Adhesive joints for composite materials produced by additive manufacturing

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Abstract. Composite materials are joined in many occasions with adhesive joints due to the condition of the materials, the ease of repair, the loading conditions, the affectation by corrosion and chemical attacks. However, the efficiency of these bonding schemes is related to multiple factors, among them, the length and the width of the adhesion zone and the thickness of the adhesive. In this work, we analyze the factors associated with the surface contact of the substrates. We define a numerical model using the finite element method and study the parameters related to the physical condition, considering optimal results based on the data of the strength provided by the suppliers of adhesives.

1. Introduction
The science and technology of adhesion is growing as a method of joining materials due to the rapid development of new adhesive formulations and the improvement of the conditions of use, and has been successfully introduced in applications reserved for other joint systems as welding or mechanical joints [1]. The popularity of adhesive bonds is due to the advantages over other binding systems, e.g., an adhesive connection distributes more evenly and homogeneously the stresses than riveted joints and screws, avoiding areas of high-stress concentration, as exhibited in the holes required in such connections [2]. Currently, there is a tendency to replace all or part of traditional fixing systems such as welding or riveting, by adhesive joints due to the high performance offered by these components [3].

Adhesives permit binding of different materials with different physical, mechanical or electrochemical properties. They result especially useful for composite materials of polymeric matrix [4,5], where conventional bonding methods could yield in stress concentrator or are not feasible. They may also act as sealants, obtaining in this way watertight mechanical joints, preventing the presence of corrosive agents (moisture, air, etc.) [6]. Adhesion is defined as the state in which two surfaces are held together by interfacial junctions [7], and cohesion denotes the state that tends to associate particles of a substance by secondary valence forces [8]. The curing or setting is the process during which an adhesive develops its cohesive strength and therefore, their physical and chemical properties [9].

A bonded joint produces a bimaterial body and, thus, yields stress discontinuities even in the absence of any geometric discontinuity due to mismatch of the elastic properties of the materials connected [10]. The mechanical test used to characterize adhesive bonds is the tensile shear test [11], because of its ease of implementation and simplicity, as well as being representative of many adhesive bonds employed in
the industry. On the other hand, numerical testing of the mechanical behavior using, e.g. the finite element (FE) method [12–14], has allowed improving our understanding of the response of complex materials. Numerical models for composite materials provide insight into the interlaminar phenomena and the bonding between the fibers and the matrix [15]. For the analysis of adhesive joints, they have been particularly successful, for example, for assessing the strength and locate the place of failure of boards flap with a wide range of adhesives, which have been predicted with reasonable accuracy [16].

Adhesive joints are finding increasing applications in various structural fields [17], and their use can lead to a reduction of costs, as well as an acceleration of assembly processes and, consequently, an improvement in the production processes for developing countries [18]. In this research, a preliminary numerical test is performed by means of the finite element method for adhesive joints in composites produced by additive manufacturing. Results are validated using the ASTM D3163-96 standard [19].

2. Materials and methodology

2.1. Materials

We investigate the adhesion between two different materials, Nylon 6, which is used as matrix support in the Mark Two 3D printer [13,20,21], and the adhesive AKEPOX® 5010. Polyamides are widely used as engineering polymers, with a multitude of applications such as fibers for clothing, ropes, structural and mechanical components, reinforcements in tires and adhesives. Because of their excellent properties, polyamides covers a considerable part of the world engineering polymers market [21]. The main use is the transportation manufacturing industry, covering 35% of the polyamide (PA) consumption [23].

Nylon 6 fiber is produced in two general product types: the regular type for textile uses and the high-strength type for industrial uses. Most nylon 6 is produced in the form of filament yarns and staple fiber yarns for the manufacture of carpets, tire cords, apparel, hosiery, upholstery, seat belts, parachutes, ropes, and industrial cords. This wide spectrum of applications can be attributed to the particular combination of material properties [24].

The AKEPOX® 5010 is made of epoxy resin, in different colors to create invisible joints in corners of facades, miter porcelain, natural and artificial stones. Due to its strong adhesion and resistance, it can be used for the manufacture of sinks, shower trays and all kinds of structures that are to be subjected to humidity or temperature changes [25]. Among its characteristics stands out the extremely high strength to the stuck, and the adherence on slightly surfaces humid. This adhesive is suitable for vertical and horizontal gluing and also for gluing different plastic materials, glass, ceramics and wood [26].

