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DESIGN STRATEGY FOR THE PROTOTYPING OF 3D-PRINTED CONTINUOUS FIBER-REINFORCED COMPONENTS FOR SOLAR-POWERED VEHICLE

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Abstract. Continuous fiber fused filament fabrication is an advanced 3D printing method that allows designers to produce high-performing lightweight structures, leading toward innovative design philosophies and sustainable production chains. In this work, we proposed a design strategy to manufacture selected components for a solar-powered vehicle, which consists of three stages. Firstly, the prototypes' CAD models are developed, considering their geometric and manufacturing requirements. Then, a finite element analysis is carried out to ensure optimal fiber reinforcement of prototypes' critical regions. Lastly, the manufacturing stage involves the slicing process and optimization of the time and cost of the printed part employing Markforged® technology. Adopting the proposed methodology, the experimental campaign investigated the print quality and performance of several prototypes of each component by adjusting printing parameters.

Keywords: 3D printing, continuous fibers, manufacturing constraints, solar-powered vehicle, Markforged®.

1. Introduction

Emilia V is a solar-powered vehicle prototype that looks to move forward the research for sustainable mobility in the automotive field, through the implementation of advanced lightweight high-strength materials. Realized in collaboration with the Onda Solare project and the University of Bologna, the prototype faces different challenges starting from the optimization of the materials employed to obtain a performant structure and weight reduction of the assembly [1]. To achieve this goal, Emilia V is built with carbon fiber-reinforced composite materials which have been known to have a competent strength and stiffness of the overall structure [2] while maintaining the lightweight property. From one side laminates of long carbon fiber reinforced thermosetting polymers have been employed to realize the main structure (the chassis) of the solar-powered car. Through this methodology, the skeleton of the vehicle was produced by means of a lamination process of the carbon fiber plies in a defined sequence followed by a curing period to strengthen and compress the layups.

On the other hand, to optimize the manufacturing of load critical components, continuous fiber fused filament fabrication (CF4) has been selected as the technology to study for this application. CF4 is an innovative 3D printing (3DP) technique, that merges the additive manufacturing (AM) process with the enhanced mechanical properties of continuous fiber reinforced materials, allowing the designer to realize design-tailored, lightweight, and high-performing components [3]. To increase the strength of the printed parts, during the extrusion process, filaments of continuous fiber, such as carbon fiber (CF), fiberglass (FG), or Kevlar, are embedded into the thermoplastic polymeric matrix [4]. The addition of high-strength high-resistance continuous fibers leads to an enhancement of the strength-to-weight ratio of the manufactured component, leading to the realization of additive manufactured piece with increased mechanical properties. While generally additive manufacturing techniques are limited in their applications to rapid prototyping and fast tooling mainly [5], this advanced technology allows to experiment new designs and through a focused optimization process, innovative prints that can represent a competitive alternative for replacing metal parts.

Several companies offer printers with the possibility to reinforce through CF4 manufacturing process, and between them, Markforged® provides a series of commercially available machines [6], able to realize short and continuous fiber-reinforced structures while optimizing the printing time and cost. Through the printing process it is possible to customize several parameters including the type of fiber reinforcement, its pattern and orientation, and the infill geometry and percentage, which can be tuned to obtain the desired reinforced structure. In addition, the several available materials and fiber fused filaments increase the possible combinations that need to be studied and investigated experimentally, since every different set of printing parameters generate unique mechanical properties of the final part [7].

