MODELLING OF SLJ BONDED JOINTS WITH DIFFERENT ADHESION DEGREES USING COHESIVE ZONE MODEL

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Abstract. *The aeronautical industry has studied ways to predict damage in structural parts since mechanical tests to numerical simulations. In regards to aircraft structures, special focus is on bonded joints [9], wich currently several researchers have been experts in order to predict the mechanical behavior of this structures. However, there are many difficulties to evaluate their failure modes because there are complex failure mechanisms in adhesion phenomenon. These failure modes can be function of deficient superficial treatments, influence of hydrophobic substances as wax; prescribed damage applying Teflon snips on the bonding region and others. In other words, they have connections with the prebonding. Based on this issue, this work aims the development of a two-dimensional numerical model in Finite Element (FE) [6] of Single Lap Joints (SLJ) specimen using the software Abaqus® [5], considering this specimen as made of composite laminated adherents. Its debonding is simulated by linking of the Cohesive Zone Model (CZM) which use mechanical parameters based on Fracture Mechanics [2]. Two cases were simulated: with and without the contamination influence of release agent on the overlap. Experimental results are used as metric in this study. Finally, it can be verifying the reduction of failure Charge and estimating how much was it.*

1. INTRODUCTION

Bonding phenomena is important in wide engineering fields. Special focus is addicted to the Aeronautical structures due to their large number of constitutive parts. Thus, mechanical tests have been carried out for studying your failure modes considering various types of superficial contaminations.

Based on this issue, several authors have studied this theme which there are many requests from experimental analyses to numerical method approaches. Flor, Medeiros and Tita (2014) [11] analyzed and identified the damage in dissimilar and similar SLJ bonded joints generated applying Teflon snips using vibrations methods and FRF. Finally, FE numerical models were carried out in order to validate the experimental results. Yavas, Shang and Bastawros (2018) [12] explored the effect of environmental contamination (aviation hydraulic fluid) on interfacial toughness and strength in composite laminate bonded joints. For this, several mechanical tests were carried out (DCB, ENF and SLJ tests). Therefore, the Mode I fracture tests presented a significant degradation of Fracture Toughness and strength with increasing of contamination, whilst the Mode II fracture properties presented insensitive to the contamination. The SLJ testing presented contradictory results due the nucleation x propagation of interfacial crack, which it revealed an increasing of the its mechanical properties.

2. DAMAGE PREDICTION IN BONDED JOINTS

Using the Cohesive Zone Model (CZM), failure mechanisms are based on the damage mechanics [5]: D parameter can be defined as triangular (also called linear law) and exponential degradation laws. Figure 1 presents the classical models from Abaqus. In the current study, it was applied the triangular law, presented by Eq. (1). δ_m^0 is the effective displacement for onset damage. δ_m^{max} is the maximum value of effective displacement reached during the loading on the adhesion region. δ_m^f is the effective displacement which generating the failure.

$$D = \frac{\delta_m^f\left(\delta_m^{max} - \delta_m^0\right)}{\delta_m^{max}\left(\delta_m^f - \delta_m^0\right)} \tag{1}$$

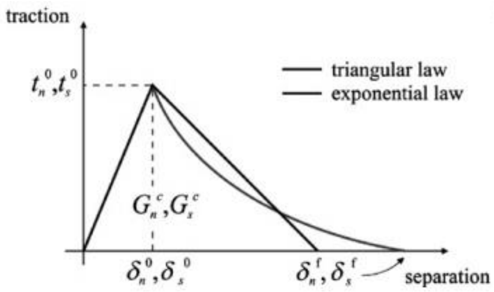

Figure 1 – Abaqus' Classical CZM models [4].