For this work, sheets of Nylon 6 substrate were used, being bonded with an epoxy-type adhesive AKEPOX® 5010. The properties of the materials are shown in Table 1.

| Table 1 Materials properties |
|-----------------------------|
| Material | Elastic modulus (N mm⁻²) | Tensile strength (N mm⁻²) | Density (g cm⁻²) |
| Nylon 6 | 2850 | 78 | 1.14 |
| Adhesive | 2750 | 35 | 1.16 |

2.2. Numerical model

The finite element analysis software ANSYS [26] is a large scale multipurpose finite element program, which is used for engineering applications. Finite element models can also be used in material science for material design, virtual material characterization, and micromechanical or multiscale analysis. Analysis of a problem in ANSYS has to go through three main modules: (i) pre-processor, (ii) solution, and (iii) postprocessor. The general pre-processor has solid modelling and mesh generation capabilities and is also used to define all the other analysis data such as geometric properties like real constants, material properties, constraints, loads, stiffness damping etc.

The geometrical parameters of overlap length, adhesion width and adhesion thickness are varied, with an increase of 10% from the initial value for the first test values for ASTM D3163-96 [19]
specimens. Following the heuristic method, that percentage was increased until evidencing a substantial change in the behavior of the model, the behavior of the adhesive bond was evaluated through finite element analysis.

The type of element used to model both materials is the SOLID45, which is an 8 nodes brick. The meshing of the adhesive union presents fine mesh in the part where the adhesive is for the three cartesian axes and the meshing for the two substrate specimens have a variable mode; in order to have more detail near the overlapping area. We performed a mesh independence analysis, for a final FE model with a number of elements of 1417 and a number of nodes of 10668.

We solve a linear elastic boundary value problem with Dirichlet and Neumann conditions using a standard Galerkin FE formulation. A force of 100 N was applied on the transverse surface of the end of the specimen. The other end has displacement constraints on all degrees of freedom.

3. Results and discussions

3.1. Overlap length

The tensile test of the adhesive bond is made by varying the length of the overlap and keeping the variable width of the adhesion and the adhesive constant. In Figure 1, the points for the maximum and minimum deformation are shown, these values corresponding to 0.1033 mm and 0.0975 mm, respectively. Figure 2 shows the linear relation between the deformation or total displacement and the overlap length.

![Adhesive bond deformation varying adhesion length.](image1)

**Figure 1.** Adhesive bond deformation varying adhesion length.

![Adhesive bond deformation varying overlap length.](image2)

**Figure 2.** Adhesive bond deformation varying overlap length.
3.2. Overlap width
For this second parameter, the overlap length and the thickness of the adhesive were kept constant, their behavior coincides with the safety factor shown in Figure 3. As expected, the thickness of the adhesive increases, the stresses decrease and the effect of the most significant shear stress along the load direction.

![Figure 3. Adhesive bond deformation varying overlap width.](image)

3.3. Overlap thickness
The line of the union represented by the thickness of the adhesion contributes significantly to the resistance of the plate to the shear stress. The displacements with respect to the thickness of the adhesive increase with the total strength of the joint, which means that the displacement in relation to the thickness of the adhesive is greater in thin joints and decreases progressively, as shown in Figure 4.

![Figure 4. Adhesive bond deformation varying overlap width.](image)

From the results through the mode of the adhesive bonding, one can find the effect that occurs in the direction of the length thereof of this measure, only a decrease in the maximum stress is obtained.

Finally, when modifying the thickness of the adhesive, its behavior shows a reduction of effective stresses along the lap length. The maximum load to be reached is responsible for breakage of adhesion; The greater the thickness of the adhesion, the greater the total displacement, after reaching a maximum load value and anticipating the breakage. In addition, the values in the shear stresses compared to the peeling stresses are lower. From the deformation criterion, it can be seen that a greater effect is present in the adhesive joint for the geometrical thickness factor.
4. Conclusions
From the results obtained through the modelling of the adhesive bond by means of the ANSYS finite element software, it can be concluded that the maximum stress decreases with the increase of the length of overlapping area.

Moreover, when modifying the thickness of the adhesive, its behavior shows a reduction of effective stresses along the lap length. The maximum load to be reached is responsible for breakage of adhesion; the greater the thickness of the adhesion, the greater the total displacement, after reaching a maximum load value and anticipating the breakage. In addition, the values in the shear stresses compared to the peeling stresses are lower. From the deformation criterion, it can be affirmed that a greater effect is present in the adhesive joint for the geometrical thickness factor.

