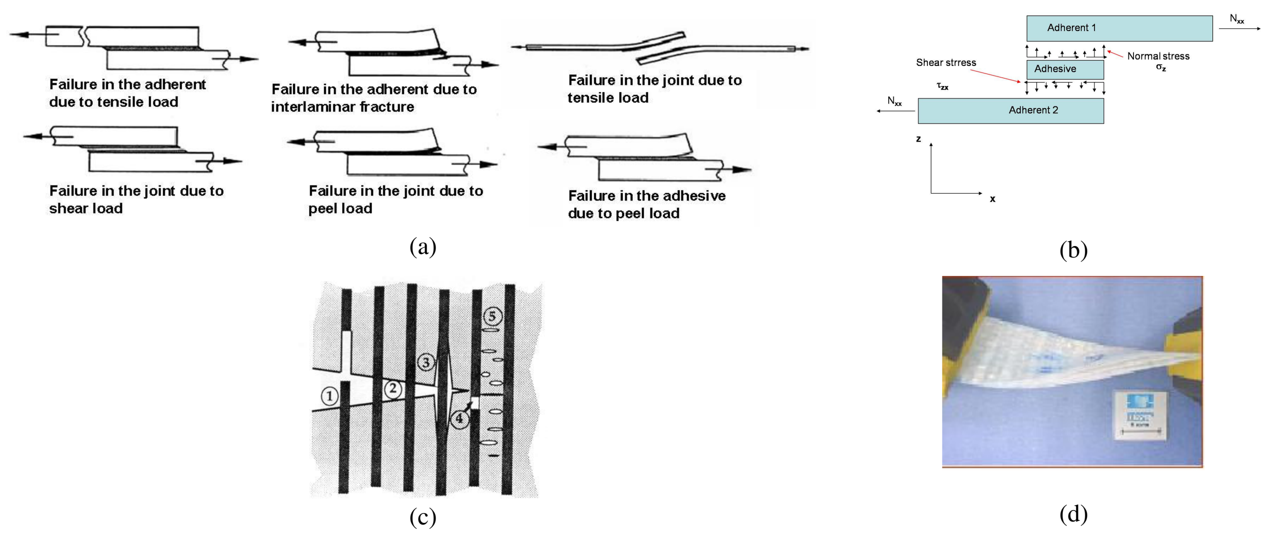


Figure 1: (a) Failure modes in single lap joint (b) normal and shear stress in lap joint; (c) intra-ply failure of composite (Anderson, 1995) ; (d) inter-ply failure of composite (delamination).

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 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.

Nowadays, there are considerable failure criteria for composite materials, subdivided into different categories. This paper considers only phenomenological criteria as proposed by Hashin (1980). After a stress analysis of the laminate, each ply failure is verified. If the failure occurs the analysis stops. Hashin's equations are showed in equations 1 to 4 for plane stress state.

Fiber compression failure mode (σ_1 <0):

$$\left(\frac{\sigma_1}{X_c}\right)^2 = e_F^{\,2} \tag{1}$$

If $e_F^{\,2} \le 1$ fiber was not damaged, if $e_F^{\,2} > 1$ fiber was damaged.

Where σ_{1_F} is the stress in the fiber direction, X_C is the lamina compression strength in the fiber direction. In this mode, for the plane stress and tridimensional stress, equations are equal.

Fiber tensile failure mode for plane stress (σ_1 >0):

$$\left(\frac{\sigma_1}{X_T}\right)^2 + \left(\frac{\sigma_{12}}{S_{12}}\right)^2 = e_F^{\,2} \tag{2}$$

Fiber tensile failure mode for tridimensional stress (σ_1 >0):

$$\left(\frac{\sigma_1}{X_T}\right)^2 + \left(\frac{\sigma_{13}}{S_{12}}\right)^2 + \left(\frac{\sigma_{12}}{S_{12}}\right)^2 = e_F^{\,2} \tag{3}$$

If $e_F^{\,2} \le 1$ fiber was not damaged, if $e_F^{\,2} > 1$ fiber was damaged.

