CHAPTER 6

Cohesive Zone Impact Analysis of Structural Adhesive Joints

Luís M.C. PERES[1]

Raul D.S.G. CAMPILHO[2]

Ricardo J.B. ROCHA[3]

Isidro J. SÁNCHEZ-ARCE[4]

Raul D.F. MOREIRA[5]

INTRODUCTION

Understand the response of a joint subjected to a dynamic load is currently a hot topic. On the one hand it is known that by using adhesive joints it is likely to obtain an significant benefits on the effect of damping vibrations (Pazand and Nobari 2016). In addition, Chowdhury et al. (2016) reported a decrease of the developed fatigue cracks when using adhesively bonded structures. In this point of view, it is clear the emerge of a strategic

1 Departamento de Engenharia Mecânica, Instituto Superior de Engenharia do Porto, Instituto Politécnico do Porto, R. Dr. António Bernardino de Almeida, 431, 4200-072 Porto, Portugal.

2 Departamento de Engenharia Mecânica, Instituto Superior de Engenharia do Porto, Instituto Politécnico do Porto, R. Dr. António Bernardino de Almeida, 431, 4200-072 Porto, Portugal. INEGI – Pólo FEUP, Rua Dr. Roberto Frias, 400, 4200-465 Porto, Portugal.

3 INEGI – Pólo FEUP, Rua Dr. Roberto Frias, 400, 4200-465 Porto, Portugal.

4 INEGI – Pólo FEUP, Rua Dr. Roberto Frias, 400, 4200-465 Porto, Portugal.

5 INEGI – Pólo FEUP, Rua Dr. Roberto Frias, 400, 4200-465 Porto, Portugal.

opportunity for the transportation industry to enhance their products by applying adhesive joints processes. Actually, the automotive industry already count on adhesive joints to enhance the collision performance (Dlugosch et al. 2017). In fact, adhesives permit the structures to deform, therefore absorbing the impact energy. Single Lap Joint (SLJ) is the most studied adhesive bonded joint due to its geometrical and manufacturing simplicity (Petrie 2007). One of the major drawbacks of this joining process, is the non-collinearity phenomena, leading to a significant peeling stress (σ_y) and therefore causing the premature failure of the bonded joint. This issue can be overcome by using a double lap joint (DLJ) which presents a slighter increase in complexity of the SLJ (Petrie 2007). Nowadays it is a common knowledge the joining area is the most important factor influencing the joints' strength, but with the introduction of geometric changes it is still possible to increase its strength.

Geometric variations can be introduced in the joint design either in terms of material or design modifications, that is as the introduction of thicker adherends to promote a more uniform stress distribution. The design of a joint, considering the area close to the adherends' edges, also affects the peak σ_y and shear (τ_{xy}) stresses and consequently it highly affects the strength of the joint strength. The effect of the local geometry variations at the edges of the overlap of a SLJ was evaluated numerically by Adams and Harris (1987) considering stress distribution and failure prediction. It was concluded that allowing to determine that it is possible to significantly increase the joint strength by inducing a fillet on the adhesive in the edges of the overlap, and also rounding the ends of the adherends. In addition, several studies can be found in the literature, which presents numerical models skilled to predict the strength of adhesively bonded joints, stress distribution and failure, when affected by the variation of geometrical design (Dean et al. 2004, Lavalette et al. 2020, Marchione 2021).

Understanding the behaviour of the joints under impact loads using numerical techniques is of great interest among the academic and industry community. Dynamic models need to take in consideration the inertial effects, that are insignificant when dealing with static analyses. To accurately perform a dynamic numerical simulation, the knowledge of material properties of the adherends and adhesive at the tested strain-rate are required. Zgoul and Crocombe (2004) and Dean et al. (1999) studied two models, a model using an adaptation to the von Mises criterion, and another applying Drucker-Prager model. The former demonstrated to be not effective with hardened adhesives. Cohesive Zone Modelling (CZM) has been implemented with great success for the design of bonded joints. Commercial software solvers demonstrated to have enough accuracy to predict impact failure, as stated by several authors such as May et al. (2014) and Clarke et al. (2013). Araújo et al. (2017) presented an industrial study focused on the impact of adhesively bonded joints in the automotive industry. The research included experimental and numerical comparisons of a novel crash resistant epoxy adhesive used to bond CFRP adherends in a SLJ design. The numerical model was validated with experimental data. The authors noticed an increase in the P_m while increasing the L_O during impact loads. For all tested setups, the proposed numerical models were skilled to accurately capture and predict the behaviour of the SLJ tested under impact loads.

