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The continuous fibre injection process (CFIP): A novel approach to lightweight design of multi-material structural components

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Abstract. The combination of different materials enables to achieve highly efficient structures in terms of lightweight and mechanical performance, as well as in terms of manufacturing costs. However, the weakest points of these structures use to be the joints. For this reason, in the last years, many studies have dealt with joining technologies for dissimilar materials. The Reinforce3D's Continuous Fibre Injection Process (CFIP) technology delivers a unique method to join dissimilar materials. CFIP is based on injecting continuous fibers, such as carbon fibers, simultaneously with liquid resin into tubular cavities within the part. Then the resin is cured and the final composite part is obtained. This work focuses on the characterization of the mechanical properties of CFIP-made specimens and describes the potential lightweight benefits of the technology. Mechanical tests were performed under tensile and bending conditions following standardized methods. The lightweight potential is addressed by developing a representative case study by implementing finite element and topology optimization methods. The results of this case study were finally compared with a monomaterial equivalent component (aluminium) demonstrating the improvement that CFIP provides in terms of lightweight while keeping the strength.

Introduction

Materials and forming processes for lightweight construction of structural parts have been intensively investigated in the last decade. High strength steels and aluminum alloys, together with carbon fibre reinforced polymers are the typical material solutions, depending on the part design and expected costs. In the last years, the evolution of additive manufacturing (AM) technologies gives and additional strategy for weight saving thanks to their capability for manufacturing highly complex and optimized geometries, such as the ones obtained from topology optimization simulations. According to ref 1 and 2, topology optimized structures can reach around a 40% of weight reduction when compared to structures manufactured by conventional methods. Even higher lightweight ratios are possible when combining different materials, following the concept of *the right material at the right place*. Optimized multi-material construction requires efficient joining techniques. However, the weakest points of multi-material structures are usually the joints. Accordingly, many solutions based on adhesive or mechanical joining methods have been developed, with advantages but also some drawbacks that hampered their wide industrial application.

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An excellent joining approach would combine chemical and mechanical bonding and would give functionality to the structure. A novel approach based on applying continuous Carbon fibers (cCf) along the structure, joining dissimilar materials, and locally strengthening and/or increasing the stiffness has been recently developed [3,4]. This process is named Continuous Fiber Injection Process (CFIP). In CFIP, the cCfs are injected inside tubular cavities within a part. Three key principles enable the process: on one hand, the fibers are injected simultaneously with pressurized liquid resin, generating a flow that contributes (i) to drag the cCf along the tubular cavity and (ii) to lubricate it and, on the other hand, (iii) a pushing force is also applied on the fibers. After the injection, the resin is cured and solidified, bonding the fibers to the part so that the final composite part is obtained. Figure 1 describes this process when applied for manufacturing a car brake pedal.

Besides reinforcing, CFIP can also integrally join different parts by injecting the cCf along them, achieving fiber continuity from end-to-end and thus delivering an ultra-high joining performance, enabling the efficient manufacturing of large and multi-material/process structures. The brake pedal shown in Figure 1 is made by the integral joining of different parts selecting the most efficient material and manufacturing method at each zone according to mechanical requirements but also to cost a production targets. Particularly, the pedal shown in Figure 1 integrates the following materials and manufacturing technologies: an epoxy resin made by AM, a machined aluminum alloy and an extruded polyamide.

Consequently, CFIP delivers a unique method for the tailored reinforcement of multi-material parts with improved joint resistance.

