Transdisciplinary Engineering Methods for Social Innovation of Industry 4.0
M. Peruzzini et al. (Eds.)
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doi:10.3233/978-1-61499-898-3-684

Modelling Stepped-Lap Adhesive Joints by the Extended Finite Element Method

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Abstract. For the joint strength prediction of bonded joints, Fracture Mechanics-based techniques are often used. In this context, the tensile (G_{IC}) and shear toughness (G_{IIC}) are two of the most important parameters to predict the joint behaviour. The Finite Element Method (FEM) has been used for strength prediction in the last decades. Cohesive zone modelling (CZM) coupled to a FEM analysis is generally accepted as an accurate method. More recently, the Extended Finite Element Method (XFEM) has emerged. This work aims to validate the XFEM to predict the behaviour of stepped-lap joints with different overlap lengths (L_O). Three adhesives, Araldite® AV138, Araldite® 2015 and Sikaforce® 7752, whose properties are quite different, were used in the analysis. For the XFEM strength prediction, different damage initiation criteria were used using either stresses or strains. The XFEM was found to be adequate to predict the joint strength using the Quadratic Stress (QUADS) and Maximum Stress (MAXS) damage initiation criteria.

Keywords. Fracture, Finite element analysis, eXtended Finite Element Method, Bonded joint.

Introduction

Adhesive bonding allows the possibility of joining dissimilar materials and preserves the joint integrity while providing more uniform stress distributions along the bonded area. In addition, it enhances the possibility to obtain lightweight and strong structures [1]. Nevertheless, few limitations of bonded joints can be appointed, such as disassembly difficulties, low resistance to humidity and temperature, and joint design orientated towards the elimination of peel stress i.e. the joint should be project so that the in-service loads should stress the adhesive mainly in shear [2]. A number of joint configurations are available offering several choices. Single-lap joints are the easiest to manufacture and probably the most studied joint type, in which the adherends are not collinear, causing significant peel stresses at the overlap end [2]. On the other hand, the stepped-lap joint design is considered one of the most efficient joining method, capable to endure higher loads through the relief of stress concentrations at the overlap ends. Actually, the steps design promotes multiple stress concentrations zones as an alternative of stresses being focussed at the bonded length edges and it allows a gradual

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load transfer from step to step [3, 4]. Despite being lower, those peak stresses still exist, and can be mitigated by changing the geometry (number of steps, edge angle or joint length) [5].

In order to a widespread use of adhesively bonded joints, one should be able to accurately predict the joints' behaviour, evaluating stresses and strains resulting from the submitted loads and predicting the possible points of failure. Finite element analysis models arisen decades ago. Continuum, fracture and damage mechanics are among several tried approaches for strength prediction. Later, Barenblatt [6, 7] in the early sixties developed the cohesive zone model concept describing the crack propagation in perfect brittle materials assuming that finite molecular cohesion forces exist near the crack faces. Subsequently, CZM was improved in order to simulate damage initiation and propagation in adhesive joints and composites. The accuracy of this method requires a truthful evaluation of the cohesive strengths in tension and in shear (t_n^0 and t_s^0, respectively), G_{IC} and G_{IIC}. An innovate FEM development is the XFEM approach that uses damage laws based on the bulk strength of materials to capture damage initiation and strain to assess failure along an arbitrary path, thus overcoming the main restriction of CZM in which damage grows only at predefined paths. Santos and Campilho [8] study consisted of an experimental and numerical study by XFEM for strength prediction of double-lap joints, including three adhesive types ranging from brittle to ductile and different geometries varying L_O from 12.5 to 50 mm. The authors used the embedded XFEM formulation available in software ABAQUS® and tested several crack initiation criteria. The main conclusions included an accurate strength prediction accomplished by the MAXS and QUADS damage initiation criteria compared with the experimental data. On the other hand, the Maximum Strain (MAXE), Quadratic Strain (QUADE), Maximum Principal Stress (MAXPS) and Maximum Principal Strain (MAXPE) criteria reached large deviations.

This work aims to validate the XFEM to predict the behaviour of stepped-lap joints with different L_O values. Three adhesives, Araldite® AV138, Araldite® 2015 and Sikaforce® 7752, whose properties are quite different, were used in the analysis. For the XFEM strength prediction, different damage initiation criteria were used using either stresses or strains.