This work studies the effect of L_O and adhesive type on the strength of composite SLJ, under impact load, by performing experimental tests and CZM analysis. Two adhesives with different ductility degrees were tested (Araldite® AV138 and Sikaforce® 7752), by bonding composite adherends with unidirectional lay-up. The joints were subjected to a drop test and validated through the numerical model.

MATERIALS AND METHODS

Materials

Unidirectional carbon pre-preg adherends and two adhesives were used to manufacture SLJs to evaluate the adhesive type effect on the impact response of bonded joints. The adherends were made of unidirectional lay-ups of twenty pre-preg plies of 0.15 mm each from SEAL® (Texipreg HS 160 RM; Legnano, Italy). The stacking sequence was made by hand lay-up. Subsequently cured in a hot-plates press using the manufacturer's curing cycle (temperature of 130 ºC and pressure of 2 bar for one hour, in-between the recommended heating and cooling slopes). The applied adhesives were the Araldite® AV138 (strong but brittle epoxy adhesive with low temperature curing characteristics) and the Sikaforce® 7752 (less strong, however with a high ductility degree polyurethane, Mechanical and fracture properties of the adhesives were determined by performing different tests at 1 and 100 mm/min. On the one hand, tensile tests to the bulk adhesive allowed to obtain the tensile strength (σ_f) and the Young´s Modulus (E). On the other hand, thick-adherend shear tests (TAST) were performed to obtain the shear modulus (G) and shear strength (τ_f). In order to obtain the required fracture properties, the Double-Cantilever Beam (DCB) and End-Notched Flexure (ENF), were used to determine the tensile fracture toughness (G_{IC}) and shear fracture toughness (G_{IIC}), respectively. The outcome of the aforementioned tests at these two test speeds (static and dynamic) is shown in Table 1.

Table 1. Adhesives' mechanical and fracture properties as a function of the test velocity.

Adhesive	Test velocity [mm/min]	t_n^0 [MPa]	t_s^0 [MPa]	G_{IC} [N/mm]	G_{IIC} [N/mm]
AV138	1	41.0	30.2	0.35	0.6
	100	49.1	36.2	-	-
	105000	70.2	51.7	0.35	0.6
7752	1	11.5	10.2	2.36	5.41
	100	18.4	15.7	-	-
	105000	29.9	26.4	2.36	5.41

Geometries and tests

The SLJ design, respective dimensions and boundary conditions are depicted in Fig. 1. General dimensions are: joint length (L_T=200 mm) and joint width (b=15 mm; not shown in the figure), overlap length (L_O=12.5, 25 and 50 mm), adhesive thickness (t_A=0.2 mm), adherend thickness (t_P=3 mm). With respect to the boundary conditions used during numerical analysis, the joint was clamped on the left side and an artificial mass is considered on the right side.

A total of 4 specimens were manufactured and tested for each joint configuration. In order to prepare the specimens for the test setup and since they are fixed on pins, it is necessary to perform a drilling operation at the end of each specimen to create a hole for an M8 pin. Furthermore, it is necessary to glue steel tabs with a 2 mm thickness to reinforce the gripping points, since when subject to impact, the CFRP adherends do not have the appropriate strength and the hole can be teared in the fibres' direction, therefore invalidating the test.