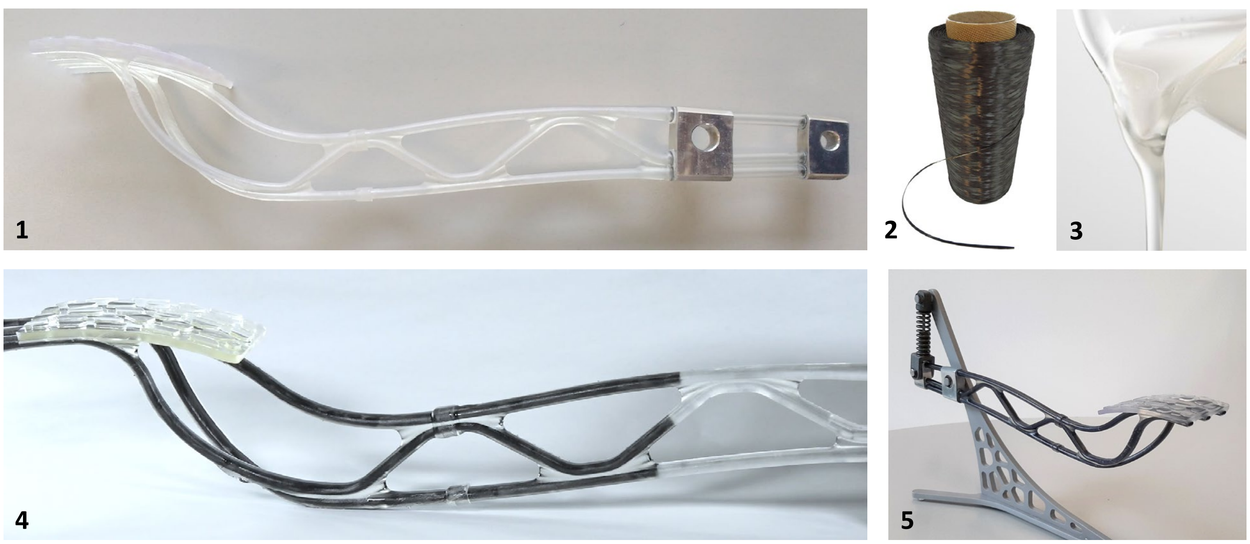


Figure 1: Scheme of the CFIP process: 1, part with tubular cavities; 2, cCf; 3, liquid resin; 4, injection of the composite material (cCfs + resin) inside the tubular cavities; and 5, final part.

AM technologies allow the manufacturing of parts containing tubular cavities following complex trajectories in all directions. For this reason, when combined with AM, CFIP provides high freedom for placing the fibers within the part, enabling their alignment to the most efficient directions, even through printing layers, which use to be the weakest direction in AM parts. Parts made by any AM technology and material can be reinforced by CFIP, including rigid and flexible polymers manufactured by Selective Laser Sintering, Multi Jet Fusion or Stereolithography or metallic alloys processed by Selective Laser Melting.

While in the composite materials market CFIP is conceived as a new mouldless method for manufacturing highly complex and optimized geometries, in the AM market it is conceived as the first technology based on reinforcing the AM part after the printing process, instead of during it.

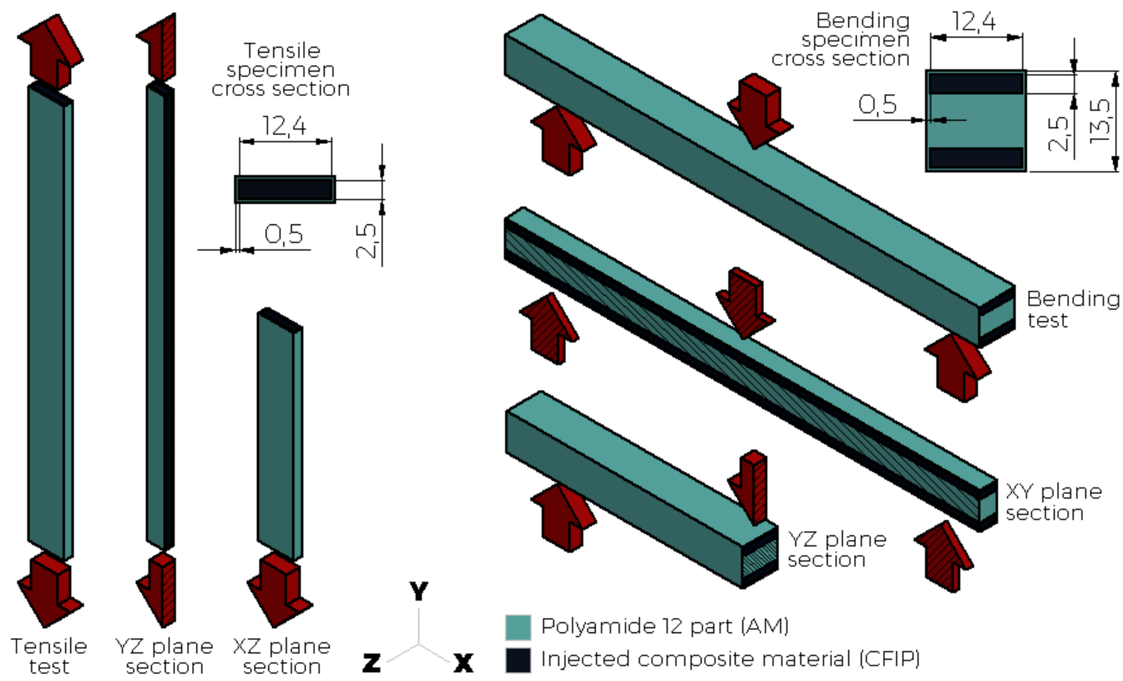
This work shows the lightweight potential of the CFIP technology by comparing the weight and mechanical performance of two demonstrators: one topologically optimized and manufactured completely in aluminum by AM and the other developed by the reinforcement and integral joining by CFIP of two AM parts made of aluminium and polyamide.

