COMBINING ADDITIVE MANUFACTURING WITH CFRP COMPOSITES: DESIGN POTENTIALS

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Abstract

The combination of Additive Manufacturing (AM) with Carbon-Fibre-Reinforced Polymers (CFRP) unlocks potential in the design and development of highly integrated lightweight structures. This paper introduces two different design potentials, where the combination of AM and CFRP can lead to better and lighter hybrid structures: First, Load Introductions often show complex superimposed loads and therefore lightweight metal alloys become a valuable alternative to CFRP. With AM, load-oriented designs that provide a more continuous introduction of the load into the fibers become possible. Secondly, tooling for complex composite structures is expensive and laborious. Here, inner tooling with AM can offer potentials in the design and development of complex-shaped composite parts. Within this paper, the potentials are highlighted by a case study that consists of the development of a Hydraulically actuated Quadruped robot (HyQ) leg. Based on the case study, the need for fundamental research in the design and processing of structures with AM and CFRP is pointed out in order to pave the way for its use in future high performance technological applications.

Keywords: Design for X (DfX), Additive Manufacturing, Carbon-Fiber-Reinforced Polymers, HyQ

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1 INTRODUCTION

Carbon Fiber Reinforced Polymers (CFRP) are materials with high strength and stiffness at low weight and are therefore of great interest for the development of high performance lightweight structures. CFRP are applied wherever a high strength-to-weight ratio is required such as in aerospace, sports goods, automotive and robotics applications. The Airbus A380, for example, is composed of 22 percent of composites and therefore has an empty weight of around 240 tons, which is 15 tons less compared to a similar but conventionally manufactured aircraft. (Bochard-Tuch, 2006) However, a considerable fraction of potential weight savings offered by CFRP remains unused in areas of (i) load introductions into composites and (ii) where complex geometries are required as the shape of CFRP components is limited by tooling.

Structural joining of composites in areas of load introductions is still a challenging process as the full strength and stiffness characteristics of the laminate often can not be transferred through the joint without a significant weight penalty. Traditionally, joints for composites and metals are either riveted (mechanically fastened) or bonded (adhesive) or both. Mechanical fastening requires drilling through reinforced fibers which creates stress concentrations and thus reduces the load carrying capability of the material. (Godwin and Matthews, 1980) To overcome this disadvantage overlap areas are increased, larger fastener arrays are used or laminates are locally thickened to reduce bearing and net-section stresses (Parkes et al., 2014). However, this strategies significantly increase the weight of the joint area. Adhesive bonding is a well understood technique that allows the design of lightweight structures with complex shapes as the weight increase is negligible. Good design for adhesive bonding involves creating a geometry that avoids critical shear stresses being exceeded (Pethrick, 2012). From this follows that optimal design shows an optimal load distribution at minimal weight. This is the principle of load-oriented design. Additive Manufacturing (AM) technologies are perfectly suited for such applications as they allow the direct production of structures with high geometric complexity (Breuninger, 2013). Furthermore, load introductions often show complex superimposed load cases and therefore a quasi-isotropic composite layup is recommended. This reduces the weight advantage of the composite and therefore isotropic lightweight metal alloys become a valuable alternative to CFRP in such critical areas.

The second point is that the design of load-oriented shaped composite structures results in complex geometries and therefore necessitate complex tooling. Design and material selection aspects for tooling consider criteria such as dimensional accuracy, laminate and surface quality as well as cost efficiency and the possibility of manufacturing highly complex shapes. Particularly the production of complex hollow parts is laborious as inner tooling is required. Typical tooling materials such as PU foam or aluminum alloys are milled to the desired shape and underlie requirements from conventional machining such as the accessibility to machine tools. Consequently, the design opportunities with composites are limited by the manufacturing process as good ideas often can not be produced (Gutowski, 1997). With additive manufacturing the production of complex inner tooling and hence the manufacturing of load-oriented composite structures is eased.

This paper presents design potentials of the process combination of AM with CFRP such as load introductions into composites and inner tooling with AM for composite structures. A case study consisting of the development of the lower leg of a Hydraulically-powered Quadruped (HyQ) robot with AM and CFRP is conducted to investigate the applicability of such potentials on part level. Two design approaches for lightweight structures are used : (i) A Multi-Material Design (MMD) approach is applied to use the specific material advantages according to their function within the structure (Noster, 2009). Consequently the load introduction is designed as a metal part made by AM, whereas CFRP performs the load transmission. The principle of (ii) load oriented design (Pahl et al., 2013) is applied throughout the whole system which is an advantage of using AM for hybrid structures with composites.