A typical drop test machine was used for the experimental testing. The setup consisted in releasing a 30 kg anvil (from a pre-determined height), which falls freely on the joint, creating the impact load. The test setup is configured so that the weight hits the joint with the desired energy (40 J). Accordingly, the machine drops the weight at a height (h) of approximately 136 mm (determined from the potential energy: $E_P=m.g.h$) which, considering the anvil mass (m) of 30 kg and gravitational acceleration, induces an impact on the joint with a release of kinetic energy (E_c) equivalent to 40 J. $E_c=½mv^2$, where m is the mass and v is the velocity.

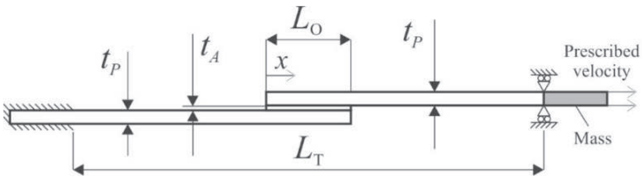

Fig. 1. SLJ architecture and boundary conditions.

Numerical modelling

The numerical work within this study was performed using the commercially available Abaqus® software with explicit solver, capable to perform the necessary dynamic simulations. A triangular CZM law shape was applied to accurately predict the impact response of the experimentally tested joints. A geometrically non-linear two-dimensional (2D) analysis type was applied. COH2D4 cohesive elements were used to capture the behaviour of the adhesive layer and CPE4 solid elements for the adherends. The numerical models were created taking into account a layer of CZM elements with a height identical to the adhesive layer (t_A). Concerning the mesh design, a minimum element size of 0.2 mm was selected, in accordance with the value of t_A, being applied at the overlap edges. Consequently, a mesh roughening was obtained with size grading to achieve a bias effect. Fig. 2 presents the mesh implemented to model the SLJ (overlap details).

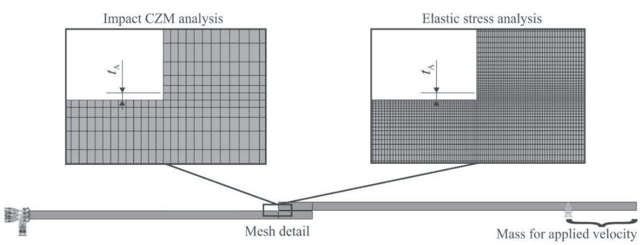

Fig. 2. Detail of the applied mesh in the impact CZM and stress analyses.

In what concerns to the boundaries conditions and impact load to simulate the experimental tests, it is possible to see the clamping of the leftmost edge of the SLJ and the transversely restraining of the right most edge (Fig. 1 and Fig. 2).

The applied impact load involved the application of an impact energy of 40 J to a mass which was artificially placed at the rightmost edge of the joint. By the equation $E_c=½mv^2$, it is possible to adjust the mass volume and density, together with the given velocity, to attain a maximum impact energy of 40 J.

CZM theory

CZM method relies on the linking among stresses and relative displacements linking similar nodes of cohesive elements. Furthermore, those relations (known as CZM laws) may be created in pure and mixed mode and make possible to capture the material's behaviour up to failure. The present study considers triangular pure and mixed-mode laws to model the adhesive layer (Abaqus® 2013).

Under pure-mode loading, damage onset occurs when the cohesive strength in tension or shear (t_n^0 or t_s^0, respectively) is attained, i.e., the material's elastic ceases to exist and degradation begin (Sane et al. 2018). Moreover, the crack proliferates up to the adjacent pair of nodes when the values of current tensile or shear cohesive stresses (t_n or t_s, respectively) become null. Under mixed-mode loading, stress and/or energetic criteria are often used to combine the pure-mode laws, and damage begins when the mixed mode cohesive strength (t_m^0) is reached (Dimitri et al. 2015). Several criteria are suitable for damage initiation and propagation when the analyses involve mixed-mode loadings. This study focused on the quadratic nominal stress criterion and a linear power law form for the damage initiation and growth, in the same order. This approach is described in detail in the work of Rocha and Campilho (2017). The adhesives' properties used in Abaqus® are depicted in Table 1, considering t_n^0 and t_s^0 as the values of σ_f and τ_f, in the same order.