1. Experimental Work

1.1. Materials used in this work

The adherends were made-up with a ductile aluminium alloy, grade AA6082 T651, chosen for its high strength and wide structural applications. This alloy was previous characterized in the work of Campilho et al. [9] where the most relevant properties were written off as follows: tensile yield stress (σ_y), Young's modulus (E), tensile failure strain (ε_f) and tensile strength (σ_f) with 261.67±7.65 MPa, 70.07±0.83 GPa, 21.70±4.24% and 324±0.16 MPa, respectively. The experimental work included the use of three structural adhesives with different ductility, namely the Araldite® AV138, which is a brittle epoxy adhesive, the Araldite® 2015 (ductile epoxy) and the ductile polyurethane Sikaforce® 7752. The mechanical properties were evaluated in previous works [9, 10]. The tensile mechanical properties E σ_y, σ_f and ε_f were acquired by bulk tests on specimens with dogbone shape. Furthermore, the shear mechanical properties were attained with Thick Adherend Shear Tests. The Double-Cantilever Beam (DCB) and End-Notched Flexure (ENF) tests were applied to assess G_{IC} and G_{IIC}, respectively. In Table 1 it is possible to see all the information about the properties of the three adhesives included in this work.

Table 1. Properties of the adhesives Araldite® AV138, Araldite® 2015 and Sikaforce® 7752 [34, 38].

Property	**AV138**	**2015**	**7752**
Young's modulus, E [GPa]	4.89±0.81	1.85±0.21	0.49±0.09
Poisson's ratio, ν	0.35 [a]	0.33 [a]	0.30 [a]
Tensile yield stress, σ_y [MPa]	36.49±2.47	12.63±0.61	3.24±0.48
Tensile failure strength, σ_f [MPa]	39.45±3.18	21.63±1.61	11.48±0.25
Tensile failure strain, ε_f [%]	1.21±0.10	4.77±0.15	19.18±1.40
Shear modulus, G [GPa]	1.56±0.01	0.56±0.21	0.19±0.01
Shear yield stress, τ_y [MPa]	25.1±0.33	14.6±1.3	5.16±1.14
Shear failure strength, τ_f [MPa]	30.2±0.40	17.9±1.8	10.17±0.64
Shear failure strain, γ_f [%]	7.8±0.7	43.9±3.4	54.82±6.38
G_{IC} [N/mm]	0.20 [b]	0.43±0.02	2.36±0.17
G_{IIC} [N/mm]	0.38 [b]	4.70±0.34	5.41±0.47

[a] manufacturer's data

[b] estimated in Campilho et al. [9]

1.2. Experimental details

The architecture of the stepped-lap joints is depicted in Figure 1. Essentially, the bonded area consists of three steps of equal length. L_O is the only variable geometric parameter (12.5, 25, 37.5 and 50mm). As for the other parameters, they were kept constant and considered as: t_P=3 mm, t_A=t_{A1}=0.2 mm and joint total length between grips L_T=180 mm. Five specimens were produced and tested for each configuration and adhesive, resulting in a total of 60 stepped-lap joints. The tensile tests were performed in a Shimadzu AG-X 100 testing machine with a 100 kN load cell, applying a velocity of 1 mm/min at room temperature. Four valid results were always provided for each joint configuration.

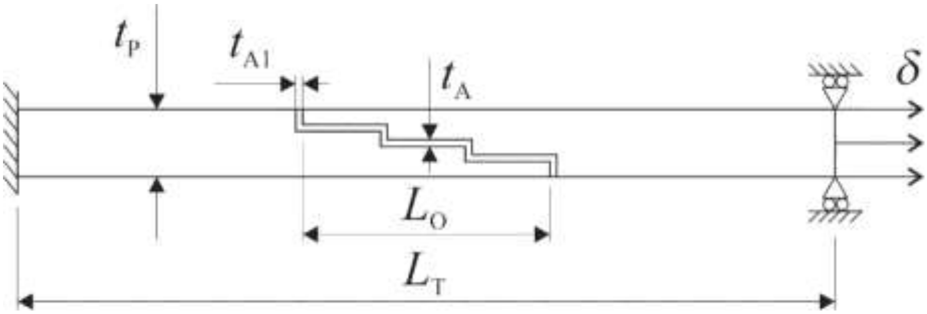

Figure 1. Geometry and dimensions of the stepped-lap joints.