This paper proceeds as follows: Section 2 compares AM with composite technologies and outlines opportunities for the design of hybrid structures with AM and CFRP. In this context the mutual facilitation of both technologies is pointed out. Section 3 presents the development of the HyQ robot leg with AM and CFRP. The case study focuses on design, manufacturing and testing. Based on the case study, the potentials for the design of hybrid structures with AM and CFRP are discussed. Section 4 concludes.

2 DESIGN POTENTIALS OF THE PROCESS COMBINATION OF AM WITH CFRP COMPOSITES

This section introduces Additive Manufacturing (AM) and composite technologies. Both are compared and potentials for the design of hybrid structures are identified.

2.1 Characteristics of AM and Composite Technologies

Composites are multi-phase materials. They result from the combination, on a macroscopic scale, of two or more constituent materials with different properties to form a fully new material (Ermanni, 2007). Carbon Fibre Reinforced Polymers (CFRP) consist of aligned continuous carbon fibers (length > 25mm) that are embedded in a polymeric resin (e.g. epoxy) (Mallick, 2007) . For many industrial high performance applications PREimPREGnated (PREPREG) fibers are laid down in a mold to form the desired shape (Hexcel, 2013). Subsequently, the layup is cured at temperatures ranging from room temperature to 180°C (Gutowski, 1997). Although curing can be performed in a variety of devices, the use of an autoclave allowing the application of defined high pressure-temperature cycles for the production of high-performance parts is state of the art in the industry. After curing, the part is demolded and surface finishing is applied.

Additive Manufacturing (AM) refers to a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies (ASTM International, 2012). AM technologies have reached a manufacturing readiness level ranging from 5 to 10, differing by application. For aerospace, production is demonstrated in a production environment and for tooling, low rate production is state of the art. (Roland Berger, 2013). Especially Selective Laser Melting (SLM), Selective Laser Sintering (SLS) and Fused Deposition Molding (FDM) show high relevance for direct manufacturing and prototyping. (VDI, 2014). SLM and SLS are powder-based processes where a high energy laser beam melts the metal powder, respectively sinters the thermoplastics powder whereas for FDM a thermoplastic filament is melted in a nozzle and deposited on a plate (Gebhardt, 2013).

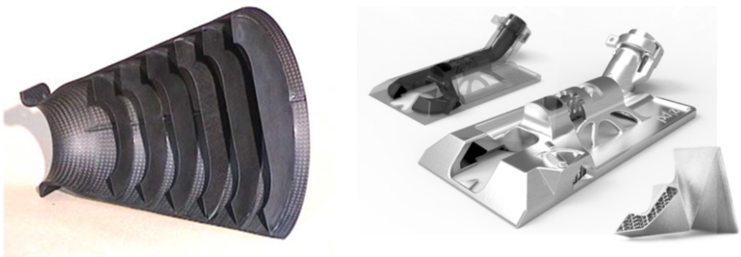

Figure 1. Composite camera baffle for the HESSI satellite (left) (Laboratory of Composite Materials & Adaptive Structures) and AM jig saw leg (right) (Leutenecker, 2015)

Common to composite and AM technology is that the material properties are generated *during* the manufacturing process as opposed to conventional subtractive machining techniques. However components made either by CFRP or AM differ in characteristics such as their specific mechanical properties, possible component size, geometrical complexity and design parameters. Parts made of AM and CFRP are compared according to these characteristics in the following section and are summarized in table 1.