Where X_T is the lamina tensile strength in the fiber direction and S_{12} is the lamina shear strength.

Matrix compression failure mode for plane stress ($\sigma_2 \le 0$):

$$\left(\frac{\sigma_2}{2S_{23}}\right)^2 + \left[\left(\frac{Y_C}{2S_{23}}\right)^2 - 1\right]\frac{\sigma_2}{Y_C} + \left(\frac{\sigma_{12}}{S_{12}}\right)^2 = e_M^{\,2} \tag{4}$$

Matrix compression failure mode for tridimensional stress ($\sigma_2 + \sigma_3 < 0$):

$$\frac{1}{4S_{23}}(\sigma_2+\sigma_3)^2 + \left[\left(\frac{Y_C}{2S_{23}}\right)^2 - 1\right]\frac{(\sigma_2+\sigma_3)}{Y_C} + \frac{1}{S_{23}^2}\left(\sigma_{23}^2 - \sigma_2\sigma_3\right) + \left(\frac{\sigma_{13}}{S_{12}}\right)^2 + \left(\frac{\sigma_{12}}{S_{12}}\right)^2 = e_M^{\,2} \tag{5}$$

If $e_M^{\,2} \le 1$ matrix was not damaged, if $e_M^{\,2} > 1$ matrix was damaged.

Where Y_C is the lamina transversal compression strength and S23 is the lamina strength in plane 2-3.

Matrix tensile failure mode for plane stress ($\sigma_2 \ge 0$):

$$\left(\frac{\sigma_2}{Y_T}\right)^2 + \left(\frac{\sigma_{12}}{S_{12}}\right)^2 = e_M^{\,2} \tag{6}$$

Matrix tensile failure mode for tridimensional stress ($\sigma_2 + \sigma_3 \ge 0$):

$$\frac{1}{Y_T^2}(\sigma_2+\sigma_3)^2+\frac{1}{S_{23}^2}\left(\sigma_{23}^2+\sigma_2\sigma_3\right)+\left(\frac{\sigma_{13}}{S_{12}}\right)^2+\left(\frac{\sigma_{12}}{S_{12}}\right)^2={e_M}^2 \tag{7}$$

If ${e_M}^2 \leq 1$ matrix was not damaged, if ${e_M}^2 > 1$ matrix was damaged.
Where Y_T is the transversal lamina tensile strength.

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)). However, the properties of the adhesive can reduce very strongly with the increase of the temperature and humidity, and, this influence has been developed.

Adhesives are ductile polymeric materials and the hypothesis of linear elastic material was no longer realistic, since the adhesive response is predominantly inelastic even at low levels of external loading. Plastic residual strains are large when compared with creep strains, so a plastic yield hypothesis could be assumed and a multidirectional state of stress could be treated as unidirectional stress state (Thomsen, 1992). SAJ and finite element models use non-linear analysis for the adhesive layer.

$$s=C_s(J_2)^{1/2}+C_vI_1 \tag{8}$$

$$C_s=\frac{\sqrt{3}(1+\lambda)}{2\lambda} \tag{9}$$

$$C_v=\frac{\lambda-1}{2\lambda} \tag{10}$$

$$e=C_s\frac{1}{1+\nu}(J_{e2})^{1/2}+C_v\frac{1}{1-2\nu}I_{e1} \tag{11}$$

Where J_2 is the second invariant of the deviatoric tensor, I_1 is the first invariant of the stress tensor, $\lambda=\sigma_c/\sigma_t$ (ratio between compressive and tensile yield stress), J_{e2} is the second invariant of the strain deviatoric tensor and I_{e1} is the first invariant of the strain tensor. This model does not consider any flow law for the plastic surface.

It is important to notice that this work focus in the adherent failure identification, not in the adhesive plasticity.