References
[1] Pocius A V 2012 Adhesives and Sealants Polymer Science: A Comprehensive Reference vol 8 (Amsterdam: Elsevier Inc.) p 305
[2] Flick E W 1993 Loctite Corp Epoxy Resins, Curing Agents, Compounds, and Modifiers (New Jersey: Elsevier Inc.) p 374
[3] Crocombe A D and Wang G 1998 Modelling crack propagation in structural adhesives under external creep loading J. Adhes. Sci. Technol. 12 655
[4] Gómez S, Ramón B B and Guzman R 2018 Comparative study of the mechanical and vibratory properties of a composite reinforced with fique fibers versus a composite with E-glass fibers Rev. UIS Ing. 17 43–50
[5] Maradei-García M F, et al. 2019 Bagasse sugarcane fibers as reinforcement agents for natural composites: description and polymer composite applications Rev. UIS Ing. 18 117
[6] Segura D M, Nurse A D, McCourt A, Phelps R and Segura A 2005 Chemistry of polyurethane adhesives and sealants Handbook of Adhesives and Sealants (Amsterdam: Elsevier B.V.) p 101
[7] Richardson G, Crocombe A D and Smith P A 1993 A comparison of two- and three-dimensional finite element analyses of adhesive joints Int. J. Adhes. Adhes. 13 193
[8] Hamoush S A and Ahmad S H 1989 Fracture energy release rate of adhesive joints Int. J. Adhes. Adhes. 9 171
[9] Agencia Española de Normalización (AENOR) 2016 Clasificación de adhesivos termoplásticos para madera de uso no estructural, UNE-EN 204:2016 (Madrid: Agencia Española de Normalización)
[10] Dundurs J 1964 Edge-bonded dissimilar orthogonal elastic wedges under normal and shear loading J. Appl. Mech. Trans. ASME 36 650
[11] Miller W S, Zhuang L, Bottema J, Wittebrood A J, De Smet P, Haszler A and Vieregge A 2000 Recent development in aluminium alloys for the automotive industry Mater. Sci. Eng. A 280 37
[12] González-Estrada O A, et al. 2016 Análisis de integridad estructural de tuberías de material compuesto para el transporte de hidrocarburos por elementos finitos Rev. UIS Ing. 15 105
[13] Argüello-Bastos J D, González-Estrada O A, Ruiz-Florían C A, Pertuz-Comas A D and V-Niño E D 2018 Study of mechanical properties under compression failure in reinforced composite materials produced by additive manufacturing J. Phys. Conf. Ser. 1126 012005
[14] Pertuz A, et al. 2018 Estudio de la fatiga en láminas de tubería compuesta de matriz epólica con fibra de vidrio para cargas de tracción Sci. Tech. 23 479
[15] González-Estrada O A, León J S and Pertuz A 2019 Influence of the boundary condition on the first ply failure and stress distribution on a multilayer composite pipe by the finite element method J. Phys. Conf. Ser. 1159 012013
[16] Adams R D, Comyn J and Wake W C 1997 Structural adhesive joints in engineering (London: Chapman & Hall)
[17] Azari S, Eskandarian M, Papini M, Schroeder J A and Spelt J K 2009 Fracture load predictions and measurements for highly toughened epoxy adhesive joints Eng. Fract. Mech. 76 2039
[18] Bilurbina L and Liesa Mestres F 1996 Polímeros termoestables Materiales no metálicos resistentes a la corrosión. (Mexico D.F.: Marcombo)
[19] American Society for Testing and Materials (ASTM) 2001 Standard test method for determining strength of adhesively bonded rigid plastic lap-shear joints in shear by tension loading, ASTM D 3163-01 (West Conshohocken: American Society for Testing and Materials)
[20] Mohammadizadeh M, Imeri A, Fidan I and Elkelany M 2019 3D printed fiber reinforced polymer composites - Structural analysis Compos. Part B Eng. 175 107112
[21] Pertuz A D, Díaz-Cardona S and González-Estrada O A 2020 Static and fatigue behaviour of continuous fibre reinforced thermoplastic composites manufactured by fused deposition modelling technique Int. J. Fatigue 130 105275

[22] Cho J W and Paul D R 2001 Nylon 6 nanocomposites by melt compounding Polymer (Guildf) 42 1083

[23] Hunt J K 1940 Nylon Ind. Eng. Chem. 32 1160

[24] Song P S, Hwang S and Sheu B C 2005 Strength properties of nylon- and polypropylene-fiber-reinforced concretes Cem. Concr. Res. 35 1546

[25] Fernández García R 2010 Las resinas epoxi: Un mundo de oportunidades Ing. Quim. 42 84

[26] Butrón Janices A and Katime Amashta I 2014 Propiedades físicas y mecánicas de sistemas bicomponentes Rev. Iberoam. Polímeros 15 376

[27] ANSYS Inc 2017 ANSYS® Academic Research Mechanical, Release 18.1, Help System (Canonsburg: ANSYS, Inc)