Material characterization

Specimens for tensile and bending tests were prepared using CFIP technology. The characteristics and dimensions of the CFIP specimens, for both the AM part and the injected composite material are given in Table 1. Figure 2 shows the test setup illustrating the direction of the injected composite material with respect to the loading direction. For the tensile specimens, a tab made of a fiberglass composite is added at the ends to give proper gripping during the tests and to promote the correct breakage of the samples (Figure 3).

Table 1: Characteristics of CFIP specimens.

AM part	Injected composite inside the tubular cavity
Tubular cavity dimensions: 2.5 x 12.4 mm	cCf and epoxy resin
Wall thickness: 0.5 mm	55% of cCf in volume
AM technology: Multi Jet Fusion	
Material: Polyamide (PA) 12	

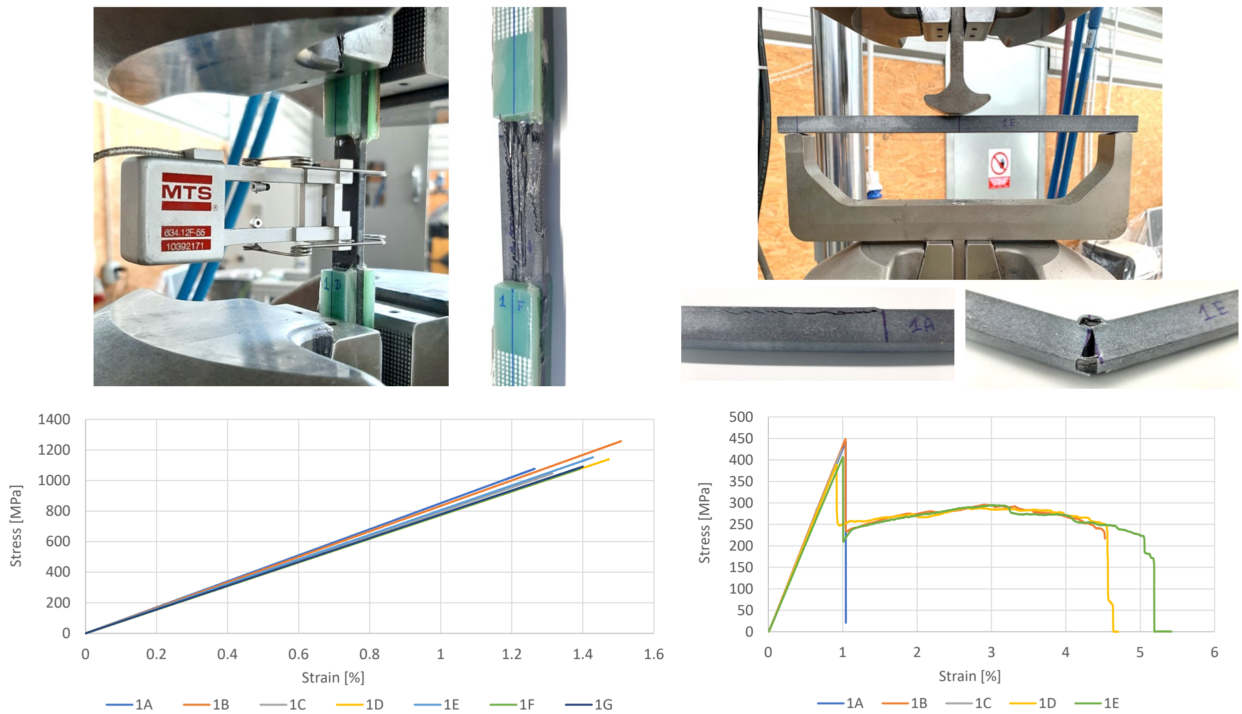


(a) (b)

Figure 2: Tests setup. (a) Tensile specimens, with one cavity aligned to the loading direction. (b) Bending specimens, with two cavities perpendicularly oriented with respect to the applied load.

Tensile tests were performed following the ASTM D3039 standard. Seven test repetitions were performed. All failed specimens show fiber breakage at the gauge zone. Results are shown in Table 2 and Figure 3a, which were calculated using the formulae described in the standard.

In a CFIP part, besides the AM material and the injected composite material, the interface between them also plays an important role. In order to evaluate the material properties of CFIP samples in a setup where the interface transfers significant loads, sandwich-like specimens under bending load have been tested following the ASTM D790 standard. Five test repetitions were performed. The load vs displacement curves are shown in Figure 3b, and the results are summarized in Table 2, which were calculated using the formulae described in the standard. Specimens 1A and 1C experienced the breakage of the upper fibers at compression followed immediately by the failure of the upper interface. Specimens 1B, 1D and 1E experienced the breakage of the upper fibers at compression followed by the breakage of the lower fibers at tension after a relevant deformation. Thus, in all the specimens the interface could withstand the maximum load and the fibres could be brought to their limit, demonstrating that CFIP can also be an efficient solution in cases where the interface withstands relevant stresses.



