CARBON FIBER-REINFORCED POLYMER PULTRUSIONS ADHESIVELY BONDED INSIDE ALUMINUM JOINTS: EXPERIMENTAL AND NUMERICAL STUDY

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Abstract
In the context of lightweight structure design for the transportation and robotics industries, new types of composite structures are being developed, in the form of trusses made of fiber-reinforced polymer composite members of small diameter. The main objective of this work is to study adhesive joints, bonding pultruded composite tubes inside aluminum pieces, numerically and experimentally. More specifically, the objective is to determine which numerical model is able to predict the joint strength the most accurately, and to examine the influence of several design parameters on the strength and weight of the joints. With this purpose, samples are manufactured with varying dimensions, and tested in tension until failure. Next to the manufacturing numerical models using either a continuum mechanics or a damage mechanics (CZM) approach are built. The comparison of the numerical results with the experimental results show that the damage mechanics approach results in the most accurate joint strength predictions. It is also found that increasing the adhesive overlap length has the highest impact on increasing the joint strength, and that reducing the adherend thickness has the highest impact on reducing the structural weight, while preserving the joint strength.

1. Introduction

In transportation engineering, and particularly in aerospace and automotive engineering, reducing the weight of structures is one of the primary concerns. The manufacturing of complex composite truss structures, combining the high longitudinal tensile strength of fiber-reinforced composite materials and the truss structures particularity of having their members loaded axially, has been a subject of interest in recent years. Some concepts of filament wound trusses can be found in the works of Weaver & Jensen [1] and Woods et al. [2], to cite a few. These examples result in generic truss geometries, limiting their range of applications. In order to be able to realize trusses of any shape, enabling any kind of application, individual truss members must be joined together.

The present work stands in this context, aiming at studying joints for such structures in order to obtain a design that is strong and light at the same time. Given the relatively small size of the intended trusses, with members that are a few millimeters thick at most, adhesive bonding is the preferred joining solution. Previous work has shown that simply joining two members with adhesive leads to a very weak joint [3], since the adhesive is loaded in tension. Several designs forcing the adhesive to be loaded in shear exclusively, by bonding the members at the truss nodes to an aluminum piece, were then proposed and analyzed numerically to have their performances compared [4]. The current joint solution, a round-based tubular carbon fiber-reinforced polymer pultruded member bonded inside an aluminum piece, is further studied in this work. The joint strengths found through experimental results are compared with those predicted by different numerical models, in order to determine the most accurate joint strength prediction strategy.

Samples and numerical simulations are made for several design parameter values to examine the influence of each parameter on the strength and weight of the joint. Those parameters are: the adhesive overlap length, the joint strength expected to be proportional to it [5]; the adhesive thickness and the adherend thickness. Additionally, the diameter of the members is also varied, to verify whether the efficiency of the joint design can be independent of the member diameter, which would make the future structural design of the trusses more straightforward to optimize. The samples are bonded using a ductile adhesive, Araldite 2015 [6], and are tested in tension. Two types of numerical models are built using the software Abaqus. The first model uses a continuum mechanics approach only. The second model is also based on continuum mechanics, and adds a damage mechanics component with Cohesive Zone Modelling (CZM). Although both models are based on continuum mechanics, in the present work they are referred to respectively as "continuum mechanics approach" and "damage mechanics approach".

2. Experimental work

The joint geometry and dimensions are presented in Figure 1. The reference parameters are L_o = 10mm, t_a = 0.2mm, t_j = 6mm and d_{out} = 3mm. To study the influence of each parameter on the joint strength, samples were fabricated for varying parameters, with in each case the non-varying ones corresponding to the reference ones. The flowing values were considered: for the overlap length L_o = 5, 10, 15 and 20mm; for the adhesive thickness t_a = 0.1, 0.2, 0.3 and 0.4mm; for the adherend thickness t_j = 2, 4, 6 and 8mm; for the member's outer diameter d_{out} = 2, 3, 4 and 5mm.