Coupons manufactured through this reinforcement type are being tested and characterized to investigate the limit and the extent of the technology, spacing from tensile [8], compression [9] and shear [10] tests,

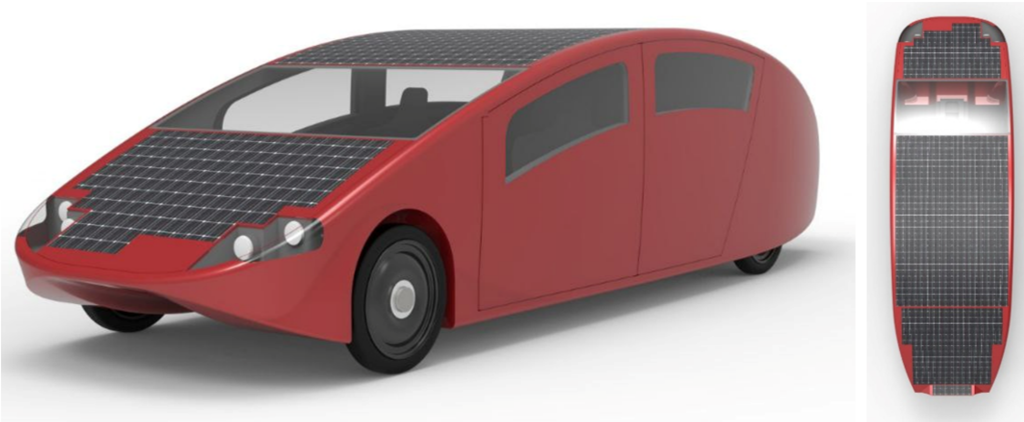


Figure 1. Rendering of Emilia V, by Davide Grandini.

Process	Fused filament fabrication, Continuous Fiber Reinforcement (CFR)
Build Volume	320 × 120 × 154 mm (12.6 × 5.2 × 6.0 in)
Layer Height	100 μm default, 250 μm maximum
Print Bed	Precision Ground Composite
Nozzles	2 (1 for plastics, 1 for fiber)

Table 1. Markforged Mark Two 3D Printer properties (available at https://markforged.com/3d-printers/mark-two.

impact damage resistance [11, 12] and so on. However, the experimentations for this technology are still restricted to material characterization and sample testing. This means that there is still a gap in the literature regarding the whole capacities of the CF4 manufacturing process, from the design strategies and parameters manipulation to the experimental campaigns that could be performed.

In this work, we investigate the capacity of the CF4 technology as a metal parts replacement methodology. In order to achieve additively manufactured parts with mechanical properties enhanced enough to compete with metal components, an optimized design strategy has to be implemented. While CF4 provides a way to reinforce polymeric structures, a defined and specific workflow is required to adjust the designed models to 3D printing capabilities and limitations, as well as, to efficiently tune the setup parameters to achieve a part able to perform under studied load cases. Therefore, in this study, we propose an optimization and design workflow to explore the strategic implementation of CF4 technology to manufacture selected critical components for Emilia V shown in Figure 1, such as, the brake pedal [13].

2. Materials and set up

In this section, the available materials, the experimental set up and the used equipment in this work are shown and expanded in the following subsections.

2.1. Set up and equipment's parameters

For the manufacturing part of this project the Mark Two 3D printer has been employed. This printer allows a print volume of 320 × 120 × 154 mm with a precision of 100–200 μm. To perform fused filament fabrication (FFF) and CF4 the printer is equipped with 2 extruders, one which prints the matrix material, and the other which allows the deposition of the fiber filament. Its properties are summarized in Table 1.

The Markforged company provides its own slicing software (Eiger) in order to convert the designed model specifics into detailed instructions for the printer.

To perform with the slicing process, it is required to provide an standard tessellation language (STL) model of the component to be printed. The 3D models have been realized through Solidworks® and then the parts files have been converted into the `.stl` format. Once the file is uploaded in the slicing software, it is possible to select the printing parameters that would affect the final properties of the part. It is important to notice that the features that significantly influence the print quality and the prototypes' mechanical properties can range from machine capabilities, to environmental factors [14], and from chosen materials, to the printing parameters set up [15], which the designer is going to select. However, in this investigation, it has been possible to control the manufacturing materials choice, which is studied in the next subsection, and part of the printing features, such as fiber deposition path, part orientation on the print bed, infill geometry pattern and percentage.