The effectiveness of strength or stiffness of a material for structural lightweight applications is commonly expressed as a ratio of the mechanical properties to the density. These strength-to-density or stiffness-to-density quotients are called (i) *specific properties*. The mechanical properties of CFRP strongly depend on the fiber angle. Unidirectional (UD) reinforced composites show high mechanical properties in longitudinal direction as the fibers are able to carry high loads. However, loads occurring perpendicular to the fiber direction are carried by the mechanically weak matrix and therefore considerably reduce the mechanical properties in transverse direction. Consequently the specific mechanical properties of CFRP are outstanding only in fiber direction. For example, the specific properties of unidirectional high-tenacity (HTA) carbon fiber reinforced epoxy (CF-EP HTA, UD) with a fiber volume content of 60% displays a specific strength of $1600.10^3\ m^2/s^2$ and a specific stiffness of $96.10^6\ m^2/s^2$ in fiber direction but only $35.10^3\ m^2/s^2$, $8.4.10^6\ m^2/s^2$ respectively perpendicular to the fibers (Wiedemann, 2007). In contrast, the mechanical properties of AM materials strongly depend on the base material and the process. Although a specific anisotropy of several percent can be observed, it is neglected during the engineering design process (Spierings and Wegener, 2013). The specific static mechanical properties of SLM metals are typically in the range of wrought conventional materials. Stainless Steel CL20ES ranges in the area of $73.10^3\ m^2/s^2$ for the specific strength, $25.10^6\ m^2/s^2$ for the specific stiffness. For aluminum AlSi12 the values amount to $121.10^3\ m^2/s^2$ for the specific strength and $28.10^3\ m^2/s^2$ for the specific strength.

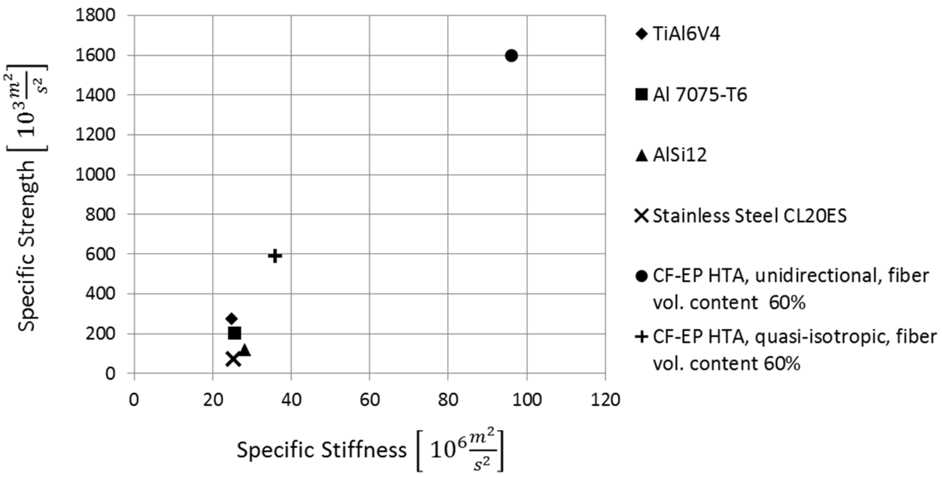

Figure 2. Comparison of specific strength and stiffness of composites, aerospace alloys and metals used for SLM (adapted from Campbell, 2010 and Wiedemann, 2007)

CFRP and AM offer different (ii) *design parameters* to tailor the mechanical characteristics of the part. By varying fiber angle and fiber volume fractions of CFRP, one can obtain an enormous range of material properties. Fibers can be placed according to the load path of the part, thus using the advantages of composites of designed anisotropy to minimize weight.

For AM, load oriented designs can be achieved by placing material where required, which often results in very high (iii) *geometrical complexity*, since the direct manufacturing of optimized three-dimensional shapes and topologies is possible. The freedom of design is enormous compared to other manufacturing technologies albeit not infinite as process dependent limitations influence the design. Therefore design rules (e.g. minimal wall thicknesses) are required. Composite technology usually is used for two-dimensional shell structures, where the thickness of the laminate is thin compared to the length or width of the part. Curved shapes are possible and require appropriate molds. Shaping of composites is bound to the usage of molds which limits the geometrical complexity of the final part. However, there are no limitations to the (iv) *part size* of composite structures. Just recently, three 75 meters long rotor blades for a six megawatt off-shore wind power plant were manufactured in one shot (Siemens). However, for AM the building space is limited. Typical FDM machines as the Stratasys Fortus have a building space of around 355 x 305 x 305 mm, whereas the SLS machine EOS P 396 covers the area of medium building spaces with 340 x 340 x 600 mm. A common SLM machine such as the EOSINT M 280 has a part volume of 250 x 250 x 325 mm (Wohlers and Caffrey, 2013). The trend in AM technology goes towards larger sized parts, higher process stability and an enlargement of the number processible materials (Gausemeier, 2013).