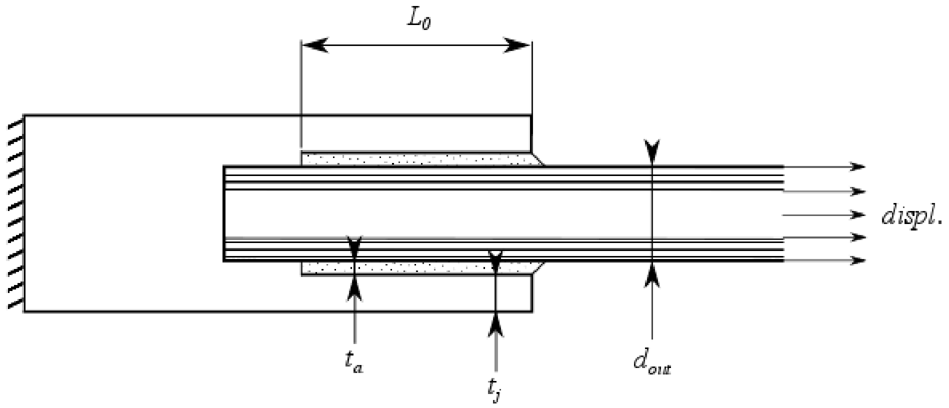

Figure 1. Geometry and dimensions of the adhesive joint.

It is important to note that in this study only the dimensions of the joints are considered as parameters for the strength of joint. It is assumed that for the same dimensions, other materials for the adhesive and adherends can lead to a stronger joint, but finding them is not the goal of this study. Therefore, readily available materials were used to manufacture the joints. The members are pultruded carbon fiber-reinforced polymer tubes with a fiber-volume fraction of 63% [7], cut to a length varying according to the different overlap lengths tested. The adhesive used to join the adherend is Araldite 2015 [6]. The joint pieces are made of aluminum 6082-T6. In addition to the hole drilled for the adhesive overlap, a hole with a depth of 2mm and a diameter equal to the diameter of the member is drilled at the bottom of the overlap. Its purpose is to center the member internally within the joint piece, in order to have a consistent adhesive thickness along the overlap. The ensemble consists of one pultruded member bonded to two aluminum pieces, one on each side, to simulate a truss member between two nodes. The samples were fabricated via the following steps: (1) the pultruded member and the inside of the aluminum piece were roughened by manual abrasion with P320 grit sandpaper and cleaned with acetone, (2) the member was inserted in the aluminum piece, (3) the ensemble was placed on a fixture used to center the member externally and (4) the adhesive was injected in the overlap through an injection hole on the side (not shown in Figure 1). The samples were left to cure at room temperature for 1 week. The tensile testing of the ensemble was performed on a tensile machine with a maximum load of 20kN, under displacement control at a speed of 1mm/min, until failure.

3. Numerical Study

3.1. Material properties

The adhesive considered for this study, Araldite 2015, is a rubber-toughened epoxy adhesive, whose mechanical properties are well defined in the literature [5, 6]. These properties, presented in Table 1, are used for the numerical models, including the elasto-plastic and damage mechanics properties. Since only the cohesive failure of the adhesive is considered in this study, the materials for both adherends are considered in the numerical models to be purely elastic. The carbon fiber-reinforced polymer member, being unidirectional, is considered orthotropic. The mechanical properties used for the composite, in the form of engineering constraints, and for the aluminum 6082-T6, are presented in Table 2 and Table 3 respectively.

Table 1. Mechanical properties of Araldite 2015

Density ρ (g/cm^3)	1.4
Young's modulus E (GPa)	1.85 ± 0.21
Shear modulus G (GPa)	0.56 ± 0.21
Poisson's ratio ν *	0.33
Tensile yield stress σ_y (MPa)	12.63 ± 0.61
Tensile failure stress σ_f (MPa)	21.63 ± 1.61
Tensile failure strain ε_f (%)	4.77 ± 0.15
Tensile failure plastic strain ε_f^p (%) **	3.60
Shear yield stress τ_y (MPa)	14.6 ± 1.3
Shear failure stress τ_f (MPa)	17.9 ± 1.8
Shear failure strain γ_f (%)	43.9 ± 3.4
Fracture energy (tension) G_n^c (N/mm)	0.43 ± 0.02
Fracture energy (shear) G_s^c (N/mm)	4.70 ± 0.34