From the settings it is possible to select two particular fiber filament deposition paths, already set by the software. These are called "isotropic" and "concentric" deposition path, which are two standard options and cannot be modified. The "isotropic" reinforcement path does not refer to an actually final isotropic property since, even through the application of continuous fibers, it is not possible to produce an isotropic piece

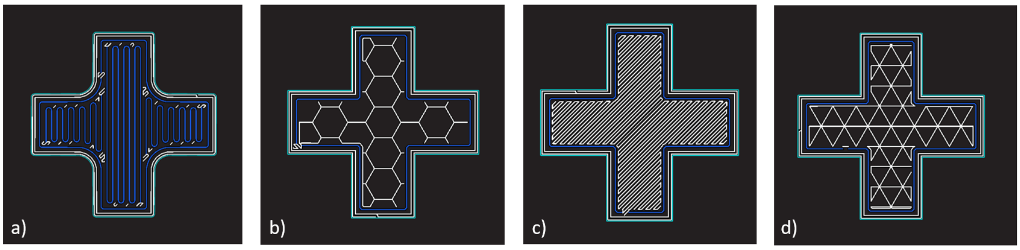


Figure 2. Markforged® Layer slicing: deposition of a) "isotropic" fiber at 90°, b) "concentric" fiber with hexagonal infill geometry, c) "concentric" fiber with solid infill geometry, d) "concentric" fiber with triangular infill geometry.

Material	**Tensile Modulus [GPa]**	**Flexural Strength [MPa]**
Carbon Fiber	60	540
Kevlar	27	240
Fiberglass	21	200
Onyx	2.4	71
Nylon	1.7	50

Table 2. Mechanical properties of the materials; data provided by the Markforged®company,

by means of additive manufacturing technique. It is named this way because it allows the designer to fill selected layers with the deposition of continuous fiber filaments at chosen angles. Therefore selecting several angles through the layer might lead to a more "isotropic" distribution of the fiber orientations and therefore to a final piece resistant to different load application angles. For example, to obtain a general reinforcement of a piece, fiber filaments are usually deposited at −45°, 0°, 45° and 90°, along at least 4 layers (one layer can only have one fiber orientation angle). Moreover, with this option, it is possible to add one or more filaments of fiber that shall follow the boundaries and perimeter of the geometry, generating a reinforcement along the thickness of the part. This is the "concentric" fiber path, which can also be selected alone, providing a fiber reinforcement around the borders of the component section that is going to be filled with the matrix material and pattern. Some examples of "isotropic" and "concentric" deposition are shown in Figure 2.

Another important factor that affect the manufacturing process is the part orientation on the printing bed, which has been shown it significantly influence the final part accuracy and in particular its mechanical properties [16, 17]. Therefore, it is necessary to study the 3D model of the part in order to efficiently select which would be the growing direction of the part (Z axis) and partly control the anisotropy of the final part. Through this section, it is also possible to choose the starting face of the print, the one that would represent the 1st layer.

Then, the designer has to select the infill geometry pattern and its percentage of filling. The slicing software provides several geometries as infill shapes, such as triangular, hexagonal, rectangular, gyroid, solid (100 % fill) [18], some of which are visible in Figure 2. Although the software recommends to use triangular infill at 37 % filling rate for an optimal print, the hexagonal infill can achieve lighter structures and reduced print time, while the solid pattern leads to heavier components with enhanced strength and stiffness characteristics. It is possible to play with this parameters and obtain several unique combinations of features which each presents different mechanical properties [19].

Prior the print launch, the set up requires to carry out a fine calibration of the print bed which must be cleared by any residue or last print, as well as the nozzles from exceed material. A good calibration level is required for a good quality final piece, since if the extruder is too far from the plane, the filaments shall not compact, while if it is too close, the nozzle does not have enough room to extrude material and may even scratch the bed. In addition, it is also necessary to add some sticking washable glue that enhances the adhesion between the printed part and the bed. This is required since the printer chamber is not heated, therefore leading to an increase of detachment issues.

