Three-dimensional numerical analysis of tubular adhesive joints under torsional loads

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Abstract: Bonding method using adhesives has gained a lot of presence in the design of mechanical structures in several industries, especially in the aeronautics and automobile industry. Bonded joints are widely used to join tubular components, in vehicle frames like aeroplanes and automobiles. For the design process of these joints, analytical or numerical predictive techniques can be used. This work performs a numerical study in order to evaluate the torsional performance of aluminium tubular adhesive joints (AW6082-T651), considering the variation of the main geometric parameters, such as overlap length (LO) and tubes’ thickness. In order to predict the strength, the Finite Element Method (FEM) was used with Cohesive Zone Models (CZM), whose analysis based itself on the internal stresses of the adhesive, namely the analysis of shear stress (τxy) and joint strength, measured by the maximum torsional moment (Mm). Previously, validation with experimental data was carried out. The technique was positively validated, and a significant geometry on Mm was found, except for LO.

Keywords: Finite Element Method, Cohesive zone models, Tubular joints, Torsional load.

1. Introduction

Adhesive bonds have benefits such as corrosion resistance, capability to join dissimilar materials and complex geometries, attainment of lighter and stronger structures, improved aesthetics (without bolt heads, rivets or welding beads), high fatigue strength, and more uniform stress fields along the bonded area [1]. However, disassembly is not feasible for most situations, adhesive joints exhibit poor peel strength and sometimes high pressures and temperatures are required to cure [2]. Concerning the large number of joint architectures available, the most typical ones are single-lap joints (SLJ) and double-lap joints (DLJ). Only a small area of development is associated with tubular joints.

It is necessary to provide data regarding the stresses and strains in this type of joint, according to the differentiated behaviour over more common adhesive joints such as SLJ and DLJ. Therefore, it is necessary to implement tools that allow the realization of such analyses. FEM techniques allowed the ability of numerically predicting a bonded joints’ behaviour, disregarding the load conditions, joint geometry or adhesives’ specifications. This method has revealed itself as a very flexible tool, with very high precision that can be used in both simple and more intricate models. The most used modelling technique is CZM, originally introduced by Barenblatt [3] and Dugdale [4]. Lubkin and Reissner [5] extended the study of tubular adhesive joints to the case of axisymmetric modelling, and these authors are considered the first to develop analytical stress studies on tubular joints under axial load. In their
work, the adhesive is an elastic medium, in practice a spring layer, transmitting shear (longitudinal) and peel (radial) efforts. Both stresses are constant over the thickness of the adhesive and are only a function of the axial coordinate. Circumferential shear stresses are not considered because they would imply joint torsion. The numerical and experimental study conducted by Hosseinzadeh et al. [6] aimed to characterize, in a simplified way, the torsional performance of metallic tubular joints connected by structural adhesives, for different $L_o$. The failure threshold of the adhesive, for various joint lengths, was characterized by using the Ramberg–Osgood plasticity model. This plasticity model was fine-tuned through comparison with the results of the FEM simulation, by application of a limited number of known parameters. It was concluded that the developed plasticity model could simulate the joints behaviour with various lengths with good accuracy. The strength capacity of the joint was highly dependent on its absorbed strain energy, i.e., as $L_o$ increased, the joint absorbed more energy, even after the joint went into a completely plastic mode. The numerical study published by Oh [7] predicted the transmission capacity of torsional moments in tubular adhesive joints with composite adherends, combining thermal and mechanical analyses. Three criteria were considered for joint failure: interfacial failure, cohesive failure of the adhesive, and adherend failure. The results were compared with experimental data [8]. It was concluded that both the failure of the adhesive and the adherend occurs at low composite stacking angles, where the influence of residual thermal stresses is insignificant. Joints with high stacking angles fail at the interface between the adhesive and the adhesive due to high residual thermal stresses.

This work performs a numerical study in order to evaluate the torsional performance of aluminium tubular adhesive joints (AW6082-T651), considering the variation of the main geometric parameters, such as $L_o$ and tubes’ thickness. In order to predict the strength, the FEM was used with CZM, whose analysis based itself on the internal stresses of the adhesive, namely the analysis of $\tau_{xy}$ stress and joint strength, measured $M_m$. Previously, validation with experimental data was carried out.