3. COMPUTATIONAL TOOL

In order to help the assessment of bonded joints a computational tool that is able to calculate the joint loads was developed, displacements, stress and adhesive/adherents stresses.

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 with adherents only. 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.

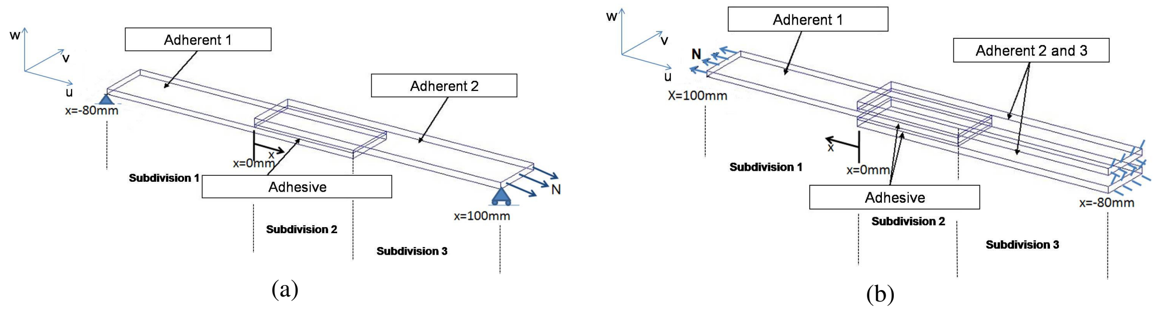


Figure 2: Single lap joint boundary conditions, loads and coordinate system, (b) Double lap joint boundary conditions, loads and coordinate system.

For each region, using the equilibrium equations of an infinitesimal element were obtained the set of differential equations for single and double lap joint. 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.3(a), these equations are for both joint types out of overlap zone. Figure 3(b) shows the equations for adherent 1 only for a double lap case inside the overlap region, and Fig.3(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.

$$\begin{aligned}
&u^i_{0,x} - a_{11}{}^i N_{xx}{}^i - a_{13}{}^i N_{xy}{}^i - b_{11}{}^i M_{xx}{}^i = 0\\
&w_{,x}{}^i + \kappa_x{}^i = 0\\
&\kappa_{x,x}{}^i - b_{11}{}^i N_{xx}{}^i - b_{13}{}^i N_{xy}{}^i - d_{11}{}^i M_{xx}{}^i = 0\\
&v^i_{0,x} - a_{21}{}^i N_{xx}{}^i - a_{23}{}^i - N_{xy}{}^i - b_{21}{}^i - M^i_{xx} = 0\\
&N^i_{xx,x} = 0\\
&N^i_{xy,x} = 0\\
&M^i_{xx,x} - Q^i_x = 0\\
&Q^i_{x,x} = 0
\end{aligned}$$

(a)

$$\begin{aligned}
&u^1_{0,x} - a_{11}{}^1 N_{xx}{}^1 - a_{13}{}^1 N_{xy}{}^1 - b_{11}{}^1 M_{xx}{}^1 = 0\\
&w_{,x}{}^1 + \kappa_x{}^1 = 0\\
&\kappa_{x,x}{}^1 - b_{11}{}^1 N_{xx}{}^1 - b_{13}{}^1 N_{xy}{}^1 - d_{11}{}^1 M_{xx}{}^1 = 0\\
&v^1_{0,x} - a_{21}{}^1 N_{xx}{}^1 - a_{23}{}^1 - N_{xy}{}^1 - b_{21}{}^1 - M^i_{xx} = 0\\
&N^1_{xx,x} + \tau^1_{ax} + \tau^2_{ax} = 0\\
&N^1_{xy,x} + \tau^1_{ay} + \tau^2_{ay} = 0\\
&M^1_{xx,x} - Q^1_x + \tau^1_{ax}\frac{t_1 + t_{a1}}{2} - \tau^2_{ax}\frac{t_1 + t_{a2}}{2} = 0\\
&Q^1_{x,x} - \sigma^1_a + \sigma^2_a = 0
\end{aligned}$$