2.2. Materials

The choice of the manufacturing materials, especially the reinforcement material, is important to define the final part elastic and stiffness features. In Table 2 are enlisted the properties of the filaments available by the manufacturer. The available printing materials provided by the Markforged® company are divided into two main categories: the matrix (infill) material and the continuous fiber filaments. The printer is compatible only with the materials provided by the company (patent) and other furnished by third parts cannot be used as an alternative.

On one side, the continuous fiber filaments provided by Markforged® space from carbon fiber (CF), fiberglass (FG) and Kevlar (Figure 3).

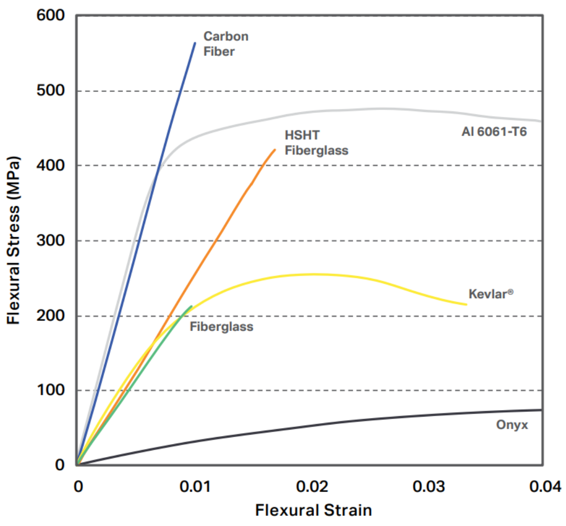


Figure 3. Materials mechanical properties; plots provided by the Markforged® company.

From the table it is highlighted that CF is the most performant under stress and therefore it has been preferred to reinforce critical parts that have to sustain greater loads, while FG has been chosen for parts that required less load response.

Regarding the thermoplastics, Markforged® allows to a large selection of materials, starting from classic PLA, nylon and the more complex and performant Onyx. Onyx is a combination of a nylon base and short (chopped) carbon fibers, randomly distributed, to generally enhance the mechanical properties of the starting component. Although it shows improved stiffness and strength with respect to other thermoplastics, this material presents high sensitivity to moisture, which is absorbed even at room temperature conditions, negatively affecting the mechanical properties [16]. Therefore, Onyx must be stored under vacuum bags or in closed dry boxes designed specifically to maintain low humidity levels. This material is compatible with the long fiber reinforcement technique, and therefore in this experimental investigation Onyx has been selected for matrix extrusion.

3. Design strategy

Since CF4 is still limited for industrial use due to the wide range of design parameters available, recent studies recommend adopting a performance-driven design practices, which can support the designer in exploiting the CF4 for general industrial applications. This study aims to develop a design strategy to realize high performance light-weight components for a Markforged (Mark Two) 3D printer in the framework of sustainable mobility (solar-powered vehicle application). The proposed design strategy involves three macro stages.

3.1. Step 1: A general workflow to tailor designs based on geometric constraints

Firstly, a systematic 3D modelling approach allows the designer to develop and tailor the part design, taking into consideration the geometric constraints and performance requirements. Starting from an initial draft, the design undergoes a process of optimization, weight reduction, reinforcement addition to adapt the geometry to the AM technology [20]. In this stage, the geometry of the component is considered a draft that satisfies the given size requirements and subsequently, shall be modified according to an iterative procedure that takes into account also the load case analysis and the manufacturing requirements. This is required because the initial draft of the part is usually designed according to metal production philosophies, but realizing the same by means of additive manufacturing would lead to a piece not optimized nor efficiently robust to operational load. Therefore, a strategy based on the AM requirements is applied taking into consideration print orientation, anisotropic behavior and fiber reinforcement constraint (e.g. required minimal thickness for fiber deposition) during the modelling sketch. This optimization process of the design is unique for each realized components thought AM, since each part presents different geometries, weight constraints and load conditions. An example of this workflow is shown in Figure 4, where the brake pedal model is considered. Starting from a sketch that includes the principal dimensions imposed by the Emilia V structure, the part has been thickened to its extent in order to generate a more robust piece. However, this leads to a significant increment of the component weight and cost due to quantity of employed material. Therefore, as a next step, a weight reduction process has been applied, paying attention to reduce the thickness only on the areas less reactive to the stress application. Doing so, the final model is realized accordingly to weight and cost reduction aims as well as structural integrity of the part.