This parameter is introduced on the constitutive equation of tension x deformation (see Eq. (2)):

$$t = (I - D)K\varepsilon \tag{2}$$

Therefore, this equation can be rewritten for two-dimensional case, as follows:

$$\begin{Bmatrix} t_n \\ t_s \end{Bmatrix} = \left(\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} - \begin{bmatrix} D_n & 0 \\ 0 & D_s \end{bmatrix} \right) \begin{bmatrix} K_{nn} & 0 \\ 0 & K_{ss} \end{bmatrix} \begin{Bmatrix} \varepsilon_n \\ \varepsilon_s \end{Bmatrix} \tag{3}$$

Considering a thin adhesive thickness, it can adopt $K_{nn} = E$ and $K_{ss} = G$.

For to reach the traction separation law, the chosen damage initiation is the Quadratic Nominal Stress criterion (QUADS) which consists of three stress components. For to begin the damage, QUADS must reach a value of one. According to Eq. (4), t_n is the component normal to the cracked surface, t_s is the shear component of the cracked surface. Finally, t_n^0 and t_s^0 are the peak values of the nominal stresses [3].

$$f = \left\{ \frac{t_n}{t_n^0} \right\}^2 + \left\{ \frac{t_s}{t_s^0} \right\}^2 \tag{4}$$

On the current study, it was chosen for the crack propagation the power law [10], which it is present by Eq. (5), consists to consider a mixed mode behavior. This criterion is ruled among of the active and peak energy values (G_I, G_{II} and G_{IC}, G_{IIC}, respectively).

$$\left\{\frac{G_I}{G_{IC}}\right\}^{\alpha} + \left\{\frac{G_{II}}{G_{IIC}}\right\}^{\alpha} = 1 \tag{5}$$

The values used of α on the current study was 0.30 and 1.0, being this last one the most common.

3. SLJ TEST MODELLING OF LAMINATED BONDED JOINTS

The informations about mechanical and geometrical aspects are descripts below.

3.1. Geometric and Mechanical Properties

According to Figure 2, both the SLJ specimens and SLJ test features are presented. In regards to the geometric dimensions used, simplifications on the current study defined as follows: length between tips (L_T) is 165 mm, Overlap (L_O) is 25 mm, width (B) is 25 mm, adherent thickness (h) is 2.40 mm, adhesive thickness (t_A) is 0.20 mm. The boundaries conditions chosen applied below of the left adherent are: $u_x = u_y = 0$ mm, and $u_x \neq 0$ and $u_y = 0$ mm applied above the top adherent.

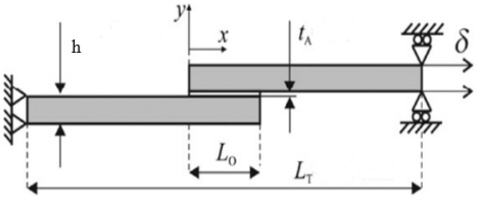

Figure 2 – The SLJ sketch containing geometric dimensions and boundary conditions [4].

Based on these issues of Figure 2, the present study evaluated three configurations of carbon composite SLJ: with and without Contamination in the Conventional configuration (Fig.3), Delamination (Fig. 4) and with and without Contamination in the Overlap region (Fig. 5).

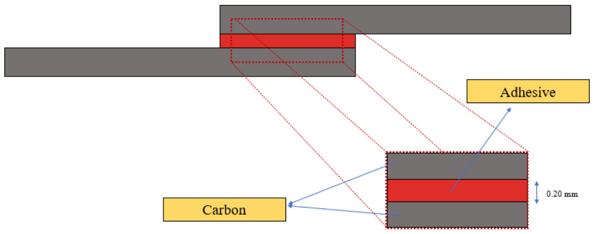

Figure 3 – The SLJ sketch containing informations about adhesive region.

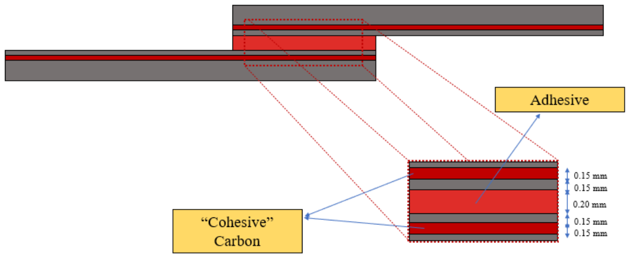

Figure 4 – The SLJ sketch containing geometric informations about adhesive regions (overlap and delamination).