(a) (b)

Figure 3: Test setups: (a) image of a broken specimen, and stress vs strain curve showing results for 7 tensile specimens; (b) image of broken specimens, and stress vs strain curve showing results for 5 bending specimens.

For simulation and analysis purposes, it is needed to know the mechanical properties of the injected composite material inside the cavity. These results have been calculated from the tensile test results subtracting the area of the wall from the total transverse area according to the measured wall thickness. Results are included in Table 2.

A part of the CFIP technology demonstrator and the whole AM demonstrator shown in the next section, are made of AlSi10Mg alloy manufactured by Laser powder bed fusion (PBF-LB/M). Thus, 3 dog bone specimens were manufactured with the same processing parameters and tested following the EN ISO 6892-1 standard. The obtained tensile properties are included in Table 2, which are similar to previously reported values for similar Al alloys processed by PBF-LB/M [5].

Table 2: Mechanical properties obtained for the CFIP material, the injected composite inside the cavities of CFIP specimens, and the Al alloy used for the AM demonstrator. CV is the coefficient of variance, calculated as the ratio between the standard deviation and the mean value.

Material	Test	Property	Mean value	CV (%)
CFIP (AM part + injected composite)	Tensile	Young's modulus (GPa)	80.2	3.8
		Tensile strength (MPa)	1120	6.3
		Elongation at fracture (%)	1.45	4.7
	Bending	Bending strength (MPa)	422	5.8
		Flexural stiffness (GPa)	42.9	2.6
Injected composite (cCf + epoxy resin)	Tensile	Young's modulus (GPa)	120.6	-
		Tensile strength (MPa)	1683	-
AlSi10Mg manufactured by AM	Tensile	Young's modulus (GPa)	68.4	0.1
		Yield strength (MPa)	325	0.3
		Tensile strength (MPa)	465	0.2