3.2. Step 2: Load case analysis suited for each component stress condition

As a second stage, a load analysis is carried out to examine the stress conditions and highlight the prototypes' critical regions. The analysis can be performed both on Ansys® software which simulates the worst-case scenario where only the matrix material is reacting to the applied loads, or through a simplified mathematical model that leads to a fast approximations of the generated stresses. Specific constraints and boundary conditions have to be set with particular attention to contact areas accordingly to the load case scenario investigated. For example, for the brake pedal analysis the chosen load condition regards an emergency brake of 100 kg, constrained at the fulcrum of the rotation through a cylindrical support, where only the Onyx material is reacting to the load. In

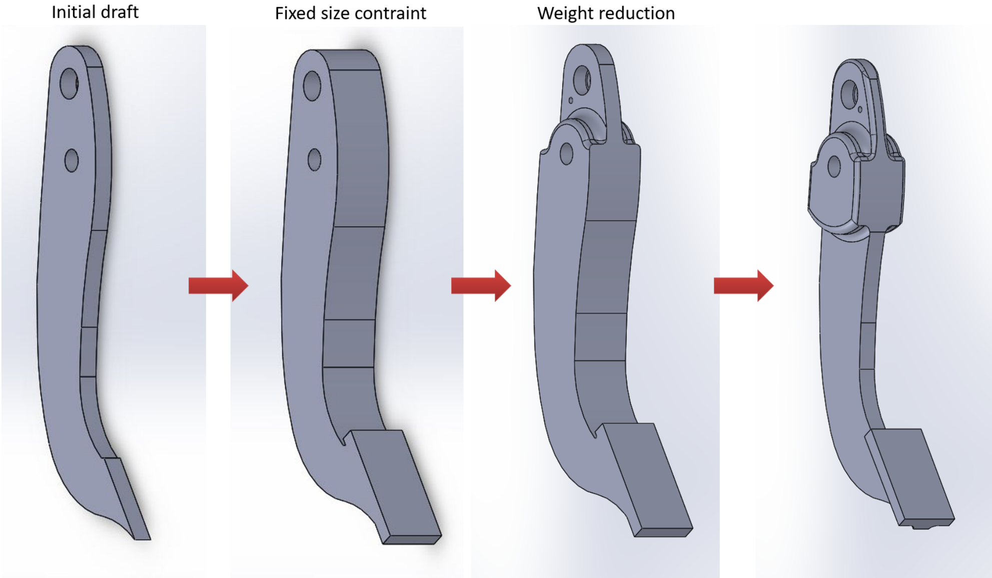


FIGURE 4. Brake pedal design optimization process.

addition, contact boundary conditions have been applied to evaluate the stresses that may arise through contact surfaces.

From the analysis outcomes (Figure 5), the critical areas of the stress field are highlighted, and are used an input in the definition of the optimal fiber reinforcement path for the structure that allows a strategic deposition of the strengthening material along the stress directions. From the same example, it is shown that some concentrated stress points are present, that would be resolved by the deposition of continuous fiber in those regions. This is possible because the long fiber allows to redistribute the stresses, avoiding to generate load peaks and concentrations in small regions.

On the other hand, an approximate analytical evaluation of the stresses is performed through the implementation of a simplified mathematical model.

Starting with an estimate of the stress the structure generates to react to the bending load applied, the flexural strength σ has been evaluated through its general formulation 1, where M represents the bending momentum expressed in [Nmm], and W_f is the section modulus indicating the resistance to bending of a selected cross-section.

$$\sigma = \frac{M}{W_\mathrm{f}} \qquad M = load \cdot arm \tag{1}$$

Defined by Eq. 2, the section modulus is express in its general formula, as the area moment of inertia I divided by y_f, which is the maximum distance from the neutral axis of the cross section. However, to calculate the section modulus, it was chosen the formulation which regards the shape of the cross-section investigated in this case, shown in Figure 6. Therefore, the corresponding modulus calculation for this kind of geometry is indicated by Eq. 3.