RESULTS

Test data

P-δ curves for the SLJ bonded with the AV138 and L_O=50 mm (a) and bonded with the 7752 and L_O=25 mm (b), are presented in Fig. 3. The oscillatory behaviour that can be noticed before reaching P_m is typical of an impact event and it is caused by the inertial effect induced by the dynamic loading and time-dependent propagation of stress waves, as presented in the work of (Valente et al. 2020). Fig. 4 shoes the average P_m and respective standard deviation for all evaluated joint configurations (including geometry/adhesive). the P_m values of all valid tests for each configuration (type of adhesive and L_O), average P_m, standard deviation (SD), percentile coefficient of variation (CV) and percentile P_m improvement considering the baseline geometry (L_O=12.5 mm), defined as ΔP_m are presented in Table 2. On the one hand, it is possible to observe that for the AV138, the *P*m improvement is not proportional to L_O, even though it can be considered as nearly linear, since the slope between consecutive data points is approximately identical. On the other hand, regarding the 7752, the P_m evolution is considerable different. The P_m-L_O relation is close to proportionality, especially for lower L_O. In addition, the P_m/L_O ratio highly worsens between L_O=25 and 50 mm. It can thus be concluded that the L_O effect on the strength of a SLJ under impact load is more relevant for ductile than with brittle adhesives.

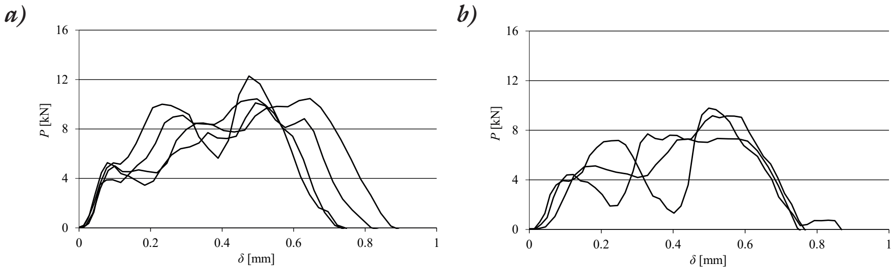

Fig. 3. P-δ curves extracted from impact load on SLJ bonded with the AV138 and L_O=50 mm (a) and bonded with the 7752 and L_O=25 mm (b).

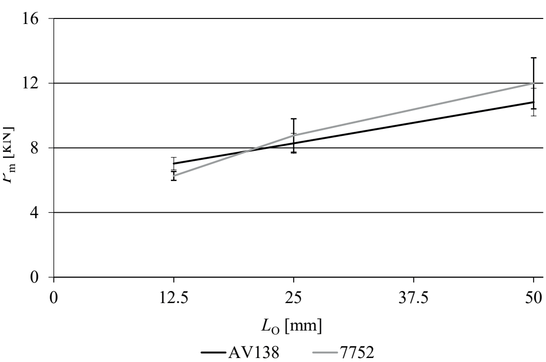

Fig. 4. P_m vs. L_O graph of the impact loaded SLJ bonded with AV138 and 7752.

Table 2. Summary of the experimental results for both adhesives.

		Araldite® AV138			Sikaforce® 7752		
L_O [mm]		12.5	25	50	12.5	25	50
Specimen	1	6.73	-	10.47	6.10	-	-
	2	6.77	8.06	-	-	9.17	10.12
	3	-	-	10.11	-	7.34	13.98
	4	7.58	7.65	12.28	6.65	9.78	11.88
	5	-	9.12	10.43	6.04	-	-
Average P_m [kN]		7.03	8.28	10.82	6.26	8.76	11.99
SD [kN]		0.39	0.62	0.85	0.27	1.04	1.58
CV [%]		5.5	7.5	7.9	4.4	11.9	13.2
ΔP_m [%]		-	17.8	53.9	-	39.9	91.5

Numerical predictions

Experimental and numerical data (P-δ curves) are now compared to validate the proposed impact CZM model in terms of P_m, failure displacement (δ_f) and the shape of the curves. Fig. 5 compares the P-δ curves for the SLJ bonded with the AV138 and an L_O=50 mm (a) and SLJ bonded with the 7752 and an L_O=25 mm (b). One can notice a good correlation between both experimental and numerical data considering the elastic part of the curve (stiffness) until P_m is attained. Nonetheless, the numerical failure displacement is slightly lower than the experimental values.