* Manufacturer's data
** Computed from σ_f and ε_f

Table 2. Mechanical properties of CFRP

ρ_{CFRP} (g/cm^3)	E_{11} (MPa)	E_{22} (MPa)	E_{33} (MPa)	ν_{12}	ν_{13}	ν_{23}	G_{12} (MPa)	G_{13} (MPa)	G_{23} (MPa)
1.5	146066	8320	8320	0.248	0.248	0.234	3135	3135	3371

Table 3. Mechanical properties of aluminum

Density ρ_j (g/cm3)	2.7
Young's modulus E_j (GPa)	71
Poisson's ratio ν_j	0.33

3.2. Finite Element model

3.2.1. Continuum mechanics approach

The first numerical model to be analyzed considers failure criteria based on a continuum mechanics approach. While this approach is not able to model the actual damage and failure of the materials considered, it allows for straightforward implementation, and this is in some cases enough for joint strength prediction. To limit the computational time of the analyses, the model represents a longitudinal section of a sample and uses axisymmetric elements, the axis corresponding to the central axis of the member. Only half of the sample geometry is modelled, with one end corresponding to the aluminum joint piece gripped by the tensile machine being fixed, and the other end corresponding to the member in tension having a displacement applied to it. The model is comprised of one part only, partitioned for the application of the different materials. The contact between adhesive and adherends is considered perfect. A bilinear elasto-plastic material model is used for the adhesive, using the properties shown in Table 1. To reduce the effect of stress singularities and represent more closely the actual samples, a small chamfer is modelled at the corner of the aluminum adherend [10], and a small fillet is created at the edge of the adhesive. The convergence study resulted in the use of 8-node axisymmetric elements with reduced integration CAX8R [11], with a mesh refined close to the adhesive overlap boundaries. Similarly to the experimental campaign, analyses are carried out for multiple overlap lengths L_o (from 5 to 25mm), adhesive thicknesses t_a (from 0.05 to 0.5mm), adherend thicknesses t_j (from 0.5 to 10mm) and member's outer diameters d_{out} (from 2 to 6mm). The non-varying dimensions are identical to the reference ones as defined previously. After each analysis, joint strength predictions are extracted using three different criteria:

(a) Maximum equivalent plastic strain: the joint is considered failed when the equivalent plastic strain, anywhere in the adhesive layer, reaches the failure value ε_f^p.
(b) Maximum shear strain: the joint is considered failed when the shear strain, anywhere in the adhesive layer, reaches the failure value γ_f.
(c) Maximum applied load: the joint is considered failed when the load applied to the member to realize the input displacement reaches its maximum.

3.2.2. Damage mechanics approach

The second numerical model used in this study is similar to the first one, the difference being that Cohesive Zone Modelling (CZM) is used to model the damage within the adhesive layer. CZM has been shown to give accurate strength predictions for joints using Araldite 2015 [8, 9, 12]. Cohesive elements are used for to model the adhesive layer instead of the general purpose CAX8R elements. A continuous approach is employed by using cohesive elements with a finite thickness between the two adherends, as opposed to a local approach consisting of zero-thickness elements being inserted between each layer of the adhesive mesh [13]. The use of cohesive elements implies a few changes in the model: (1) to ensure a good connectivity between used for the adhesive layer, using 4-node axisymmetric cohesive elements (COHAX4) and the remainder of the model, the adherends are modelled using 4-node CAX4 elements instead of the 8-node CAX8R elements, (2) using the continuous approach, only one layer of cohesive elements is allowed through the adhesive thickness and (3) the adherend chamfer and adhesive fillet are not modelled. A triangular traction-separation law is used to model the damage initiation, damage progression and failure of the cohesive elements, using the mechanical properties shown in Table 1. After each analysis, a joint strength prediction is made, based on the maximum applied load.

4. Results and discussion

4.1. Joint strength prediction

In order to determine which model and which failure criterion results in the best joint strength predictions, the numerical and experimental results are compared for each parameter variation, and presented in Figure 2. The joint strength is represented in terms of failure load in kN.