2. Experimental details

2.1. Materials

The material used for the adherends of the tubular joints was an aluminium alloy, namely the high-strength AW6082-T651. This aluminium alloy belongs to the aluminium-magnesium-silicon family (6000 or 6xxx series), which is one of the most popular alloys (together with alloys 6005, 6061 and 6063) [9]. This material was previously characterized by experimentation by the ASTM -E8M-04 standard [10], considering tensile bulk testing. Relevant properties achieved while experimenting were: Young’s modulus ($E$) of 70.07±0.83 GPa, tensile yield stress ($\sigma$) of 261.67±7.65 MPa, tensile strength ($\sigma_f$) of 324±0.16 MPa and tensile failure strain ($\varepsilon_f$) of 21.70±4.24%. To promote the union between the adherends, the adhesive Araldite® 2015 (ductile epoxy) was selected [11]. The adhesive’s mechanical properties were obtained by carrying out dedicated tests in former works [10,12]. All the procedure, from fabrication to testing, followed the 11003-2:2001 ISO standard [13]. Tensile testing of bulk specimens were carried out, under the indications of the NF T 76-142 standard [14], presenting the values of $E$, $\sigma$, $\sigma_l$ and $\sigma_t$. Thick Adherend Shear Tests (TAST) of joints with C45E steel adherends were used in order to establish the shear mechanical properties [12,15]. In this work the required fracture properties in tension and shear needed in the simulations ($G_{IC}$ and $G_{IIC}$, respectively) were obtained from double-cantilever beam [12] and end-notched flexure testing [15], using a suitable method or theory. It should be mentioned that these tests were made under identical geometry and adherend restraining conditions (namely the same adhesive thickness or $t_A$), due to the known $t_A$ effects in these properties [16]. The obtained results can be observed in table 1.

2.2. Geometry, fabrication and testing

Figure 1 presents the generic geometry of the tubular joint addressed in this work. Here are defined the most important dimensions (in mm): $L_o=20$ and 40, adherends’ length between grips $L_S=50$ (for $L_o=20$ and $L_o=40$), joint length between grips $L_T=80$, outer diameter of the inner tube $d_{SI}=20$, outer diameter of the outer tube $d_{SE}=22.4$, thickness of the inner tube $t_{SI}=2$, thickness of the outer tube $t_{SE}=2$ and $t_A=0.2$. 

Table 1. Mechanical and fracture properties of the adhesive Araldite® 2015 [10,12].

| Property                        | 2015       |
|---------------------------------|------------|
| Young’s modulus, $E$ [GPa]      | 1.85±0.21  |
| Poisson’s ratio, $ν$             | 0.33 *     |
| Tensile yield stress, $σ_y$ [MPa] | 12.63±0.61 |
| Tensile strength, $σ_f$ [MPa]   | 21.63±1.61 |
| Tensile failure strain, $ε_f$ [%] | 4.77±0.15  |
| Shear modulus, $G$ [GPa]        | 0.70 b     |
| Shear yield stress, $τ_y$ [MPa]  | 14.6±1.3   |
| Shear strength, $τ_f$ [MPa]     | 17.9±1.8   |
| Shear failure strain, $γ_f$ [%]  | 43.9±3.4   |
| Toughness in tension, $G_{IC}$ [N/mm] | 0.43±0.02 |
| Toughness in shear, $G_{IIC}$ [N/mm] | 4.70±0.34 |

*a* manufacturer’s data  

*b* estimated from the Hooke’s law using $E$ and $ν$

Figure 1. Geometry and characteristic dimensions of the tubular joints.