2. Numerical work

2.1. Models' construction

The numerical work was carried out in ABAQUS®, which has an XFEM module that allows for crack growth modelling with this technique, aiming for the strength prediction of the stepped joints. The analyses were run in two-dimensions (2D) considering geometrical non-linearities. In both stress and strength analyses, the adherends were modelled continuum elements with elasto-plastic properties. Solid elements with XFEM enriched formulation were considered. Plane-strain solid elements (CPE4 from ABAQUS®) were used to model the adherends and adhesive layer. In the adhesive layer thickness direction, only one solid element was equated (square elements with 0.2×0.2 mm). Figure 2 gives an example of mesh refinement for the stepped joint model with L_O=50 mm. Element size grading was also considered horizontally from the adherends free edge in the direction of the bonded edge, in order to accomplish a reduction of the computational cost associated to the simulations [11]. The joints were restrained and loaded to best reproduce the experimental tests. Thus, one of the joint edges was fully clamped, while the opposite one was transversely restrained and pulled in tension. The XFEM technique and the different damage initiation criteria are explained next.

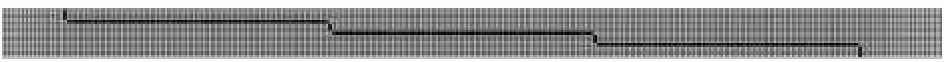

Figure 2. Mesh detail at the bonded region for a model with L_O=50 mm

2.2. XFEM background

As an extension to the conventional FEM, the XFEM is based on the integration of enrichment functions in the FEM formulation [12]. These functions allow modelling the displacement jump between crack faces that occur during the propagation of a crack. The ABAQUS® XFEM formulation enables the user to create a pre-crack or it can initiate cracks in un-cracked regions by using initiation criteria. In this last scenario, considered in this work, damage initiates and subsequently propagates during the simulation at regions experiencing stresses and/or strains greater than the corresponding limiting values. Six crack initiation criteria are available in ABAQUS®. The MAXPS and MAXPE criteria are based on the introduction of the following functions (by the respective order)

$$f=\left\{\frac{\langle\sigma_{\max}\rangle}{\sigma^{\mathrm{o}}_{\max}}\right\} \quad \text{or} \quad f=\left\{\frac{\langle\varepsilon_{\max}\rangle}{\varepsilon^{\mathrm{o}}_{\max}}\right\} \tag{1}$$

$\sigma_{\max}$ and $\sigma^{\mathrm{o}}_{\max}$ represent the current and allowable maximum principal stress. The Macaulay brackets indicate that a purely compressive stress state does not induce damage. $\varepsilon_{\max}$ and $\varepsilon^{\mathrm{o}}_{\max}$ represent the current and allowable maximum principal strain. Crack growth for the MAXPS and MAXPE criteria is software defined as orthogonal to the maximum principal stress/strain direction. The MAXS and MAXE criteria are represented by the following functions, respectively

$$f = \max\left\{\frac{\langle t_n \rangle}{t_n^{\mathrm{o}}}, \frac{t_s}{t_s^{\mathrm{o}}}\right\} \quad \text{or} \quad f = \max\left\{\frac{\langle \varepsilon_n \rangle}{\varepsilon_n^{\mathrm{o}}}, \frac{\varepsilon_s}{\varepsilon_s^{\mathrm{o}}}\right\} \tag{2}$$

t_n and t_s are the current normal and shear traction components to the cracked surface. t_n^0 and t_s^0 represent the respective limiting values. The strain parameters have identical significance. The QUADS and QUADE criteria are based on the introduction of the following functions, respectively

$$f = \left\{\frac{\langle t_n \rangle}{t_n^{\mathrm{o}}}\right\}^2 + \left\{\frac{t_s}{t_s^{\mathrm{o}}}\right\}^2 \quad \text{or} \quad f = \left\{\frac{\langle \varepsilon_n \rangle}{\varepsilon_n^{\mathrm{o}}}\right\}^2 + \left\{\frac{\varepsilon_s}{\varepsilon_s^{\mathrm{o}}}\right\}^2 \tag{3}$$

For the MAXS, MAXE, QUADS and QUADE criteria the user can select between horizontal or vertical crack growth (in this work horizontal growth, i.e., along the adhesive layers' length, was selected). All the six aforementioned criteria are fulfilled, and damage initiates, when f reaches unity. For damage growth, the fundamental expression of the displacement vector **u** is written as [13]

$$\mathbf{u} = \sum_{i=1}^{N} N_i(x)\left[\mathbf{u}_i + H(x)\mathbf{a}_i\right]. \tag{4}$$