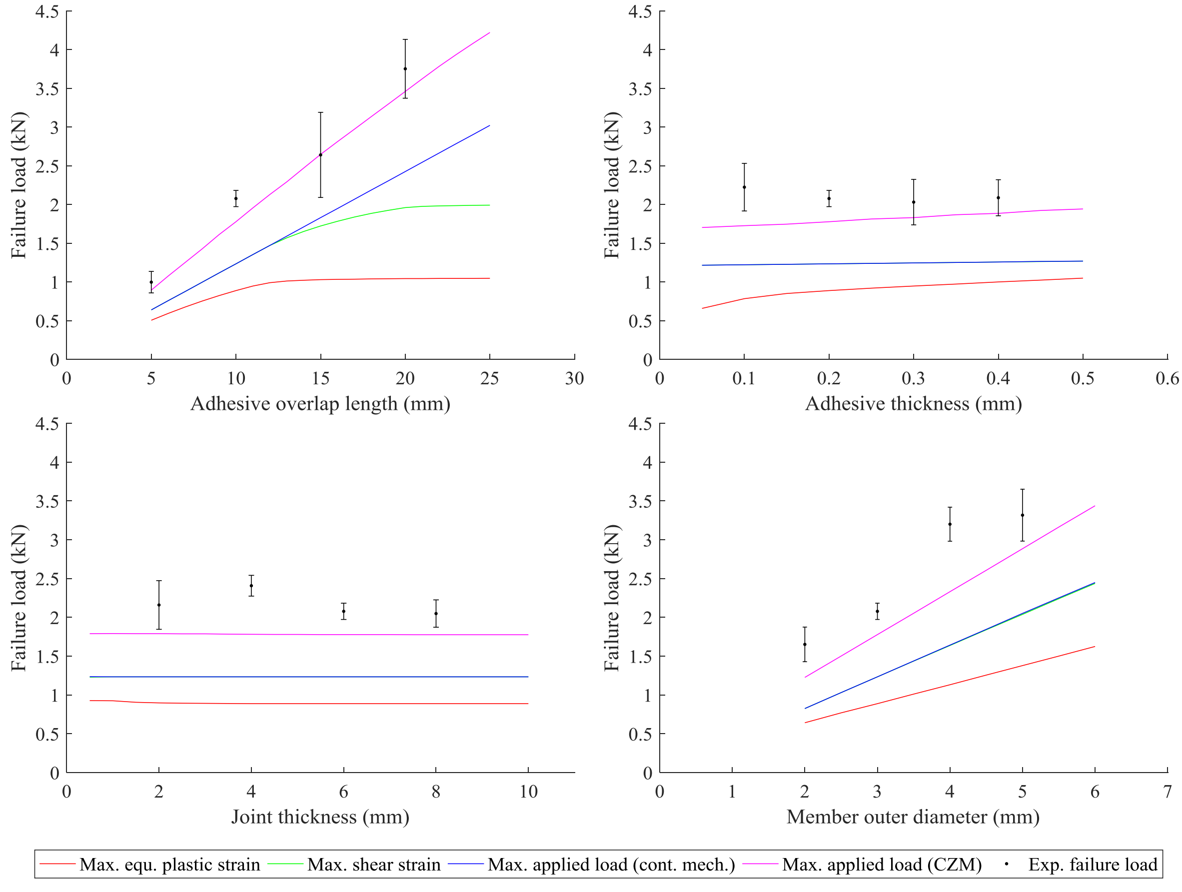

Figure 2. Experimental and numerical failure loads for multiple (a) adhesive overlap lengths, (b) adhesive thicknesses, (c) adherend thicknesses and (d) member diameters.

The results show that the continuum mechanics approach based model underpredicts the actual strength of the joints for all criteria, with the maximum plastic strain criterion being the least accurate. The results from the maximum shear strain criterion and the maximum applied load are overlapping up to a certain overlap length, after which only the strength predicted by the maximum applied load keeps increasing proportionally, following the trend of the experimental results (Figure 2a). The fact that the strengths predicted by the maximum plastic and shear strain criteria reach a plateau after a certain overlap length, while the actual strengths continue to increase proportionally, confirms that ductile adhesives like Araldite 2015 fail only when the whole overlap fails. Those two criteria characterize in fact the first failure of the adhesive, by considering the first occurrence a failure strain value is reached within the adhesive. These results show that, contrary to brittle adhesives, ductile adhesives can redistribute the stresses along the overlap, resulting in an actual failure of the adhesive joint way past the first failure load.