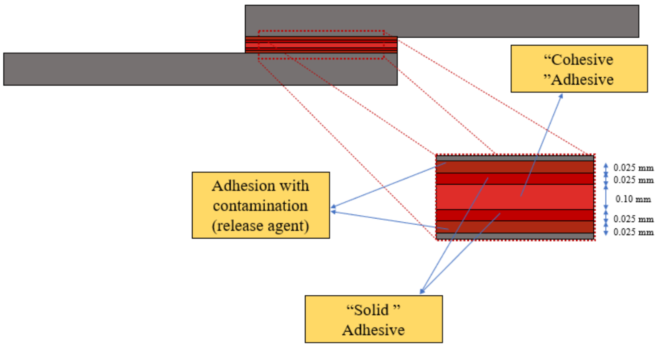

Figure 5 – The SLJ sketch containing geometric informations about cohesive regions between the adhesive and adherents (healthful and contaminated regions of adhesion).

For FE models the SLJ model, it was used the software Abaqus® (2014) [3]. Figure 6 presents geometric features of FE. The cohesive element COH2D4, which has 4-node two-dimensional is used. In the overlap region where are applied the CZM. For the adherents, the element CPE4R, which has 4-node bilinear plane strain quadrilateral, reduced integration hourglass control.

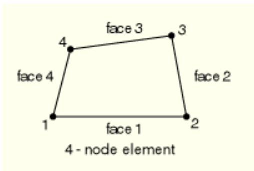

Figure 6 – CPE4R/COH2D4 element [5].

Thereby, the mechanical properties of adherends manufactured of Carbon/Epoxy prepreg (SEAL® Texpreg HS 160 RM). The adherents are carbon laminated composed of 16 plies with fiber orientation of 0 degree ($[0°]_{16}$). In Tab. 1 presents the mechanical properties of adherents and adhesive used on the FE SLJ modelling without contamination of release agent. In Tab. 2 presents the mechanical properties of contaminated adhesive of release agent.

Table 1 – Mechanical properties of Adherents and Adhesive used in the present study.

Mechanical properties	Carbon/Epóxi Prepreg (SEAL® Texipreg HS 160 RM) (Adherents)	Denatite Nagase-ChemteX® XNR6852E-3 (Adhesive)
E_x [GPa]	109.0	-
E_y [GPa]	8.819	-
E_z [GPa)	8.819	-
ν_{xy} [-]	0.342	-
ν_{xz} [-]	0.342	-
ν_{yz} [-]	0.380	-
G_{xy} [GPa]	4.315	-
G_{xz} [GPa]	4.315	-
G_{yz} [GPa]	3.200	-
Young Modulus, E [GPa]	-	1.800**
Shear Modulus, G [GPa]	-	0.665**
Tensile Strength, t_n^0[MPa]	40*	48.50**
Shear Strength, t_s^0 [MPa]	35*	44.90**
Poisson Coefficient, ν [-]	-	0.35**
Critical Release Rate Mode I, G_{IC} [N/mm]	0.59*	9.2**
Critical Release Rate Mode II, G_{IIC} [N/mm]	1.17*	51**

Campilho et al. (11)[3], Araújo (2016) [1] *, Nunes (2018) [8] **.

Table 2 – Mechanical properties of contaminated adhesive used in the present study.

Mechanical properties	Normal	Contaminated (Release Agent)
Tensile Strength, t_n^0 [MPa]	-	11.67
Shear Strength, t_s^0 [MPa]	-	1.12
Critical Release Rate Mode I, G_{IC} [N/mm]	2.346	0.489
Critical Release Rate Mode II, G_{IIC} [N/mm]	-	2.00*

*Obtained from FE modelling numerical calibration.

3.2. Numerical Modelling

According to numerical analyses, three bidimensional numerical models were developed without release agent contamination (see below the Fig. 7, 8 and 9).