(b)

$$\begin{aligned}
&u^i_{0,x} - a_{11}{}^i N_{xx}{}^i - a_{13}{}^i N_{xy}{}^i - b_{11}{}^i M_{xx}{}^i = 0\\
&w_{,x}{}^i + \kappa_x{}^i = 0\\
&\kappa_{x,x}{}^i - b_{11}{}^i N_{xx}{}^i - b_{13}{}^i N_{xy}{}^i - d_{11}{}^i M_{xx}{}^i = 0\\
&v^1_{0,x} - a_{21}{}^1 N_{xx}{}^1 - a_{23}{}^1 - N_{xy}{}^1 - b_{21}{}^1 - M^i_{xx} = 0\\
&N^i_{xx,x} + \tau^i_{ax} = 0\\
&N^i_{xy,x} + \tau^i_{ay} = 0\\
&M^i_{xx,x} - Q^i_x + \tau^1_{ax}\frac{t_1 + t_a}{2} = 0\\
&Q^i_{x,x} - \sigma^i_a = 0
\end{aligned}$$

(c)

Figure 3:(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.

The adhesive was simulated as tension/compression and shear springs, Eq. 12 to Eq. 14 shows the equations for the adhesive model.

$$\tau_{ax} = \frac{G_a}{t_a}\left(u^i_0 - \frac{t_i(x)}{2}\cdot \kappa^i_x - u^j_0 - \frac{t_j(x)}{2}\cdot \kappa^j_x \right) \tag{12}$$

$$\tau_{ay} = \frac{G_a}{t_a}\left(v^i_0 - v^j_0\right) \tag{13}$$

$$\sigma_{ax} = \frac{E_a}{t_a}\left(w^i - w^j\right) \tag{14}$$

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

In order to deal with adhesive plasticity, the multidirectional state of stress was treated as simple stress state and a non-linear procedure was used in order to correct the adhesive stress state.

The non-linear procedure was based in the method presents by Thomsen (1992), which consider the compressive tensile stress ratio (λ) and Poisson constant and all time-dependent and temperature-dependent effects were ignored. Figure 5 shows the non-linear procedure used for adhesive, the effective young modulus were calculated by Eq. 15.

$$E_i = \left(1 - \chi \frac{\Delta s_i}{s_i}\right) E_{i-1} \tag{15}$$

Where χ is a non negative factor, $\Delta s_i = s_i^* - s_i$. Figure 4 shows the non-linear schema used for the adhesive layer.

The adhesive non-linear procedure begins obtaining the stress state for each adhesive point using Eq. 8 and comparing with adhesive yield tension (σ_0), if the stress state (s_i^*) is greater than σ_0 than the real stress (experimental stress-strain curve) for the strain is calculated by Eq. 11.

The difference between calculated stress and actual stress (Δs), and the secant modulus were calculated using Eq. 15 for each adhesive point, where plasticity occurs. This procedure repeats until the difference between calculated stress and actual stress is less than an acceptable tolerance.

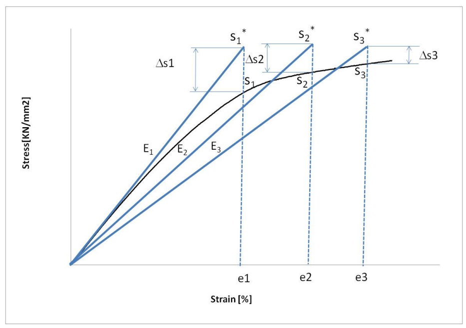
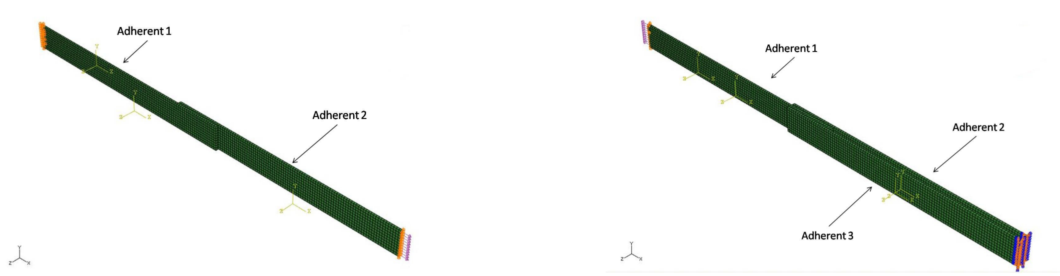