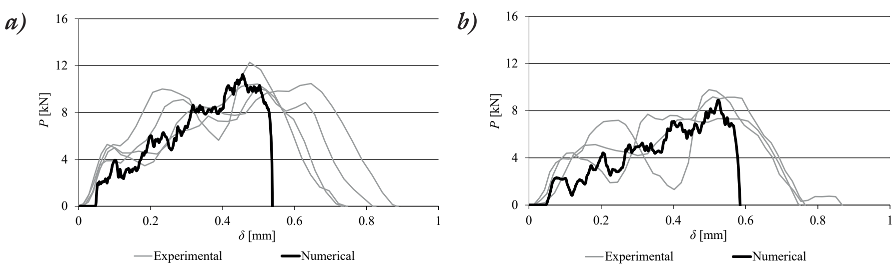

Fig. 5. Experimental and numerical P-δ curves extracted from impact event on SLJ with bonded with the AV138 and L_O=50 mm (a) and SLJ bonded with the 7752 and L_O=25 mm (b).

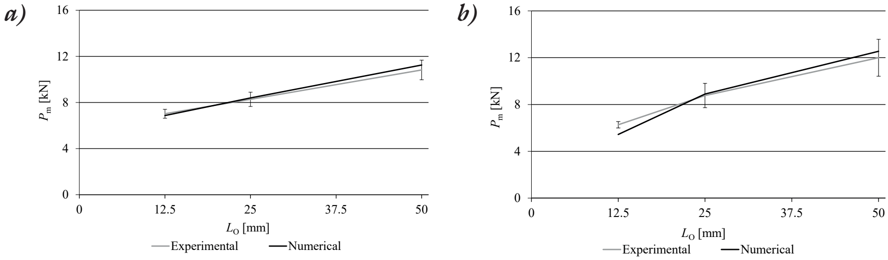

Fig. 6. Experimental and numerical P_m comparison for SLJs with bonded with the AV138 (a) and 7752 (b).

Fig. 6 presents a comparison between P_m data from testing and CZM impact simulations for the joints bonded with the AV138 (a) and 7752 (b) and all tested L_O values. It is clear the excellent correlation depicted in the plot of the AV138 adhesive. Actually, the relative P_m deviations, between tested and simulation data, were between -1.5 and 3.9% for L_O=25 and 50 mm, respectively. Nonetheless, slightly different results were found for the 7752, where relative PM deviations between -13.1 and +1.5% were found for L_O=12.5 and 50 mm, in the same order. The reported deviations occur due the applied CZM law shape (triangular) presents some issues in capturing the high degree of plasticization inherent of this adhesive. Supported by the reported data, the applied CZM impact model can be considered as valid. This methodology revealed to be accurate to model impact behaviour in adhesive joints, allowing the select the best performing design and type of adhesive for under the studied conditions.

CONCLUSION

CZM approach was used to predict the strength of a SLJ subjected to impact loads. To accomplish this objective, two adhesives with distinct ductility were used to bond unidirectional carbon composites adherends in a SLJ architecture. Geometrical effects were considered to evaluate the impact behaviour under different conditions and make available design considerations for this narrowly addressed load. In order to accurately capture the impact event and joint response, the adhesive was characterized at high velocities. Subsequently, the proposed and implemented design was validated with experimental drop weight tests. The experimental outcomes showed that the brittle AV138 was the best perfume solution for the lowest L_O, nonetheless the P_m-L_O evolution was extremely non-proportional. Despite the ductile 7752 presents as the less performing for L_O=12.5 mm, the noticeable P_m improvement for higher L_O, supported by the allowable ductility, allowed it to overcome the performance of the brittle AV138 for the other tested L_O. The coefficients of variations, although acceptable, were higher than usual for static analyses. The CZM approach successfully captured the joint behaviour during impact tests, both on the P-δ curves' shape and P_m, even though failure was sudden soon after reaching P_m, contradictory to the experimental data. The impact adapted CZM technique can be viewed as a suitable and valuable tool for this significant loading case.