$N_i(x)$ and $\mathbf{u}_i$ relate to the conventional Finite Element formulation, corresponding to the nodal shape functions and nodal displacement vector linked to the continuous part of the formulation, respectively. The second term between brackets, $H(x)\mathbf{a}_i$, is only active in the nodes for which any relating shape function is cut by the crack and can be expressed by the product of the nodal enriched degree of freedom vector including the mentioned nodes, $\mathbf{a}_i$, with the associated discontinuous shape function, $H(x)$, across the crack surfaces. The parameters introduced in ABAQUS® were taken from Table 1. A linear softening XFEM law was considered with an energetic failure power law criterion of the following type, where α is the power law parameter (α=1 was considered)

$$\left(\frac{G_{\mathrm{I}}}{G_{\mathrm{IC}}}\right)^{\alpha} + \left(\frac{G_{\mathrm{II}}}{G_{\mathrm{IIC}}}\right)^{\alpha} = 1. \tag{5}$$

3. Results

3.1. Failure modes

In the experimental tests, a cohesive failure on all joints was found. With these results, it can be concluded that the bonding procedure was correctly accomplished. This is a relevant information for the XFEM analysis to the joints, since the XFEM aims to promote crack growth in the adhesive to simulate this failure mode.

3.2. Experimental strength

Figure 3 presents the experimental (average and standard deviation) P_{m} as function of L_{O} for the joints bonded with all tested adhesives.

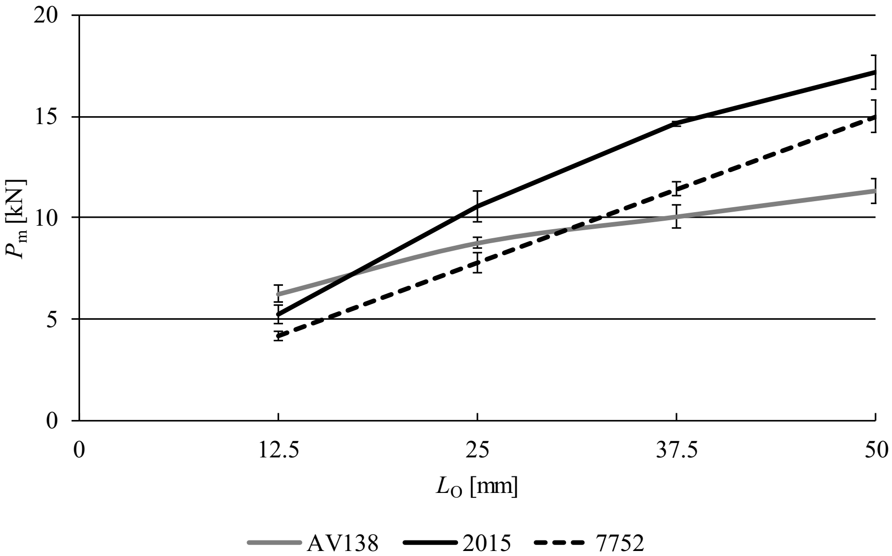

Figure 3. Experimental results of P_m as a function of L_O for the three adhesives

It is clear that P_m is highly dependent on L_O and the chosen adhesive. Actually, regarding L_O, the percentile increases between 12.5 and 50 mm were different, depending on the adhesive: 81.2% for the brittle Araldite® AV138, 227.6% for the intermediate Araldite® 2015 and 259.0% for the ductile Sikaforce® 7752. The smallest improvement for the Araldite® AV138 is due to the inability of this adhesive to deal with the peak stress that typically take place in these joints, because of its marked brittleness. Between adhesives, for L_O=12.5 mm, the brittle Araldite® AV138 is the optimal solution, with an average P_m of 6.2 kN. The other adhesives are offset by defect of 16.1% (Araldite® 2015) and 33.2% (Sikaforce® 7752). However, the behaviour changes drastically by increasing L_O, since bigger L_O is invariably linked to higher peak stresses. Thus, the brittle adhesive loses performance, whilst the other adhesives become better suited. The Araldite® 2015 excels the other adhesives for L_O=25 mm with a P_m of 10.6 kN, with percentile differences of 16.9% for the Araldite® AV138 and 26.2% for the Sikaforce® 7752. Further, increasing L_O shows an identical trend, since the Araldite® 2015 reaches P_m=14.6 kN and the Araldite® 2015 and Sikaforce® 7752 fall short by 22.1% and 31.3%, respectively. The Araldite® 2015 is kept as the best solution for the biggest L_O, of 50 mm, with P_m=17.2 kN. However, the Sikaforce® 7752, due to its high ductility, has a practically proportional relation between P_m and L_O, which permits it to gain ground and, for this L_O, having a difference of only 14.6%. The Araldite® AV138, on the other hand, is offset by 34.0%.

