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Investigation of the Mechanical Strength of CFRP with Co-Cured Additively Manufactured Metal Inserts

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Abstract

Multi-material structures, combining metal alloys and composite materials, are widely used in industries such as aeronautics. Traditional joining methods, such as riveting or adhesives, require surface treatment, drilling holes, alignment, and cleaning of residues, adding time and cost to production. This paper presents the numerical modeling and experimental validation of metal-composite joints based on surface morphology modification through additive manufacturing (AM). We used laser-based powder bed fusion (LB-PBF) to build the metal part, creating a superficial pattern of three-dimensional elements with various shapes and sizes. These elements act as anchors for the composite, creating local interactions with the carbon fibers. We built laboratory samples using carbon fiber fabrics with a 90° orientation and resin impregnation. After curing at ambient pressure and temperature, we fabricated tensile samples. The results provide design information about the joint strength with respect to the characteristics of the 3D anchors used at the interface.

Keywords: Joints; additive manufacturing; CFRP; LB-PBF; lightweight.

1. Introduction

Joining carbon-fiber reinforced polymers (CFRP) and metals typically involves adhesives or mechanical elements such as rivets or threaded elements. Adhesives create a permanent joint preserving the structural integrity, while

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mechanical elements alter the stress distribution through holes and sometimes allow for disassembly, as reported by Clyne and Hull (2019). To preserve joint integrity, a preliminary coating of the metal part is often used, especially in humid environments. Long-term exposure to water can alter polymer matrices and epoxy adhesives, which is why the selection of the appropriate adhesive is crucial based on factors such as joint materials, surface roughness, joint stiffness, load, joint shape complexity, and environmental characteristics. The preparation of surfaces strongly influences the mechanical efficiency of adhesives, as reported in Kopanitsa et al. (2016).

Co-cured joints eliminate the need for adhesives, reducing synthetic pollutants, and can be built during lamination, reducing process complexity (Kim and Lee, 2007). The fabrication of co-cured metal/CFRP joints can be improved by additive manufacturing (AM) of metal parts, where appropriate design and fabrication methods can functionalize the metal part surface to interact mechanically with the composite (Nguyen et. al 2020, Zou et al. 2020). A 3D pattern can be used to increase resin penetration and engage fibers mechanically, improving the behavior of the co-cured joint with patterned surfaces compared to planar functional surfaces.

This paper proposes a co-cured joint typology between Inconel 625 and CFRP, investigating the effects of a 3D pattern applied to the metal surface on final mechanical strength. The joint's static behavior is simulated using two modeling strategies based on the finite elements method (FEM). Finally, experimental characterization of joint samples is provided to validate the calculations.

2. Applications to aeronautic structures

Many aerostructures, including primary flight control (PFC) structures in medium and large aircraft, are typically composed of CFRP skin and internal metal parts, usually made of aluminum alloy, that are coupled together using rivets, a well-established method of assembly in the aeronautics industry. However, this type of joint has several drawbacks, such as the need for a long assembly time (which results in high man-hours cost), loss of fiber integrity due to rivet holes, the weight of the rivets, the need for joint surface treatment with paint, rivet failure issues, and the difficulty of inspecting and maintaining the rivets. For instance, steel rivets weighing 100,000 units weigh 120 kg (43 kg for aluminum rivets), and each aircraft has thousands of rivets (Belarbi et al., 2016).

The co-cured solution offers several significant advantages. First, the mechanical load is transferred through the carbon fibers, which have -35% density (ρ), x4 Young's modulus (E), x8 tensile stress (σ), x6.8 specific Young's modulus (E/ρ), and x13 specific tensile stress (σ/ρ) compared to aluminum rivets (Tab. 1). The differences are much greater when compared to steel rivets. Second, the feasibility of the joining process has been demonstrated by experimental proof of concepts and laboratory tests conducted by 1-POL (De Pasquale et al. 2022), which yielded promising load-at-failure per unit area (apparent shear strength) in the range of 26-36 MPa for 20x30 mm^2 joint samples. In comparison, the same area joined with steel rivets (5 mm diameter, D) yields 7000 N maximum shear load, 360 MPa maximum rivet stress, and 12 MPa maximum load per unit area (apparent shear strength, 3D rivets pitch). As an alternative to rivets, epoxy adhesives yield apparent shear strength in the range of 7-20 MPa (Ventrella et al. 2010, Casalegno et al. 2018). Therefore, the proposed joint strength is demonstrated to be 54-67% and 23-80% higher than riveted and adhesive-bonded joints, respectively.