Table 1. Characteristics of components made of CFRP and AM

	CFRP		*AM*
+	High specific mechanical properties (Stiffness & Strength)	+	Mechanical properties strongly depend on process and material
+	Designed anisotropy	o	Quasi-isotropic material properties
-	Complex-shaped parts	+	Parts with extremely high geometrical complexity
+	Big size structures	-	Limited building space

2.2 Design Potentials for Hybrid Materials with AM and CFRP

In order to identify design potentials for parts produced by AM and CFRP it is necessary to analyze the functions and constraints of the specific part. For load carrying structures these functions are: (i) *load introduction*, as almost every part requires the design of joints and bonds where concentrated forces are introduced into the structure or led out of it. (ii) *Load transmission* fulfill the function of guiding the load as direct as possible. For composites, this means that (iii) *tooling* has to be considered as it strongly influences the parts' shape and thereby the load transmission. Two design potentials for AM and CFRP will be presented below: Load introductions and inner tooling with AM.

2.2.1 Load Introduction

Strength problems such as bearing, breaking or cleavage typically appear at critical points such as concentrated load introductions, joints and cutouts. All these critical points disturb the elementary load distribution by geometrical or material discontinuities and result in stress peaks ultimately reducing the service life of dynamically loaded structures (Wiedemann, 2007). To make things worse, several superimposed load cases appear in such critical points. Design measures reducing stress peaks and minimizing stress discontinuities are required. Therefore a quasi-isotropic layup is recommended for CFRP at load introductions (Schürmann, 2007). Quasi-isotropic laminates exhibit isotropic in plane response, that is independent of direction. In that case more material is required to reach a specific stiffness and thus the weight advantage of CFRP compared to lightweight metal alloys is lost. Figure 2 shows the specific stiffness of quasi-isotropic CF-HTA and selected lightweight materials. In effect the weight advantage is reduced to a factor of 1.44 compared to titanium TiAl6V4, and to aerospace aluminum Al 7075-T6.

Another design measure reducing stress peaks is design optimization. This often results in highly complex geometries and the manufacturing of such complex CFRP load introductions is associated with high effort. Consequently, CFRP is not the best option for multi-axial load introductions and an alternative technology, allowing highly complex designs, is required. As seen in Section 2.1 AM is well suited for the design of such structures. This specific characteristic of AM allows the design of load oriented parts and therefore stress peaks and stress discontinuities are minimized.

2.2.2 Inner Tooling with AM

According to Ashby (2011) the properties of engineering materials can be thought of as defining the axes of a multidimensional space, with each property as a dimension. Hybrid materials combine the properties of two (or more) monolithic materials in a chosen configuration and scale. The possibilities of hybridization of CFRP with AM displayed in Figure 3 show the potential of inner tooling with AM for the production of complex-shaped CFRP parts. The *geometrical complexity* is shown on the x-axis and *the specific mechanical properties* are located on the y axis. As seen in section 2.1 CFRP have outstanding mechanical properties and AM allows the production of highly complex shapes. A tooling made by AM provides the necessary shape complexity. The CFRP layup is done on the AM tool and the part is cured under specific conditions. The tooling can be removed afterwards. The resulting CFRP part displays the properties of CFRP and the shape complexity of the AM tool. Consequently the greatest of both properties (*geometrical complexity, specific properties*) are reached.

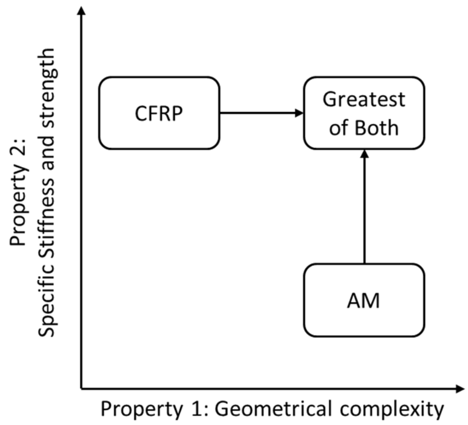

Figure 3. The possibilities of hybridization according to Ashby (2011) applied for AM and CFRP

3 DEVELOPMENT OF A NOVEL HYQ ROBOT LEG WITH AM AND CFRP

This section highlights the design potentials emerging from the combination of additive manufacturing (AM) technologies with Carbon Fiber Reinforced Plastics (CFRP) Prepregs through a case study in the field of robotics. The lower leg of a hydraulically actuated quadruped (HyQ) robot is developed with AM and CFRP Prepregs. Design and manufacturing steps of the novel multi-material leg design are presented.