The common way to compare the lightweight potential of different materials is through the ratio of strength versus density, known as the specific strength. Such value was calculated for the studied CFIP material (density of 1.22 g/cm^3), and compared with the AlSi10Mg manufactured by AM (density of 2.7 g/cm^3), the polyamide 12 (PA12) manufactured by AM (strength of 48 MPa and density of 1.01 g/cm^3, extracted from ref 6), and other lightweight solutions based on cCfs manufactured by AM available in the literature (tensile strength of 700 MPa and density of 1.19 g/cm^3, extracted from ref 7 and 8). The results are shown in Figure 4, where it is observed that the specific strength of CFIP material is clearly higher than the other materials and processing methods. Therefore, CFIP stands as the technology with the highest lightweight capacity while also allowing to take advantage of the freedom for design given by the flexibility of the AM techniques.

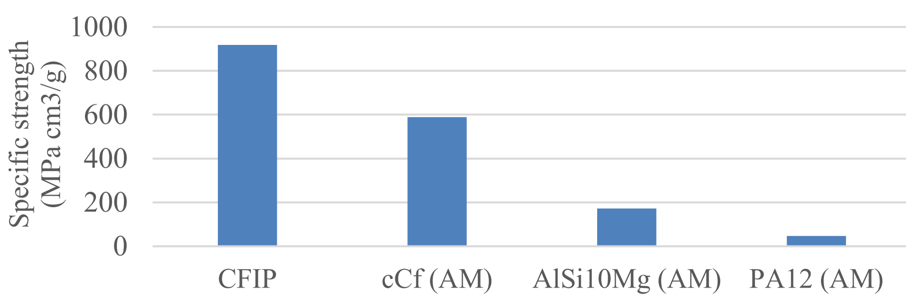


Figure 4: Specific strength of the different material options to build lightweight parts by AM: CFIP material, cCf composite material [7,8], Al alloy and polyamide 12 [6].

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CFIP technology validation: case study

The mechanical and lightweight performance of a structure is derived from the materials properties and geometry. To evaluate the performance of CFIP at the demonstrator level, a representative case study has been defined, consisting of a structure of 120x100x240 mm clamped through 4 bolts and submitted to a load in the Y direction of -5000 N. Figure 5 shows the created design space highlighting the clamping and loading zones. The objective is to minimize the weight while keeping the structural integrity following two different strategies:

(a) Demonstrator designed to fully exploit the lightweight potential of the CFIP technology. From now on it is named as CFIP demonstrator.
(b) Demonstrator manufactured with AlSi10Mg ally by Laser powder bed fusion (PBF-LB/M) with a topologically optimized geometry to fully exploit its lightweight potential. It is named as AM demonstrator.

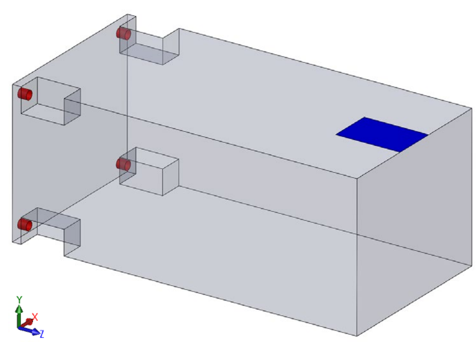


Figure 5: Design space of the defined case study. Clamped zones in red and loading zone in blue.

The CFIP demonstrator has been developed by the reinforcement and integral joining of two different parts manufactured by AM (Figure 6). At the clamped zone and specially around the bolts and CFIP units, high stress levels in all directions are produced, so an isotropic material with high specific properties is the best option. Thus, an AlSi10Mg alloy part manufactured by PBF-LB/M has been used at this zone, aiming to efficiently transfer the loads from the bolts to the injected CFIP units. For the central and loading zones, a PA12 part made by Multi Jet Fusion has been used aiming to save costs while providing the required mechanical properties.

The design of the fibre trajectories has been done by following three main criteria: (i) trace them from the loading zone to the clamped zone in order to efficiently transfer the loads, (ii) separate them where the moments are higher in order to increase the inertia and strength, and (iii) connect both parts in order to integrally join them.

Six CFIP units made of cCfs and epoxy resin have been used. A variant cross-section from circular (clamped zone) to squared (loading zone) has been designed with an effective diameter of 7 mm, aiming to efficiently transfer the shear loads between the injected composite material and the AM parts at both regions.