Figure 4: Non-linear procedure.

For composite adherents, SAJ uses Hashin damage criteria for plane stress state, in order to obtain the mode and the load intensity that cause first ply failure, and the analysis stop.

3.2. Finite element model

A finite element model for single and double lap joint using commercial software ABAQUS™ were used to compare to the SAJ computational results. The finite element model uses 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. Due to ABAQUS™ limitations, when using the Hashin failure criteria where only plane stress elements are allowed, the finite element models were made using a 8 node hexahedron continuum shell element (SC8). For the failure study, also the adhesive plasticity was considered.



(a) (b)

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

ABAQUS™ 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. ABAQUS™ user material (UMAT)

An UMAT (User Material Subroutine) is implemented by Fortran language. That allows to program a new constitutive material law and failure criteria. After that, this subroutine is liked to ABAQUS™ in order to simulate a finite element model. In this work, it is implemented Hashin's criteria for tridimensional stress state, which can be used for solid elements like element C3D20 (20 node hexahedron continuum solid element). More details about UMAT implementation can be found at Abaqus Manual (2006)

4. FAILURE ANALYSIS: MEF x SAJ

For the analysis the boundary conditions were the same as showed in Fig. 2(a) for single lap joint and Fig. 2(b) for double lap joint. For all analysis and joints types the overlap length was equal 20.0mm. The adhesive and composite properties are shown in Tab. 1 and 2.

Table 1: Epoxy adhesive and prepreg M10 (Hexcel™).

	Epoxy adhesive	Prepreg M10/38%/200/THR/460
E_{11}	1,485GPa	127 GPa
E_{22}	-	10,0 GPa
υ	0,35	0,306
$G_{12}=G_{31}$	-	5,4 GPa
Thickness	0,5mm	0,2mm

Table 2: Prepreg M10 (Hexcel™) strength values.

Prepreg M10/38%/200/THR/460 strength values	
Lamina tensile strength in fiber direction (X_T)	1400 MPa
Compression lamina strength in fiber direction (X_C)	930 MPa
Lamina tensile strength perpendicular to fiber direction (Y_T)	47 MPa
Lamina compression strength perpendicular to fiber direction (Y_C)	130 MPa
Plane 12 shear strength (S_{12})	53 MPa
Plane 2-3 shear strength (S_{23})	89 MPa

The experimental stress strain curve for adhesive used in SAJ and finite element analysis and the forth order polynomial equation used for SAJ non-linear procedure are show in Fig. 6.

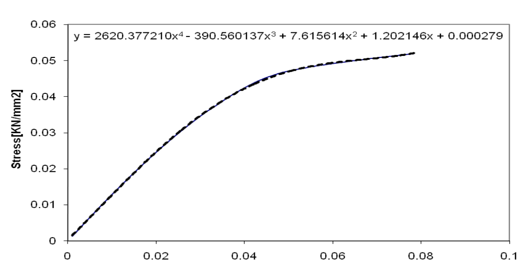


Figure 6: Experimental adhesive stress – strain curve and forth order interpolation equation.

First, a comparison between SAJ and finite element displacement field is showed in Fig. 7 in order to verify SAJ results. Figure 7(a) shows finite element displacement field for a single lap joint, Fig. 7(b) shows the finite element model displacement for a double lap joint. Figure 7(c) shows the displacements comparison between SAJ and finite element for a single lap bonded joint and Fig. 7(d) shows the displacements comparison between SAJ and finite element for a double lap bonded joint.