3.3. Numerical results with different initiation criteria

Stress (MAXS, QUADS and MAXPS) and strain (MAXE, QUADE and MAXPE) based damage initiation criteria were tested numerically (XFEM). Since the MAXPE and MAXPS criteria rely on maximum principal stresses and strains, respectively, crack will grow orthogonally to those stresses/strains. The intrinsic formulation of these criteria does not allow modelling such conditions, therefore, P_m is obtained when damage initiation occurs in the adhesive layer.

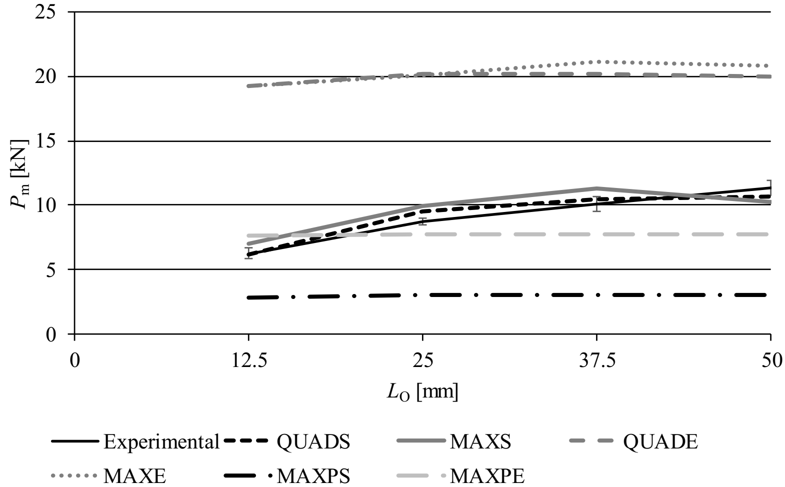

Figure 4. P_m comparison between the experimental data and different damage initiation criteria as a function of L_O for the joints bonded with the adhesive Araldite® AV138

Figure 4 shows the comparative experimental and numerical results of P_m vs. L_O obtained for the adhesive Araldite® AV138. Close results were obtained for both QUADS and MAXS criteria. Actually, the P_m predictions with those criteria showed the highest deviations for L_O=12.5 mm (13% for MAXS and -1% for QUADS). Regarding MAXPS and MAXPE results, they under estimate P_m, attaining the worst XFEM results compared with the experimental ones. The maximum deviations for these criteria were 73% and 31%, respectively, found for L_O=50 mm. On the other hand, both MAXE and QUADE criteria over estimated by a large amount the experimental P_m results, with maximum deviations of 209% considering L_O=12.5 mm.

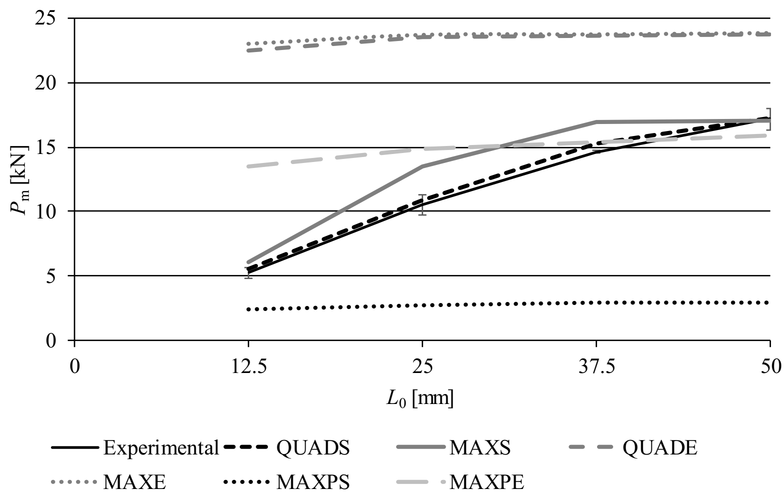

Figure 5. P_m comparison between the experimental data and different damage initiation criteria as a function of L_O for the joints bonded with the adhesive Araldite® 2015