Figure 7 is the SLJ modelling without contamination. This model contains 12376 nodes and 11525 elements (11400 of CPE4R and 125 of COH2D4).

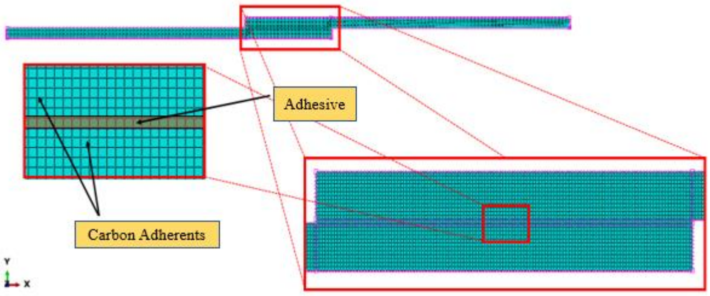

Figure 7 – Modelling of SLJ without contamination of release agent.

Figure 8 presents a model of delamination which it is constituted of 18360 nodes and 17252 elements (15886 of CPE4R and 1366 of COH2D4).

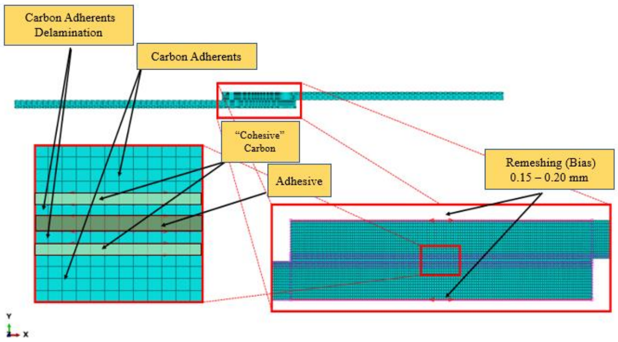

Figure 8 – Modelling of SLJ considering delamination.

Finally, Figure 9 presents the model containing release agent contamination. This model contains 26242 nodes and 25046 elements (23660 of CPE4R and 1386 of COH2D4).

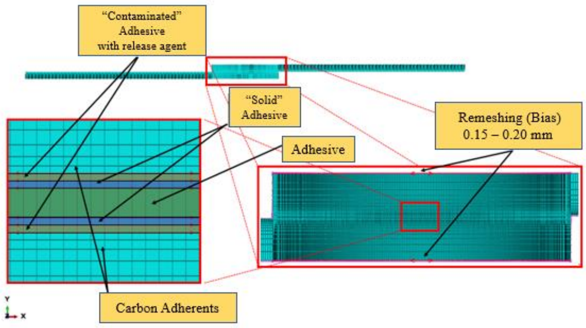

Figure 9 – Modelling of SLJ containing release agent contamination.

4. RESULTS AND DISCUSSIONS

Based on the numerical modelling explanations cited above, they were obtained numerical results. Fig. 10 presents results without contamination and Fig, 11 presents with contamination. Comparing the Curves in both figures, it can see the great difference of the obtained values with and without release agent contamination.

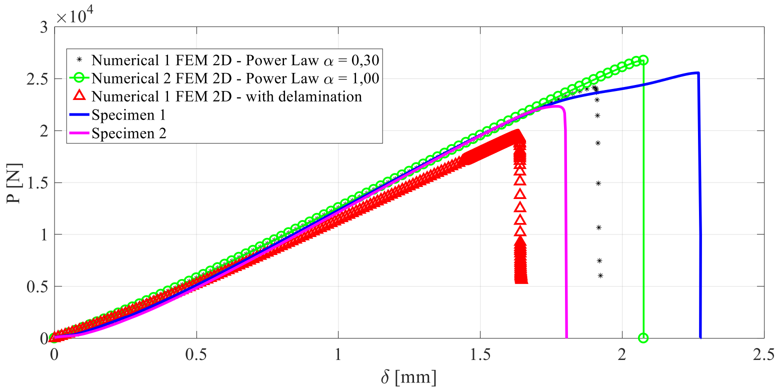

Figure 10 – Numerical and Experimental results of SLJ test without release agent contamination.