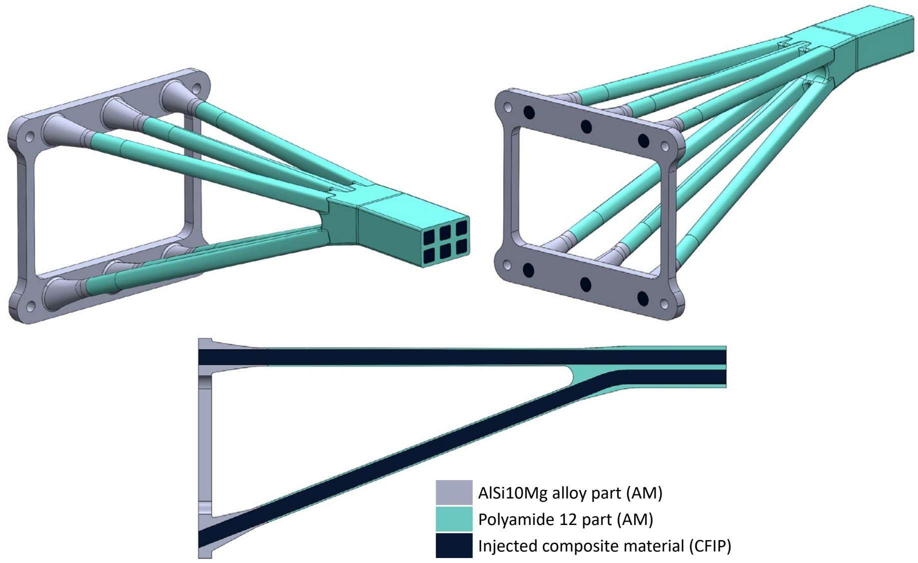
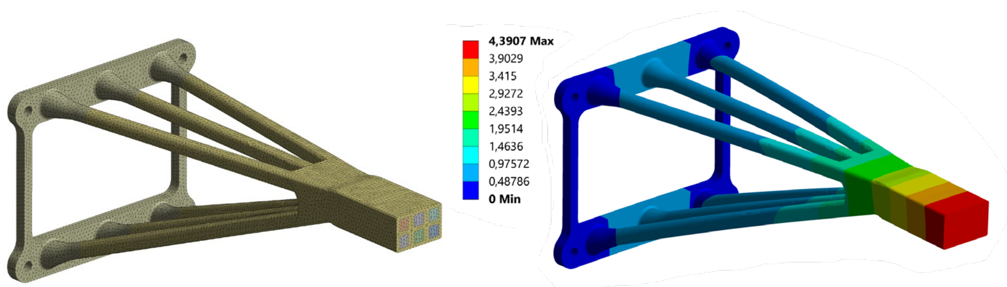


Figure 6. Design of the CFIP demonstrator: AlSi10Mg alloy part in grey, PA12 part in cyan, and injected composite material by CFIP in black.

The mechanical performance of this design was analyzed by the Finite Element Method (FEM) in ANSYS. The AlSi10Mg and PA12 materials have been modelled by defining a plasticity material model based on a bilinear isotropic law. . The CFIP units have been modeled as a unidirectional composite material using an orthotropic model. Discrete orientations have been also defined on the CFIP units to align the X direction of the material to the longitudinal direction of the units at each element. The geometry has been meshed with tetrahedral quadratic elements with an average size of 2 mm, as shown in Figure 7a. The obtained displacements after FEM analysis are shown in Figure 7b.



(a) (b)

Figure 7. FEM model of the CFIP demonstrator: (a) Mesh, (b) Displacements (mm).

The stress distribution in the CFIP demonstrator must be analyzed in detail in the AM parts, the injected composite material and also at the interface itself. Figure 8 shows the FEM results for such regions. In the aluminum part, the stresses are slightly above the yield strength at the clamped zones but below the tensile strength (Figure 8a), indicating that very localized plasticity could occur. In the PA12 part the stresses are far below the yield strength (Figure 8b). Figure 8c shows the distribution of shear stresses at the interface. It is observed that the stresses reach significant levels above 20 MPa only in localized zones close to the clamped regions. The stresses in the injected composite material have also been analyzed, showing values much below the tensile strength. A buckling analysis has been also performed on the structure, indicating that no global or local buckling will occur.