The adherends were provided as 120 mm-long solid round bars with a diameter just above $d_{SI}$ and $d_{SE}$. The fabrication procedure began by turning the bars in a lathe in order to obtain their final dimensions. The outside dimensions were turned with a carbide turning insert. The longitudinal holes were opened using a carbide drill. The tubes’ edges other than the bonding portions were milled to provide two parallel flat surfaces, allowing the possibility of gripping the specimens in the testing machine. The bonding surfaces were roughened by grit blasting with F60 grade corundum abrasive particles. Following, the roughened surfaces were cleaned with acetone, which later provided a strong bond and produced cohesive failures of the adhesive in all specimens. The accurate $L_Ο$ was attained by measuring the relative position between both adherends with a digital calliper. The tubular joints were then placed in a jig to prevent misalignments between the tubes and left to cure for one week at room temperature (RT). To complete the fabrication process, the adhesive excess resulting from the assembly process was trimmed. Testing was undertaken in an Autograph AG-X machine (Shimadzu), using a 100 kN load cell. The joints were tested at RT with a loading rate of 1 mm/min. For each joint condition, five tests were considered.

3. Numerical details

3.1. FE models

The analysis by the FEM is based on three-dimensional (3D) modelling, using eight-node C3D8 solid elements to model the adherends. For the strength and failure analysis, cohesive elements (COH3D8 of ABAQUS®) are used for the adhesive layer, providing precise results for this type of geometries. On the other hand, for the elastic stress analysis in the adhesive layer, C3D8 solid elements were used, equal to the adherends. The CZM used is the triangular damage model that is available in ABAQUS®.
analyses, the non-linear geometric behaviour was considered. The adherends and adhesive were initially modelled as one part, which was then divided into partitions, followed by material assignment. The boundary conditions applied to the adhesive joint are intended to emulate a torsion loading at one end of joint, whilst the other end is clamped. To apply the torsion load, a reference point was created in the middle of the tube and it was connected to the cross-sectional face at one joint end, which allowed to apply a torsional angle boundary condition and thus perform the tests.

The joint meshes were built after defining the mesh sizes in each edge of the model. The areas where the largest stress gradients occur should be as refined as possible. Thus, the mesh is more refined at the overlap region (where the two tubes are joined by adhesive) and at the vicinity, as observed in figure 2 for the strength analysis, when compared to the adhesive-free portions of the adherends. Due to the need to obtain high precision in the computed stresses and strains, bias ratio was applied to the chosen refinement, to ensure maximum refinement at the overlap edges. In the adhesive-free portions of the model (1 and 3 in figure 2) the element size varied from 0.2 mm (near the overlap edges) and 3 mm (at the other edge), using a single-bias effect, i.e., grading in the direction of the overlap. In the overlap portion (2 in figure 2), double-bias was applied, i.e., towards both overlap edges, with a minimum size of 0.2 mm and maximum size of 1 mm. Through-thickness, single-bias was applied with higher refinement near the adhesive layer, with element sizes between 0.2 and 1.5 mm. The mesh used in the stress analysis test is much more refined than the mesh used for strength analysis, to capture the high-stress gradients in the adhesive. Thus, the formerly mentioned element sizes for the strength analysis were divided by four to achieve a higher precision in the elastic stress fields.

**Figure 2.** Example of mesh refinement.

### 3.2. Triangular model

CZM are based on relationships between stresses and relative displacements connecting homologous nodes of the cohesive elements, usually addressed as CZM laws. These laws simulate the elastic behaviour up to a peak load and subsequent softening, to model the gradual degradation of material properties up to complete failure. The areas under the traction-separation laws in tension or shear are equalled to $G_{IC}$ or $G_{IIC}$, respectively. Under pure mode, failure between homologous CZM nodes (connecting the two tubes orthogonally to the adhesive length) and respective damage propagation occur when the stresses are released in the respective traction-separation law. Under mixed mode, energetic criteria are often used to combine tension and shear \[17\]. In this work, triangular pure and mixed-mode laws were considered. The elastic behaviour of the cohesive elements up to the tipping tractions is defined by an elastic constitutive matrix relating stresses and strains across the interface, containing $E$ and the Poisson’s ratio (\(\nu\)) as main parameters. In this work, the quadratic nominal stress criterion was considered for the initiation of damage \[11\]. After the cohesive strength in mixed-mode ($t_m^0$) is attained, the material stiffness is degraded. Complete separation is predicted by a linear power law form of the required energies for failure in the pure modes. For full details of the presented model, the reader can refer to reference \[10\]. The relevant CZM parameters used in this work were taken from table 1.