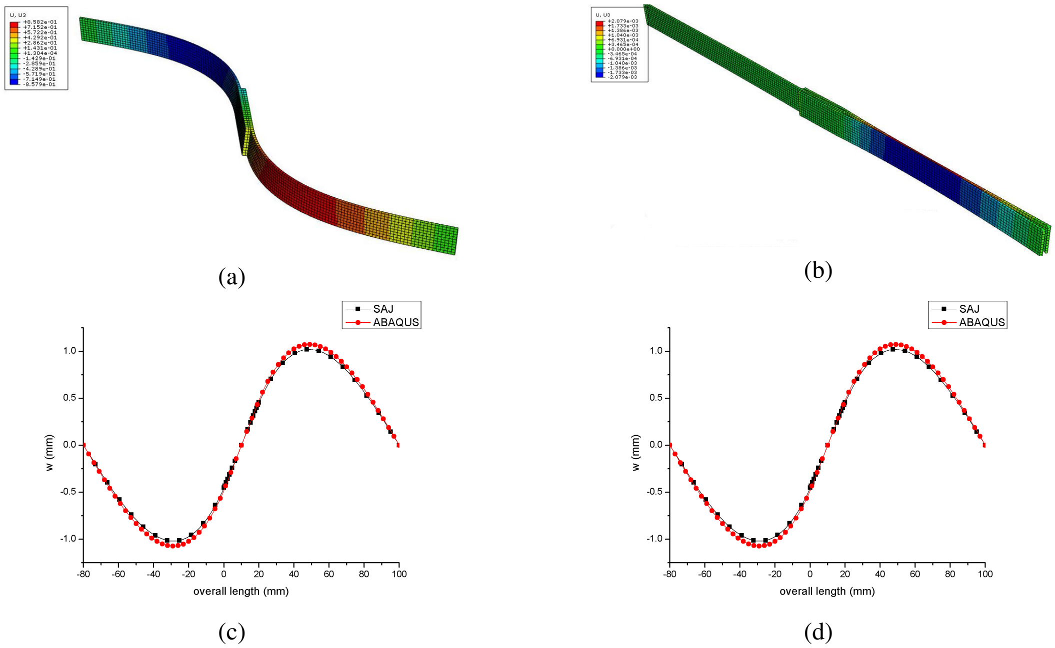


Figure 7: Single lap joint displacement field, finite element (a); Double lap joint displacement field, finite element (b); Displacement comparison between SAJ and ABAQUS™ for single lap bonded joint (c); Displacement comparison between SAJ and ABAQUS™ for double lap bonded joint(d).

After this verification (see more details in Tita, Angelico and Ribeiro 2008 and Ribeiro 2009), the failure analysis were carried out. Different plies orientations were used for this analysis, as well as, symmetric and asymmetric configurations. The same procedure was applied for double lap joints.

Table 3 shows the results for single lap joints and Tab. 4 shows double lap joints results. Regarding in which elements the failure occurs, not considering elements near where load were applied and near boundary conditions.

For single lap bonded joint, a considerable difference between tri-dimensional stress state (ABAQUS – C3D20) and plane stress state (SAJ and ABAQUS – SC8) occurs mostly for symmetric laminates.

Table 3: Single lap bonded joints results.

SINGLE LAP BONDED JOINT

Case	Stack sequence	SAJ	ABAQUS - SC8		ABAQUS - C3D20	
		Failure Load [N/mm]	Failure Load [N/mm]	Difference (Eq.15)	Failure Load [N/mm]	Difference
1	[90/0/90/0]	44	42	4,55%	43	2,33%
2	$[0/90]_s$	149	138	7,38%	63	136,51%
3	$[0/45/90]_s$	178	184	3,37%	78	128,21%
4	[0/30/45/90/45/30]	40	48	20,00%	27	48,15%

For double lap bonded joints, the results (Tab. 4) obtained with plane stress state models and tri-dimensional stress state model are considerably close even for symmetric laminates or asymmetric laminates.