The CZM model, while still underpredicting the actual joint strength in most cases, gives the most accurate predictions of all the models and criteria considered in this study. It shows that modelling the damage propagation in the adhesive layer is key to an accurate strength prediction for these joints, which cannot be attained through a continuum mechanics approach using stress-strain failure criteria. A joint design based on a model representing the first failure only would lead to a conservative and therefore heavier design. As the overall objective of this research focuses on providing lightweight structures, the CZM model is the more appropriate choice for future analyses.

4.2. Influence of varying parameters

In this section, only the numerical results from the CZM model will be used, since they give the most accurate predictions. Furthermore, in order to examine the influence of the varying parameters, it is more appropriate to represent the performance of the joints in terms of efficiency rather than pure strength. The joint efficiency η is defined by the ratio of joint strength over member strength. Its value is calculated through Eq. 2, where ${P_f}^j$ is the failure load of the joint, ${\sigma_f}^m$ = 2500 MPa is the tensile strength of the pultruded composite members [7] and A is the member's cross-sectional area.

$$\eta = \frac{P_f^j}{\sigma_f^m . A} \tag{2}$$

The diameter of the members remaining the same when varying the overlap length, adhesive thickness and adherend thickness, the evolution of the joint efficiency with respect to these parameters follows the exact same trend as in Figure 2a, 2b and 2c. The results show that the only parameter leading to substantial efficiency changes is the adhesive overlap length. Varying the other parameters leads to relatively constant joint efficiencies. The change of joint efficiency with increasing member diameters, and thus increasing member cross-sectional areas, is presented in Figure 3.

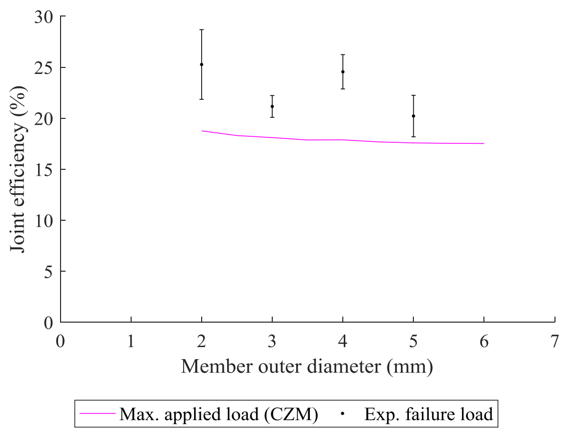

Figure 3. Experimental and numerical joint efficiency for multiple member diameters.

The numerical model predicts a relatively constant efficiency for increasing member diameters, explained by the fact that although the joint failure load increases (due to an increase of the adhesion surface), the member failure load increases as well (due to an increase of the member cross-sectional area). Although this constant efficiency does not clearly appear in the experimental results, they don't suggest an increase or decrease of efficiency with the increase of member diameter.

In the light of the objective of this work, the weight of the joints must be considered alongside their strengths. Typically, a stronger joint will often imply a higher weight, so the influences of the design parameters on both strength and weight must be examined. To achieve this, the ratio of joint efficiency over joint weight is calculated for the varying parameters, and presented in Figure 4. Figure 4a shows that the ratio increases slightly with the overlap length. Although the efficiency of the joint increases substantially with the overlap length, the associated increase in weight is almost equally substantial, resulting in invariant behavior. A similar invariant effect is seen for the variation of adhesive thickness. Figure 2b and Figure 4b show that this parameter has very little influence on the strength and weight of the joint. Combining Figure 2c and the weight of the adherend results in Figure 4c shows that although the adherend thickness has little to no influence on the joint strength, it has a substantial impact on the weight. Besides, it is important to note that while varying the overlap length, the adherend thickness was kept at a constant value of 6mm. Therefore it is easy to imagine that with a much thinner adherend, the increase of weight associated to the increase of overlap length would be much lower, for the same strength.