### 4. Validation with experiments

This Section aims to present the experimental results of the validation study, i.e., tubular joints under tensile loads, and respective comparison with the numerical CZM predictions, to substantiate the numerical torsional analysis that follows and is presented in Section 5. All numerical conditions were
identical to those previously described, except for the applied load, consisting of a pure tensile load instead of the torsional load at one of the joint’s edges. It was also possible to construct the models as two-dimensional (2D) axisymmetric, which is not possible in the models of this work due to the torsional load. Thus, the considered element types were CPE4 (plane-strain) for the adherends and, for the adhesive, either CPE4 (stress analysis) or COH2D4 cohesive elements (strength analysis).

4.1. Experimental failure modes
Visual inspection of the fractured joints revealed that all failures were cohesive in the adhesive layer. Figure 3 depicts example failures for the joints bonded with the Araldite® 2015 and \( L_O=20 \) figure 3(a) and 40 mm figure 3(b). Thus, in the numerical models, only this failure mode will be equated, as described previously.

4.2. Experimental-numerical \( P_m \) comparison
This section aims to assess the validity of the numerical maximum load (\( P_m \)) results, by the comparison with experimental results. Figure 4 presents the experimental and numerical \( P_m \) vs. \( L_O \) for the tubular joints bonded with the Araldite® 2015, including the standard deviation. The numerical strength predictions are in close agreement with the values obtained experimentally. For \( L_O=20 \) mm, a 6.1% difference was found between the average of the experimental results and the numerical one. The difference between is even smaller for \( L_O=40 \) mm, since it is approximately 2.9%. Despite the small differences observed, which are acceptable in view of experimental processes, the values obtained by the CZM predictions are considered as adequate.

5. Numerical torsional analysis

5.1. Stress analysis
\( \tau_{xy} \) stresses at the adhesive layer mid-thickness are analysed. Since this study relates to a pure torsional loading, \( \sigma_y \) stresses are nil. Figure 5 presents \( \tau_{xy}/\tau_{avg} \), in which \( \tau_{avg} \) is the average \( \tau_{xy} \) along the adhesive.
layer for the respective \( L_O \), as a function of \( L_O \). \( \tau_{xy} \) stress distributions show reduced values at the central overlap region, peaking at the overlap ends. Actually, at the inner overlap, the shear-lag effects are cancelled, leading to a smaller magnitude of stresses [18,19]. The \( \tau_{xy} \) stresses increase with \( L_O \) is due to the increasing gradient of longitudinal strains in the adherends, caused by the larger bonded areas and applied loads. However, as the Araldite\textsuperscript{\textregistered} 2015 is a ductile adhesive, it is possible to suffer moderate plasticization and partially absorb these peak stresses. There is a clear distinction between stress peaks, where the \( \tau_{xy} \) shear stresses near \( x/L_O=1 \) is much higher than the opposite one. This difference arises due to the different cross-sectional areas of both tubes.

![Figure 5. \( \tau_{xy}/\tau_{avg} \) stresses in the adhesive layer as a function of \( L_O \).](image)

Figure 6 shows \( \tau_{xy}/\tau_{avg} \) stresses in the adhesive layer depending on the adherends’ thickness: \( L_O=20 \) mm and variation of \( t_{SI} \) (a), \( L_O=20 \) mm and variation of \( t_{SE} \) (b), \( L_O=40 \) mm and variation of \( t_{SI} \) (c) and \( L_O=40 \) mm and variation of \( t_{SE} \) (d). All curves have a similar shape, peaking at the overlap edges, and the aforementioned \( L_O \) effect is visible in both \( t_{SI} \) (figure 6(a) and figure 6(c)) and \( t_{SE} \) plots (figure 6(b) and figure 6(d)). For both \( L_O \), changing \( t_{SI} \) mainly affects \( \tau_{xy} \) peak stresses near \( x/L_O=0 \), due to changes in the axial stiffness of the inner tube, in the sense that reducing \( t_{SI} \) highly increases stresses and vice-
versa. $\tau_{xy/\tau_{avg}}$ peak stresses at $x/L_O=0$ increased from 3.40 ($t_{SI}=1$ mm) to 6.57 ($t_{SI}=5$ mm) for $L_O=20$ mm. These values increased to 6.78 and 13.07, respectively, for $L_O=40$ mm. On the other hand, varying $t_{SE}$ resulted in a major modification of $\tau_{xy/\tau_{avg}}$ peak stresses near $x/L_O=1$, caused by the marked variation of the outer tube’s thickness. Considering the tubular joints with $L_O=20$ mm, the $t_{SI}$ change caused $\tau_{xy/\tau_{avg}}$ peak stresses at $x/L_O=1$ to change from 0.78 (1 mm) to 4.66 (5 mm). These numbers increased to 1.49 and 9.32 for $L_O=40$ mm, by the same order.