Table 4: Double lap bonded joints results.

DOUBLE LAP BONDED JOINT

Case	Stack sequence	SAJ	ABAQUS - SC8		ABAQUS - C3D20	
		Failure Load [N/mm]	Failure Load [N/mm]	Difference (Eq.15)	Failure Load [N/mm]	Difference
1	[90/0/90/0]	213	170	20,19%	188	11,74%
2	$[0/90]_s$	340	324	4,71%	344	1,18%
3	$[0/45/90]_s$	383	363	5,22%	378	1,31%
4	[0/30/45/90/45/30]	107	105	1,87%	108	0,93%

$$\left| \frac{\left(P_{SAJ} - P_{fem} \right)}{P_{SAJ}} \right| \quad (15)$$

Where P_{SAJ} is the SAJ failure load and P_{fem} is the finite element model failure load.

For all studied cases, the failure mode is due to tensile efforts in the matrix, for plies 90^o oriented.

As showed, a huge difference happens when comparing tridimensional stress state failure loads with plane stress failure loads for single lap bonded joints. These results pointed for the relevance of out-of-plane stresses for composite damage.

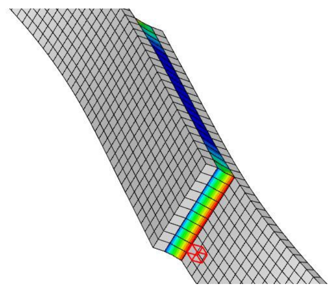


Figure 8: Single lap bonded joint – The failure occurs in the element near to the adhesive edge.

First regarding the single lap bonded joint, the composite failure occurs near the adhesive (Fig.8) for symmetric laminates. In this region the out-of-plane stresses (σ_{33}, τ_{13} e τ_{23}) in the adhesive layer is considerable and that induces a raise of out-of-plane stresses in the adherent, which leads to lower failure loads. For tested asymmetric laminates the failure occurs in regions considerably distant from overlap zone due to a non-zero coupling stiffness matrix, which induces in-plane shear stresses higher than symmetric laminates.

The secondary bending moment, which is higher in single lap joints, leads to lower failure loads for single lap bonded joint as showed in Tab. 3 and Tab. 4. For double lap bonded joints, asymmetric or symmetric adherents, the failure occurs in subdivision 1 (Fig. 2(b), region with only one adherent), which is the more loaded component of the joint.

As pointed, the failure load is ply-orientation dependent. The asymmetric laminates presents the lower first ply failure loads values for single or double lap joints.

Also the first ply failure loads are considerably greater for double lap joints, which point that the displacement field could affect the failure load. These higher loads could be explained by lower secondary bending moments and displacement field.

5. CONCLUSIONS

Concerning plane stress state, SAJ is capable to determine the stresses in each laminate ply and predict the failure mode for laminate adherents both for single and double bonded lap joints. Since the differences between SAJ and ABAQUS™ finite element mode are small, mostly for double lap joints, SAJ is a strategic computational tool to determine the joint stress state.

Meanwhile, when studying single lap bonded joints, the prediction of failure must be conducted carefully using plane stress state. It is desirable to investigate the out-of-plane stresses before proceed with failure analysis, checking the intensity of out-of-plane stresses in order to reduce the errors on predicting the bonded joints behavior.

Due to these results, the authors are already implementing a method that is capable to calculate the out-of-plane stresses in SAJ, as well as Hashin´s failure criteria for tridimensional stress state. The results will be submitted for publishing.

At last, the authors are concerned about delamination, which more detailed studies must be carried out, once the out-of-plane stresses could reach considerable values.

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8. RESPONSIBILITY NOTICE

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