The results for the adhesive Araldite® 2015 are depicted in Figure 5. Among the tested criteria, the QUADS criterion presented the closest results to the experimental ones. Actually, the maximum relative P_m deviation found with this criterion was 7%, for L_O=12.5 mm. Regarding the MAXS criterion, the maximum deviation was 28%, found for L_O=25 mm. Furthermore, both MAXE and QUADE criteria showed a large P_m over prediction, of 338 and 329%, respectively, for L_O=12.5 mm. Applying the MAXPS criterion, P_m was once more under estimated regardless the L_O value, with a maximum deviation of 83% being found for L_O=50 mm. Regarding the MAXPE criterion, the maximum deviation for the experimental P_m was 158% for L_O=12.5 mm.

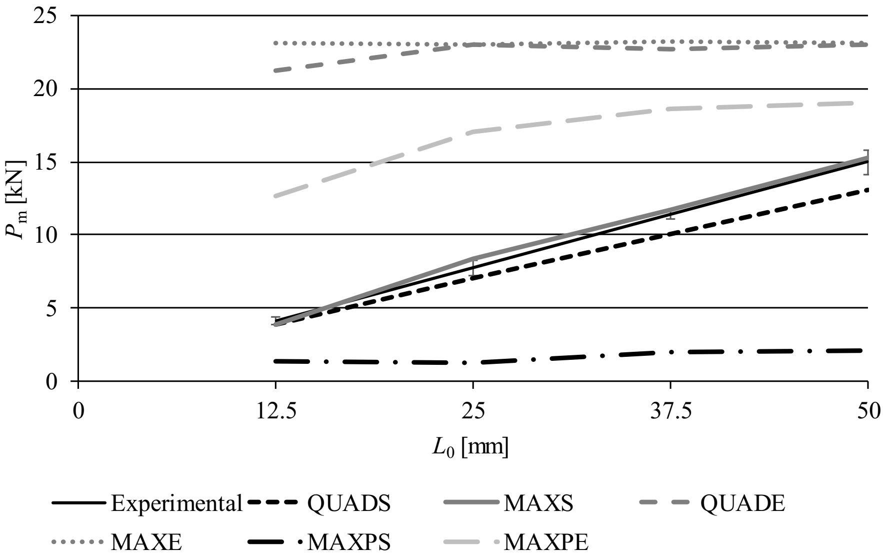

Figure 6. P_m comparison between the experimental data and different damage initiation criteria as a function of L_O for the joints bonded with the adhesive Sikaforce® 7752

Figure 6 presents the comparative XFEM/experimental results for the adhesive Sikaforce® 7752. Close results were attained by the MAXS criterion, since the experimental and MAXS curves are practically overlapped. In fact, the maximum deviation was 7%, found for the joint with L_O=25 mm. For the QUADS criterion, P_m was under estimated with a maximum deviation of 13% (L_O=50 mm). Both MAXE and QUADE criteria failed to predict P_m since they largely overshoot the experimental results. The P_m predictions are identical irrespectively of L_O, giving maximum deviations of 454 and 409%, respectively, found for L_O=12.5 mm. Contrarily, the MAXPS criterion under estimated P_m by a large difference to the experiments, with a maximum deviation of 86%, found for L_O=50 mm. The XFEM predictions with the MAXPE criterion also over estimate P_m by large a large amount, with a maximum difference of 204% (L_O=12.5 mm).

4. Conclusions

This work was intended at validating the XFEM to predict the tensile behavior of stepped-lap joints, as a function of the adhesive type and geometry (L_O).

Experimentally, it was found that P_m of the stepped-lap joints highly varies with the adhesive and L_O. The joints bonded with the Araldite® AV138 showed an abrupt and brittle failure, whilst the other ductile adhesives revealed a more progressive failure. Due to this different failure mode, the plots of P_m-L_O for the Araldite® AV138 show a smaller P_m improvement with L_O. The XFEM analysis consisted of the study of the damage initiation criterion. The MAXS and QUADS damage initiation criteria (stress based) generally worked well in brittle and ductile adhesives, with percentile deviations to the experiments generally below 10%. The other criteria gave results much offset from the real behaviour and, thus, they were considered inadequate to the predict the joints' behaviour. Thus, it was demonstrated that, provided that the modelling conditions are carefully chosen, the XFEM is a powerful tool for the strength prediction of adhesive joints. Compared to CZM modelling, the XFEM excels in not requiring the definition of the failure paths.

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