Table 1. Mechanical properties comparison among high strength (HS), high module (HM) and ultra high module (UHM) carbon fibers and steel rivets.

Layer	ρ (g/cm^3)	E (GPa)	σ (MPa)	E/ρ (MN*m/kg)	σ/ρ (MN*m/kg)
Carbon HS	1.76	228	3500	129	2
Carbon HM	1.77	390	3100	220	1.7
Carbon UHM	1.85	440	2000	237	1.08
Steel rivet	7.80	210	400-500	27	0.03-0.04
Al rivet	2.80	70	320	25	0.11

Two different configurations are proposed to join the ribs to the composite skin, depending on the rib body dimensions. The first solution in Fig. 1a is suitable for small ribs (generally <400 mm length), which can be fabricated using laser powder bed fusion (L-PBF). Here, the AM-CFRP joint is created along the rib perimeter. In the second configuration of Fig. 1b (suitable for longer ribs), several inserts are joined to the skin internal surface using AM-CFRP joints. The large rib body, fabricated using traditional processes (such as stamping or cutting), is then fixed onto the inserts using reversible bolts and eventual unscrewing devices.

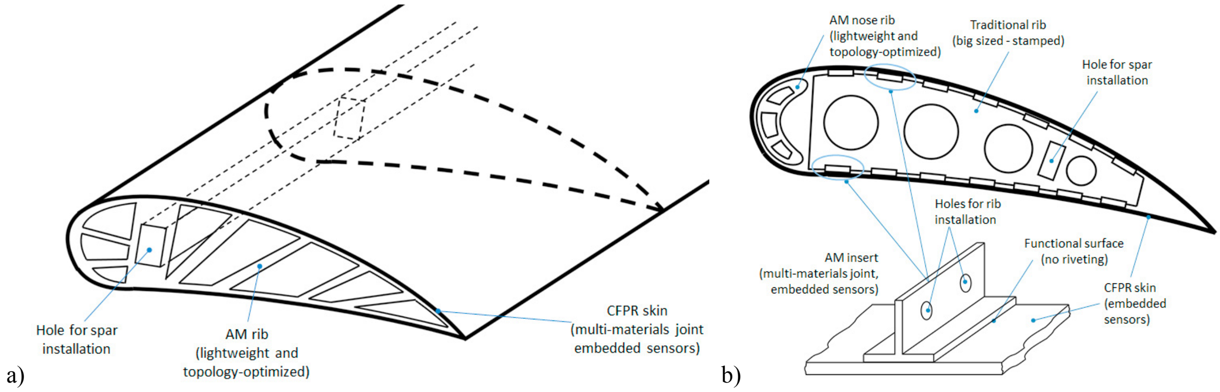
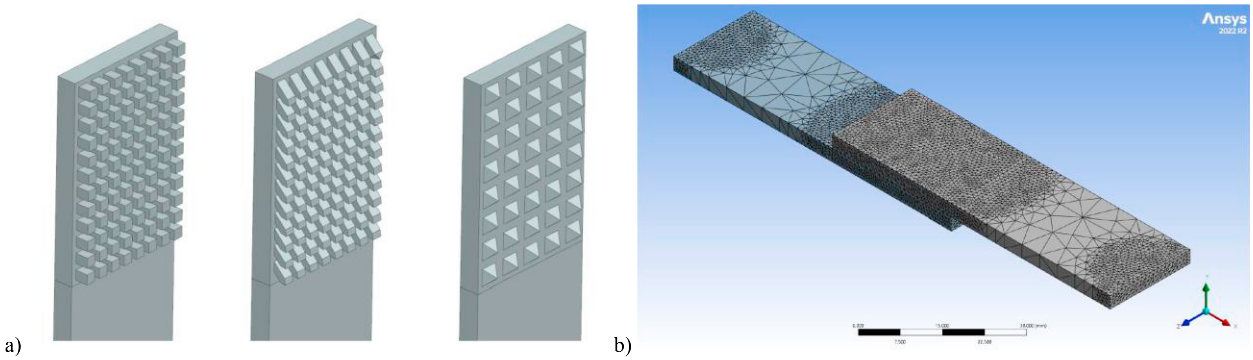
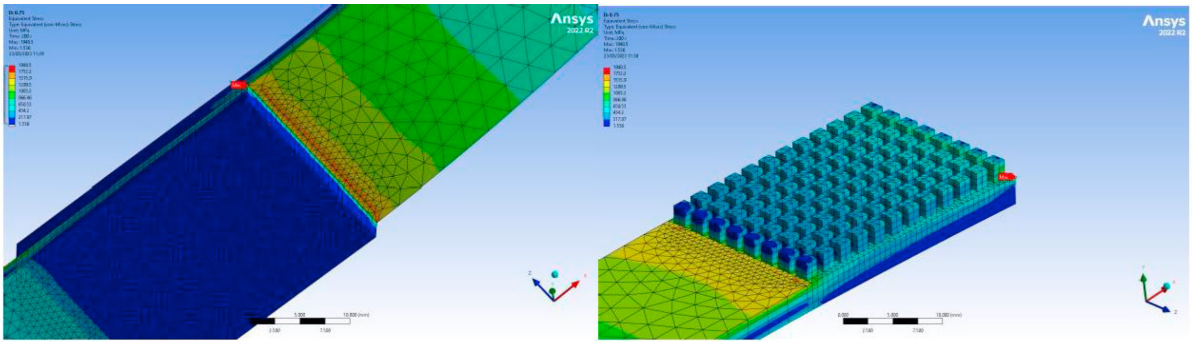