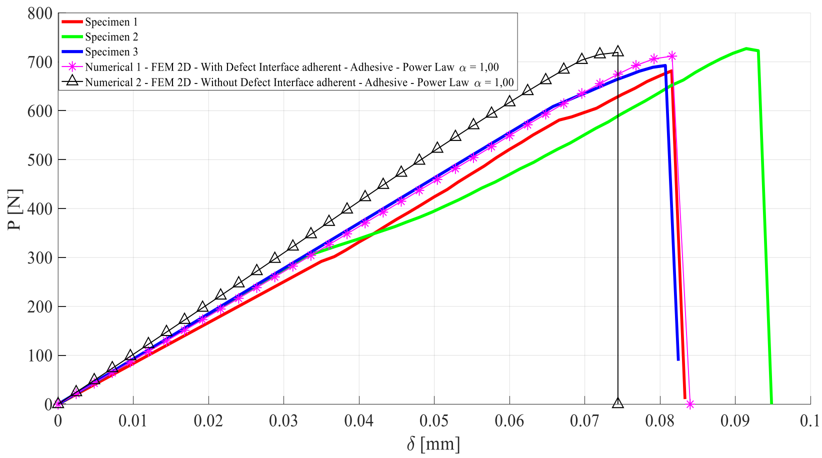

Figure 11 – Numerical and Experimental results of SLJ test with release agent contamination.

Verifying the maximum values of peak forces of the curves from graphics presented above, it can claim the influence of release agent is significative because it reduced the peak force is around of 97.16%.

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REFERENCES

[1] H.A.M. Araújo. *Impact and damping behaviour of Composite Adhesive Joints*. MSc. Thesis in Mechanical Engineering. Faculty of Engineering of University of Porto, FEUP. (2016).
[2] D. Broek. *Elementary Engineering Fracture Mechanics - 3rd Edition*. Martinus Nijhoff Publishers. The Netherlands. (1984).
[3] R.D.S.G. Campilho et al. eXtended Finite Element Method for fracture characterization of adhesive joints in pure mode I. *Computational Materials Science 50*. (2011).
[4] R. D. S. G. Campilho et al. Modelling adhesive joints with Cohesive Zone Models: effect of the cohesive law shape of the adhesive layer. *International Journal of Adhesion and Adhesives v. 44*. (2013).
[5] Dassault Systèmes, Abaqus® 6.14-1 Documentation: Analysis User's Manual. (2014).
[6] J. Fish, T. Belytschko. *A first course in Finite Elements*. John Wiley & Sons Ltd. (2007).
[7] M. F. S. F. Moura, R. D. S. G. Campilho, J. P. M. Gonçalves. Crack equivalent concept applied to the fracture characterization of bonded joints under pure mode I loading. *Composite Science and Technology 68*. (2008).
[8] P.D.P. Nunes. *Impact strength of dissimilar joints for the automotive industry*. MSc. Thesis in Mechanical Engineering. Faculty of Engineering of University of Porto, FEUP. (2018).
[9] L. F. M. Silva, A. G. Magalhães, M. F. S. F. Moura. *Juntas Adesivas Estruturais*. Publindústria Edições Técnicas. (2007).
[10] E.M. Wu, R.C. Reuter Jr. *Crack extension in fiberglass reinforced plastics*. T and M report, University of Illinois (1965).
[11] F.R. Flor, R. Medeiros, V. Tita. Numerical and Experimental Damage Identification in Metal-Composite Bonded Joints. *Journal of Adhesion, v. 91*, p. 863-882 (2014).
[12] D.Yavas, X. Shang, A. Bastawros. Contamination-Induced Degradation/Enhancement of interfacial Toughness and Strength in Polymer-Matrix Composite Interface. *Fracture, Fatigue and Damage Evolution*, v. 7. (2018)

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