5.2. Strength prediction

For the strength prediction, the parameter to be controlled is $M_m$, which indicates the value of the maximum torsional moment sustained in the numerical simulation at the clamped edge. Failure always took place cohesively in the adhesive layer, but sometimes induced by excessive shear plastic straining in the adherends, nearby to the overlap edges. Figure 7 shows the evolution of $M_m$ by the CZM analysis in ABAQUS®, for both $t_{SI}$ and $t_{SE}$, and dividing the results by $L_O=20$ figure 7(a) and 40 mm figure 7(b).

![Figure 7. $M_m$ as a function of $t_{SI}$ and $t_{SE}$, for: (a) $L_O=20$. (b) 40 mm.](image)

The base value for $t_{SI}$ and $t_{SE}$, i.e., when the respective modification is not accomplished, is always 2 mm. Compared to the base geometry ($t_{SI}=t_{SE}=2$ mm), for $L_O=20$ mm (figure 7(a)), a significant $t_{SI}$ effect was found, with a relative reduction of $M_m$ of 45.6% for $t_{SI}=1$ mm and a gradual improvement up to 48.3% for $t_{SI}=5$ mm. On the other hand, a smaller $t_{SI}$ was found, with major $M_m$ reduction for $t_{SE}=1$ mm (33.9%), but virtually no improvement for $t_{SE}>2$ mm. This behaviour was due to failure in the adhesive layer disregarding $t_{SE}$, thus making further improvements in this parameter irrelevant. Actually, starting from $t_{SE}=2$ mm, excessive plastic strain takes place in the inner tube close to the overlap end at $x/L_O=0$, triggering premature failure of the adhesive layer and cancelling any benefit possibly arising from higher $t_{SE}$. These results generally confirm the stress analysis carried out in the previous section, which showed that bigger $t_{SI}$ and/or $t_{SE}$ are associated to lower peak stresses and, thus, higher $M_m$ are allowed. Since this adhesive has an acceptable ductility, it can moderately absorb peak stresses, but overall smaller peaks always lead to a higher average stress at the instant of $M_m$. The results for $L_O=40$ mm (figure 7(b)) show an identical trend to $L_O=20$ mm, although with marginally higher $M_m$. Actually, compared to $t_{SI}=t_{SE}=2$ mm, $t_{SI}=1$ mm reduces $M_m$ by 44.4%, while $t_{SI}=5$ mm increases it by 51.2%. On the other hand, $t_{SE}=1$ mm diminishes $M_m$ by 29.8%, while no visible increases take place for $t_{SE}>2$ mm. Compared to $L_O=20$ mm, the maximum $M_m$ improvement was 7.1%, obtained for $t_{SI}=2$ mm and $t_{SE}=1$ mm. This short improvement is related to the degradation of $\tau_{xy}$ peak stresses by increasing $L_O$, as shown in figure 6, thus triggering premature failure at the overlap edges.