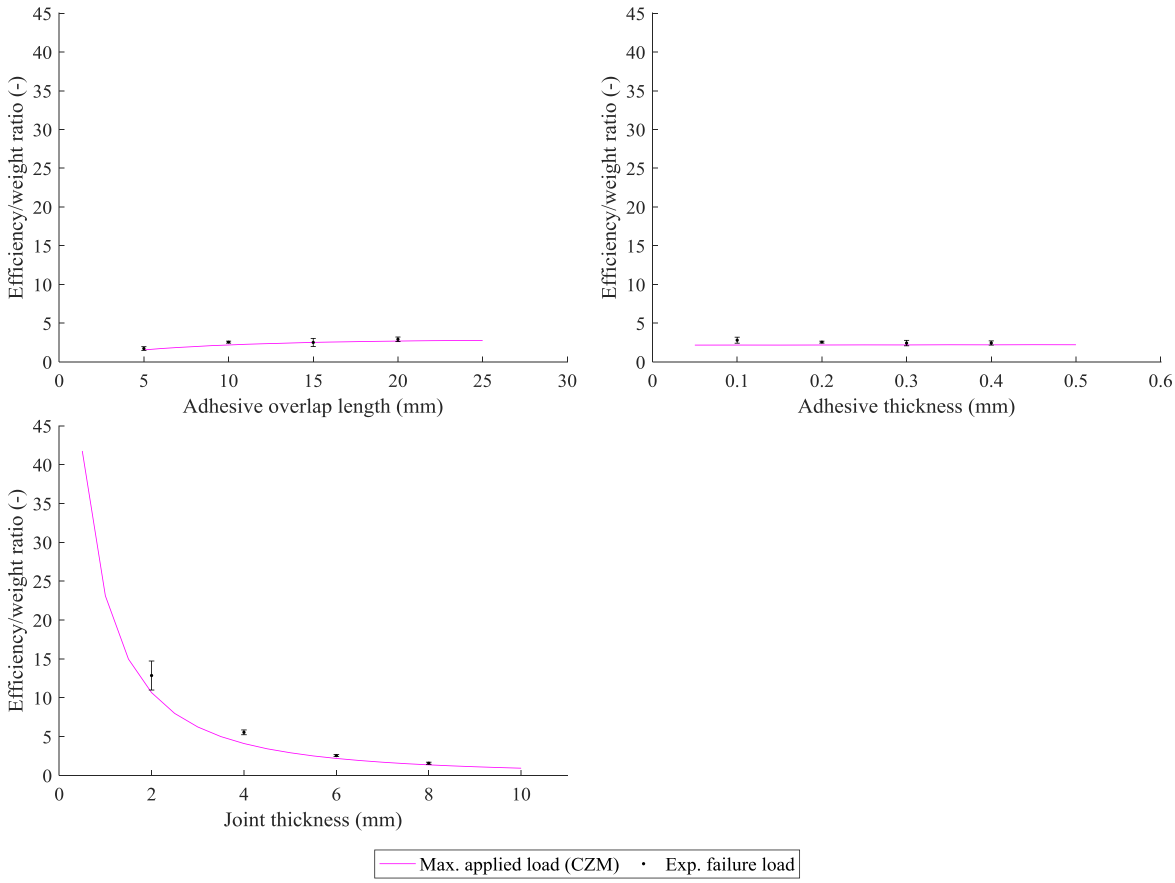

Figure 4. Experimental and numerical efficiency/weight ratios for multiple (a) adhesive overlap lengths, (b) adhesive thicknesses and (c) adherend thicknesses.

5. Conclusions

The main objective of this work was to study adhesive joints bonding carbon-fiber reinforced polymer pultruded tubes inside aluminum pieces, numerically and experimentally. In particular, the objective was to determine which numerical model was able to predict the joint strength the most accurately, and to examine the influence of several design parameters on the strength and weight of the joints. With this purpose, samples were made with varying dimensions, and tested in tension until failure. In the meantime, numerical models using either a continuum mechanics or a damage mechanics approach were built. The comparison between numerical and experimental results showed that modelling damage in the adhesive layer results in the most accurate joint strength predictions. In future work, this model will be used to assess the strength of a joint within a design optimization problem. In terms of influence of the design parameters on the performance of the joint, it was found that increasing the overlap length has the highest impact on increasing the joint strength, and that reducing the adherend thickness has the highest impact on reducing the structural weight, while preserving the strength.

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