Fig. 1. Configurations of metal ribs and composite skin integrated by AM-CFRP joints. a) The rib body is produced by AM process and joined along the perimeter: solution suitable for small structures (rib length < 400mm). b) The rib body is produced by stamping/cutting process and fixed on AM inserts joined to the CFRP: solution mandatory for large structures (rib length > 400mm), but also applicable to small ones.

3. Numerical modeling

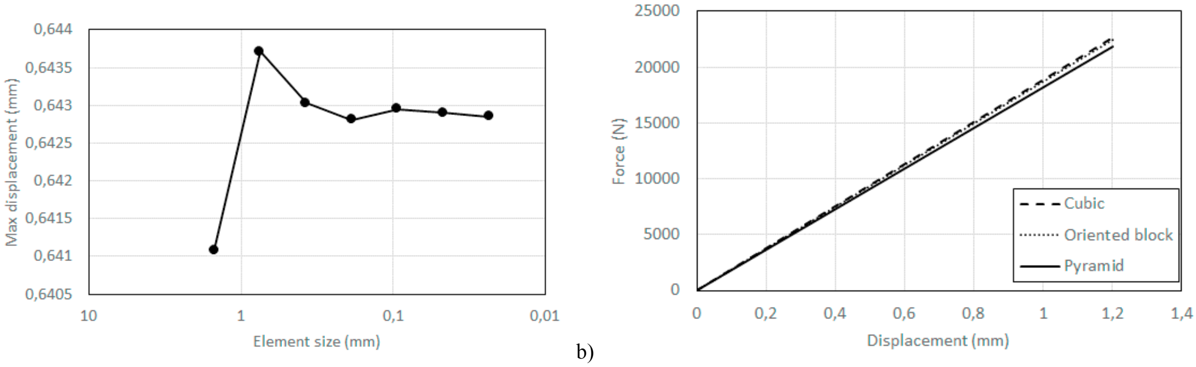
The present study provides numerical models of three types of joints: cubic, oriented block, and pyramid. The cohesive zone modeling (CZM) approach is employed to simulate the contact surface using Ansys software (version 2022R2). The 3D anchor's shape and geometry are presented in Fig. 2a. The mesh shape and size are optimized to achieve convergence of the results. Fig. 2b shows an example of the discretized structure. The modeling outcomes, in terms of the equivalent Von Mises stress for the cubic anchor shape, are displayed in Fig. 2c, referring to the outer surface and the internal anchoring profile. The mesh sensitivity analysis on the displacement result is demonstrated in Fig. 3a. The force-displacement relationship, calculated with a mesh size of 0.75 mm, is illustrated in Fig. 3b.





c)

Fig. 2. Geometry of 3D anchors considered in the analysis (a), example of optimized structural mesh (b), Von Mises equivalent stress results on the sample version with cubic 3D anchors shape (c).