6. Conclusions

This work studied the torsional behaviour of aluminium tubular joints by CZM. Initially, validation with experimental data a different loading type was undertaken, showing good results. In the numerical work of torsional joints, 3D models were constructed to accurately simulate the torsion effect between tubes. The $\tau_{xy}$ stress analysis showed a marked difference between $L_O=20$ and 40 mm, with the latter case showing more concentrated peak stresses at the overlap edges. A significant $t_{SI}$ and $t_{SE}$ effect was also
detected, with higher values of these two parameters leading to smaller $\tau_{xy}$ peak stresses. These differences then reflected on $M_m$, in the sense that higher $t_{SI}$ and $t_{SE}$ yielded higher $M_m$, but $t_{SE} > 2$ mm was ineffective due to inner tube yielding leading to premature failure in the adhesive layer. In the end, recommendations are given for the design of tubular joints under torsion, which can be valuable in the mechanical design of structures with these joints.

References

[1] Adams R D 2005 Adhesive bonding: science, technology and applications (Amsterdam, Netherlands: Elsevier)
[2] da Silva L F M and Öchsner A 2008 Modeling of adhesively bonded joints (Heidelberg, Germany: Springer)
[3] Barenblatt G I 1959 The formation of equilibrium cracks during brittle fracture. General ideas and hypothesis. Axisymmetrical cracks Journal of Applied Mathematics and Mechanics 23 pp 622–636
[4] Dugdale D S 1960 Yielding of steel sheets containing slits Journal of the Mechanics and Physics of Solids 8 pp 100–104
[5] Lubkin J L and Reissner E 1956 Stress distribution and design data for adhesive lap joints between circular tubes Journal of Applied Mechanics 78 pp 1213–1221
[6] Hosseinzadeh R, Shahin K and Taheri F 2007 A simple approach for characterizing the performance of metallic tubular adhesively-bonded joints under torsion loading Journal of Adhesion Science and Technology 21 pp 1613–1631
[7] Oh J H 2007 Strength prediction of tubular composite adhesive joints under torsion Composites science and technology 67 pp 1340–1347
[8] Choi J K and Lee D G 1995 Torque transmission capabilities of bonded polygonal lap joints for carbon fiber epoxy composites The Journal of Adhesion 48 pp 235–250
[9] Avallone E A, Baumeister III T and Sadehg A 2007 Marks’ standard handbook for mechanical engineers (New-York, USA: McGraw-Hill Education)
[10] Campilho R D S G, Banea M D, Pinto A M G, da Silva L F M and de Jesus A M P 2011 Strength prediction of single- and double-lap joints by standard and extended finite element modelling International Journal of Adhesion and Adhesives 31 pp 363–372
[11] Nunes S L S, Campilho R D S G, da Silva F J G, de Sousa C C R G, Fernandes T A B, Banea M D and da Silva L F M 2016 Comparative failure assessment of single and double-lap joints with varying adhesive systems The Journal of Adhesion 92 pp 610–634
[12] Campilho R D S G, Banea M D, Neto J A B P and da Silva L F M 2013 Modelling adhesive joints with cohesive zone models: effect of the cohesive law shape of the adhesive layer International Journal of Adhesion and Adhesives 44 pp 48–56
[13] International Organization for Standardization ISO 11003-2:2001 Standard. Adhesives - Determination of shear behaviour of structural adhesives -- Part 2: Tensile test method using thick adherends
[14] Association française de Normalisation (AFNOR) 1988 NF T 76-142 Standard. Méthode de préparation de plaques d’adhésifs structuraux pour la réalisation d’éprouvettes d’essai de caractérisation
[15] Faneco T, Campilho R, Silva F and Lopes R 2017 Strength and fracture characterization of a novel polyurethane adhesive for the automotive industry Journal of Testing and Evaluation 45 pp 398–407
[16] Ji G, Ouyang Z, Li G, Ibekwe S and Pang S-S 2010 Effects of adhesive thickness on global and local Mode-I interfacial fracture of bonded joints International Journal of Solids and Structures 47 pp 2445–2458
[17] Kim K 2015 Softening behaviour modelling of aluminium alloy 6082 using a non-linear cohesive zone law Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials Design and Applications 229 pp 431–435
[18] Luo Q and Tong L 2007 Fully-coupled nonlinear analysis of single lap adhesive joints

International Journal of Solids and Structures 44 pp 2349–2370

[19] Vable M and Maddi J R 2006 Boundary element analysis of adhesively bonded joints

International journal of adhesion and adhesives 26 pp 133–144