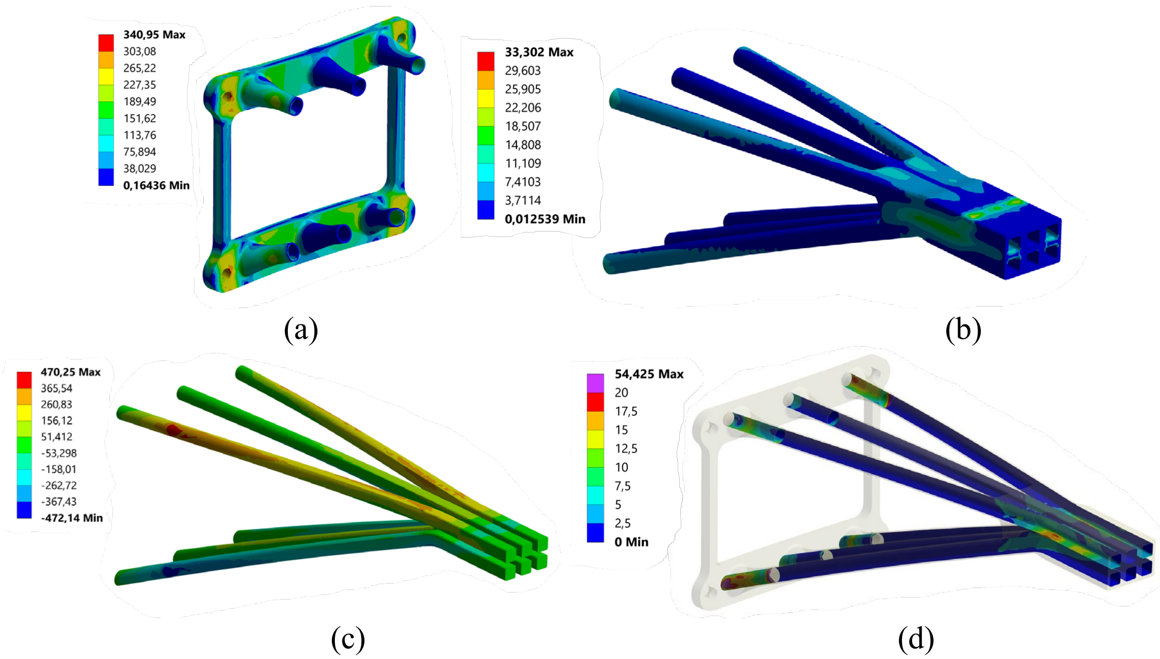


Figure 8: FEM results on the CFIP demonstrator: (a) Von-Mises stresses (MPa) at the AlSi10Mg alloy part. (b) Von-Mises stresses (MPa) at the PA12 part. (c) Longitudinal stresses (MPa) at the injected composite material. (d) Shear stresses (MPa) at the interface.

The AM demonstrator has been topology optimized by using the ALTAIR Optistruct solver, aiming to fully exploit its lightweight potential. The yield strength of the AlSi10Mg material has been defined as a constraint and the objective has been set to minimize the weight. The obtained geometry has been detailed in a CAD software in order to reach a functional design. FEM analysis have been also performed on this design using ANSYS. A plasticity material model has been defined by using a bilinear isotropic law. The geometry was meshed using quadratic tetrahedral elements with an average size of 2 mm (Figure 9a). A buckling analysis was also performed on this demonstrator, indicating that no global or local buckling will occur. Figure 9 also shows the distribution of displacements and stresses. It is observed how the stresses at the clamped zones are just at the yield strength of the material (Figure 9c), a really similar situation as in the CFIP demonstrator. It is also observed that the displacements are significantly lower compared to the CFIP structure, although they are relatively low in both cases compared to the dimensions of the structure and no requirements in terms of stiffness have been defined in the case study.