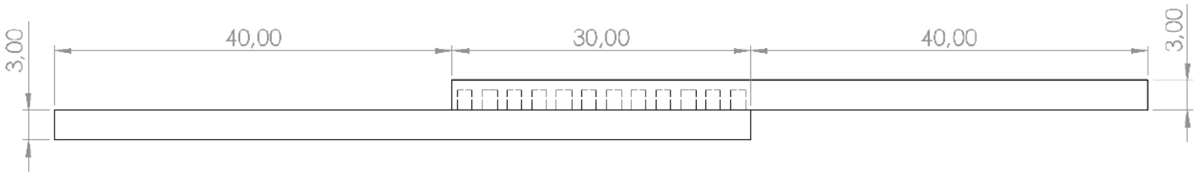


a) b)

Fig. 3. Mesh sensitivity analysis (a), force-displacement numerical results for three anchoring geometries (b).

4. Experimental validation

Six jointed samples made of AM-CFRP with the geometry shown in Fig. 4a were analyzed. The metal parts were fabricated using the Renishaw AM500M system with In625 material, and the process parameters are provided in Tab. 2. The composite was laminated at ambient conditions, with 24 hours of polymerization time and a 3 mm thickness of the laminate. The metal insert was co-cured with the composite. The servo-hydraulic testing system Instron 8801 (with a maximum load of 100 kN) was employed to characterize the joint samples (Fig. 4b). All tests were conducted at controlled displacement with an imposed velocity of 1 mm/min. The experimental results are reported in Fig. 4c.



a)

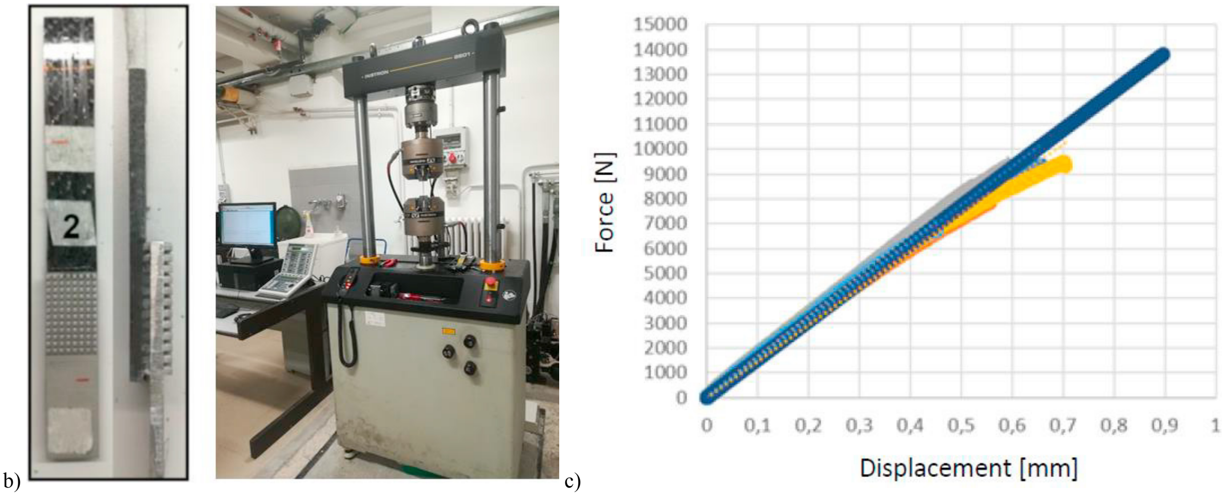


Fig. 4. Geometry and dimension of tensile joint samples (a), experimental setup (b), experimental tensile test results on six samples with cubic pattern shape and linear interpolation (c).

Table 2. Process parameters for the AM of the metal parts.

Layer	Hatch	Border
Layer thickness: 40 µm	Power: 190 W	Number of borders: 1
	Hatch distance: 110 µm	Power: 190 W
	Point distance: 90 µm	Point distance: 90 µm
	Exposure time: 100 µs	Exposure time: 100 µs
	Hatch offset: -20 µm	

5. Conclusions

This study investigates a metal-composite joining technique for aeronautic structures that is based on co-curing rather than adhesives or riveting. Different anchoring shapes were considered and realized with the AM process on metal parts. The composite was then laminated with co-cured metal inserts, resulting in self-adhesion and mechanical gripping between the fibers and metal anchors. The numerical modeling of the joint is proposed using the CZM approach. The experimental characterization of the joint samples under tensile load was performed to validate the calculated results.

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