REFERENCES

Abaqus® (2013). Documentation of the software Abaqus®. Dassault Systèmes. Vélizy-Villacoublay

Adams, R. and Harris, J., 1987. The influence of local geometry on the strength of adhesive joints. International Journal of Adhesion and Adhesives 7(2), 69-80.

Araújo, H. A. M., Machado, J. J. M., Marques, E. A. S. and da Silva, L. F. M., 2017. Dynamic behaviour of composite adhesive joints for the automotive industry. Composite Structures 171, 549-561.

Chowdhury, N. M., Wang, J., Chiu, W. K. and Chang, P., 2016. Experimental and finite element studies of thin bonded and hybrid carbon fibre double lap joints used in aircraft structures. Composites Part B: Engineering 85, 233-242.

Clarke, M. I., Broughton, J. G., Hutchinson, A. R. and Buckley, M., 2013. Application of the design of experiments procedure to the behaviour of adhesively bonded joints with plastically deformable adherends to enable further understanding of strain rate sensitivity. International Journal of Adhesion and Adhesives 44, 226-231.

Dean, G., Lord, G. and Duncan, B. (1999). Comparison of the measured and predicted performance of adhesive joints under impact. NPL Report Cmmt (A) 206 Appendix 1 Finite Element Analysis Perforated Single-Lap Joint NPL Report Cmmt (A) 206, Citeseer.

Dimitri, R., Trullo, M., De Lorenzis, L. and Zavarise, G., 2015. Coupled cohesive zone models for mixed-mode fracture: A comparative study. Engineering Fracture Mechanics 148, 145-179.

Dlugosch, M., Fritsch, J., Lukaszewicz, D. and Hiermaier, S., 2017. Experimental investigation and evaluation of numerical modeling approaches for hybrid-FRP-steel sections under impact loading for the application in automotive crash-structures. Composite Structures 174, 338-347.

May, M., Voß, H. and Hiermaier, S., 2014. Predictive modeling of damage and failure in adhesively bonded metallic joints using cohesive interface elements. International Journal of Adhesion and Adhesives 49, 7-17.

Pazand, K. and Nobari, A. S., 2016. Identification of the effect of debonding on the linear and nonlinear effective damping of an adhesive joint. Journal of Sound and Vibration 380, 267-278.

Petrie, E. (2007). Handbook of Adhesives and Sealants, McGraw-Hill Education.

Rocha, R. J. B. and Campilho, R. D. S. G., 2017. Evaluation of different modelling conditions in the cohesive zone analysis of single-lap bonded joints. The Journal of Adhesion, in press.

Sane, A. U., Padole, P. M., Manjunatha, C. M., Uddanwadiker, R. V. and Jhunjhunwala, P., 2018. Mixed mode cohesive zone modelling and analysis of adhesively bonded composite T-joint under pull-out load. Journal of the Brazilian Society of Mechanical Sciences and Engineering 40(3), 167.

Valente, J. P. A., Campilho, R. D. S. G., Marques, E. A. S., Machado, J. J. M. and da Silva, L. F. M., 2020. Geometrical optimization of adhesive joints under tensile impact loads using cohesive zone modelling. International Journal of Adhesion and Adhesives 97, 102492.

Zgoul, M. and Crocombe, A. D., 2004. Numerical modelling of lap joints bonded with a rate-dependent adhesive. International journal of adhesion and adhesives 24(4), 355-366.