The final weight of each demonstrator is shown in Table 3. CFIP technology gives a 32% of weight reduction compared to the topologically optimized AM design in aluminum. As shown in other works [1, 2], such topology optimization for AM allows a 40% of weight savings with respect to conventionally manufactured parts. It means that the lightweight potential of CFIP technology can reach up to 60% when compared to traditional manufacturing methods, thanks to the efficient combination of different materials in highly optimized designs.

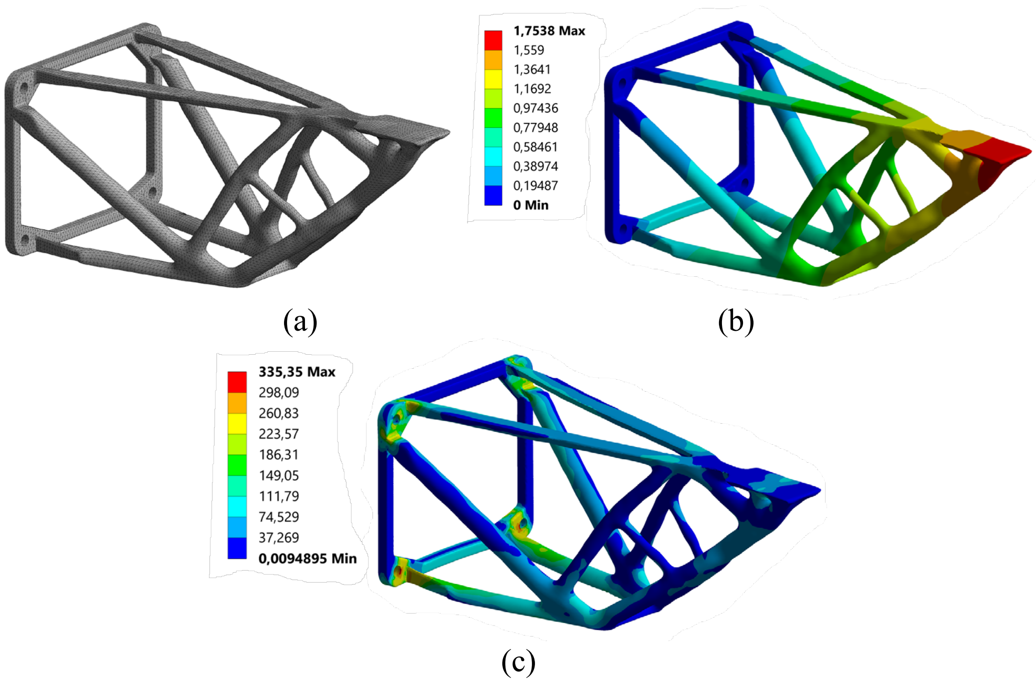


Figure 9: (a) Topology optimized geometry for AM demonstrator showing the mesh for FEM analysis. FEM results: (b) Displacement (mm), (c) Von-Mises stresses (MPa).

Table 3: Comparison of the weight of the two demonstrators.

Demonstrator	**Weight (g)**	**Weight reduction (%)**
Topologically optimized design for AM, Al alloy	329	-
CFIP technology, multi-material solution	224	32

Conclusions

This work presents the CFIP technology as an innovative approach to extremely optimize the lightweight and mechanical performance of structures, thanks to the reinforcement of highly optimized parts with continuous carbon fibers. The performance was evaluated at material and at demonstrator level for the CFIP approach and for AM in aluminum alloy.

The development of the CFIP demonstrator was assessed by the reinforcement and integral joining of two parts made by AM, one in aluminum alloy and the other in polyamide 12. The design was numerically evaluated by the FEM and compared with a topologically optimized part developed completely by AM in aluminum alloy. A weight reduction of 32% was obtained.

Such significant lightweight potential is attained thanks to the use of highly optimized AM parts, the efficient combination of materials and the optimal distribution of the continuous carbon fibers within the AM parts, which could not be achieved by other composites manufacturing methods based on layer-by-layer distribution of the fibers. Compared to conventionally manufactured components, the CFIP technology can reach a weight reduction of 60%.

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