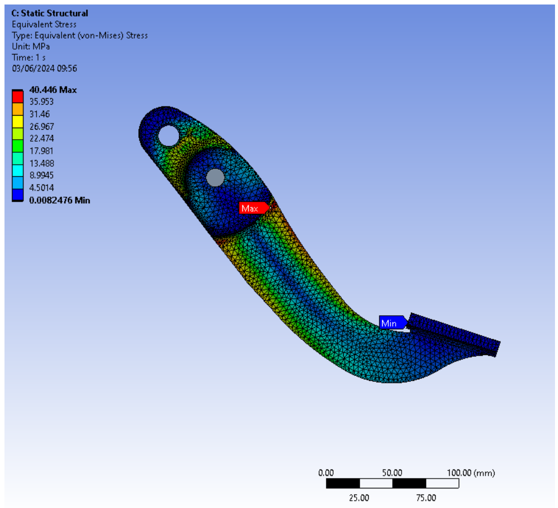


FIGURE 5. FEA results of brake pedal loading condition for equivalent stress.

$$W_\mathrm{f} = \frac{I}{y_\mathrm{f}} \tag{2}$$

$$W_\mathrm{f} = \frac{b(H^3 - h^3)}{6H} \tag{3}$$

The process allows a comparison between the two maximum stress values the component has to sustain and works as a check of the simulation results. For the case of the brake pedal, while the simulation output corresponds to a maximum stress value of 40.4 MPa, from the formulas the obtained result corresponds to 38.5 MPa. In addition, the iterative design procedure expects to adjust the original draft of the component in the case the FEA or the mathematical estimation of the loads highlight stress concentration points unsustainable for the structure.

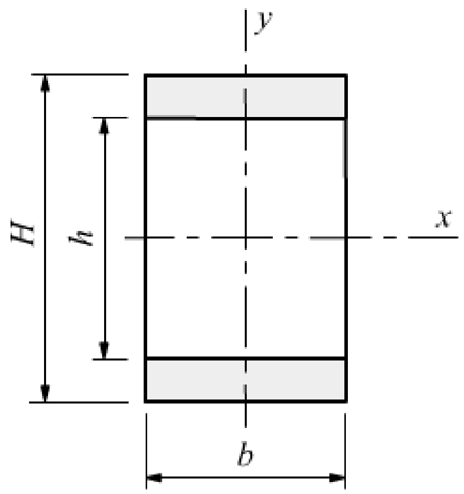


Figure 6. Rectangular cross-section.

3.3. Step 3: Manufacturing process of high-performance advanced light-weight structures

Lastly, employing the Mark Two 3D printer, the components have been manufactured as a subsequent step of the slicing process and the optimization of the time and cost of the part. The available instrumentation provides the manipulation of the several setup parameters enlisted in the previous section (fiber deposition path, part orientation on the print bed, infill geometry pattern and percentage, and choice of the reinforcement material). At the end of the slicing process, a new iteration of the design may be required, since from the view layer-by-layer, some defects in the printing can arise. For example, since the printer requires a fixed thickness to deposit the fiber, the design may present features too thin, which the printer is not able to reinforce. Therefore, the geometry shall be updated and modified accordingly. In addition, the tolerances of the printer accuracy must be taken into account, in order to avoid obtaining components that cannot work together because of strict or loose plays. Through the optimal combination of the tunable manufacturing features, it is possible to obtain a desired final part with a specific enhancement of its mechanical properties and weight reduction.

4. Results

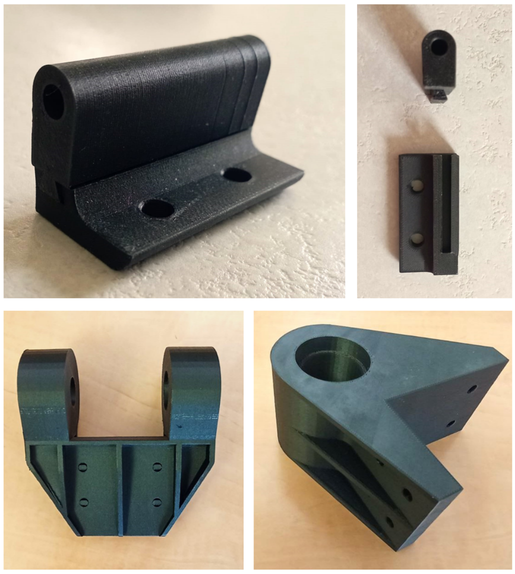
Through the proposed strategy, several prototypes have been manufactured leading to an evaluation of the combinations of chosen design, adjustable printing parameters and material properties. The high-performance advanced light-weight components are obtained through CF4 technology achieving a significant weight reduction while maintaining structural integrity. These critical components include the brake pedal (Figure 7a), the suspension joints, the door hinges (Figure 7b) and others. All these parts have been assembled on the Emilia V chassis and are being tested throughout the duration of the next solar challenge competition at which it participate (Sasol Solar Challenge, South Africa, Sempt 2024). The obtained component have been compared based on weight, cost, printing time and quality. Each of these parts is a result of a different combination of parameters leading to a unique optimization that needs to be tested in the following steps of this work. For the brake pedal carbon fiber has been deposited at −45°, 0°, 45°, 90° in the layers where the thickness changes occur in order to generally strengthen the structure. Moreover, three filaments of continuous fibers have been applied at the borders of the cross section along the whole thickness to prevent the formation of stress concentration points. To reduce the weight of the part, the internal matrix had been filled with hexagonal shaped infill. The pedal print had taken around 24 hours to be completed, and the final piece weighted less then 200 grams. Similarly to the brake pedal, the suspension joints have been reinforced with CF deposited at the borders and "isotropically" but the infill is solid to increase the stiffness and resistance to the applied load. Lastly, the door hinges have been realized through a separated design in order to reinforce the base structure horizontally around the contact joints, while the fulcrum part had been printed transversely to strengthen the main hole. The model has been studied and designed to these requirement, and therefore to fit the two pieces together at the end of the print a dovetail joint has been employed to merge the parts in a whole component. Moreover, in this application FG has been selected as the reinforcement material.

5. Conclusions

A statistical dataset on Markforged® is being collected, and subsequently will offer detailed insight into the addressed printing parameters, allowing the generation of a system to catalog the final parts based on their quality, performance, print time, and cost. The limitation and capabilities of the printer are also analysed, leading to a significant know-how of the Mark Two and therefore, to a finer prints. Moreover, the Emilia V project is being completed by means of the continuous fiber-reinforced structures to enhance the parts mechanical properties such as tensile strength and flexural strength. This allows to optimize the time and cost of the required components and reduce the solar-powered car's weight due to the substitution of metal parts with 3D-printed continuous fiber-reinforced prototypes.

On the other hand, the planned future work includes tensile, shear, and compression tests of selected samples to investigate the effect of fiber reinforcement patterns and infill geometries on the mechanical properties. Furthermore, investigations on the moisture effect on the material mechanical properties is required to be carried out in order to examine the strength and stiffness changes over time during humidity absorbing periods. Finally, the proposed methodology will be

(a). Brake pedal: on the left the slicing view of a layer, on the right the final printed component.



(b). On the top, door hinge reinforced through FG filaments; on the bottom, suspension joints realized in solid infill with addition of CF reinforcement.

Figure 7. Examples of outcomes of the design strategy and CF4 manufacturing process.

updated and optimized during the next studies and therefore implemented as support in other projects, such as the realization of a solar-powered boat that will eventually compete in the Monaco Energy Boat Challenge.

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