3.1 Framework of the Case Study

3.1.1 HyQ – Hydraulically Actuated Quadruped Robot

The Hydraulically actuated Quadruped (HyQ) robot was developed at the Istituto Italiano di Tecnologia (IIT), Genoa, Italy to serve as a platform to study not only highly dynamic motions such as running and jumping, but also careful navigation over very rough terrain. HyQ stands 1 meter tall, weighs roughly 90kg and features 12 torque-controlled joints powered by hydraulic actuators (Semini et al., 2011). The most important parts of the robot structure are the legs, as their properties are highly relevant to the overall robot performance in terms of weight and inertia. Figure 4 shows the CAD model of the leg. The upper leg is attached to the robot torso with a basic structure and hydraulic actuators are used to move three revolute degrees of freedom. The lower leg, constructed in aluminum, weighs 801g including the basic foot. Two encoders are integrated into the lower leg structure (Semini, 2010). The scope of this case study is limited to the development of the lower leg structure.

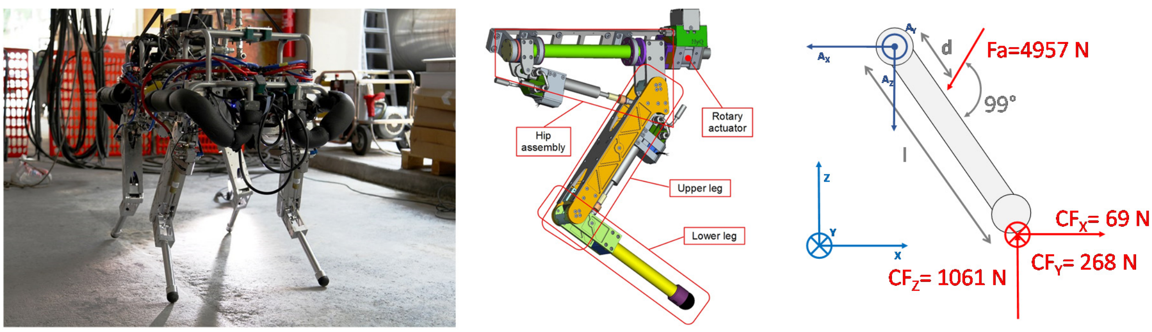

Figure 4. IIT's Hydraulic Quadruped robot HyQ (Semini, 2010), CAD model of the leg structure and external forces acting on the lower leg structure for the walking trot load case

3.1.2 Load Cases

The robot is able to perform several dynamic motions such as (i) walking with different gaits over flat and rough terrain which is called the *walking trot*. Thereby diagonal leg pairs move together, always a minimum of two feet on the ground. In the (ii) *flying trot*, the robot is able to run with different gaits, where diagonal leg pairs move together, with the robot in the air between the steps (*flight phase*), landing on two diagonal legs at a trotting speed of 2 m/s (Barasuol et al., 2013). An actuator applies a maximum force of 5000 newton to maneuver the lower leg. The external forces acting on the lower leg are extracted for every load case from measurement data of the HyQ provided by the IIT. The external forces for the walking trot case are shown in Figure 4 on the right.

3.2 Leg Design

3.2.1 Design Concept

A novel design concept of the lower HyQ leg is presented aiming at reducing the structural weight by applying a multi-material design. AM and CFRP are used in a way to benefit from the specific advantages of each material and production technology resulting in a highly integrated hybrid lightweight structure shown in Figure 5. The load introduction is designed as a metallic part produced with SLM since it has to withstand large superimposed loads. The inner tooling of the leg shaft is a plastic part manufactured additively in a FDM process and provides the CFRP Prepreg a load oriented shape. The CFRP is processed by hand layup and the fibers are oriented according to the loads.

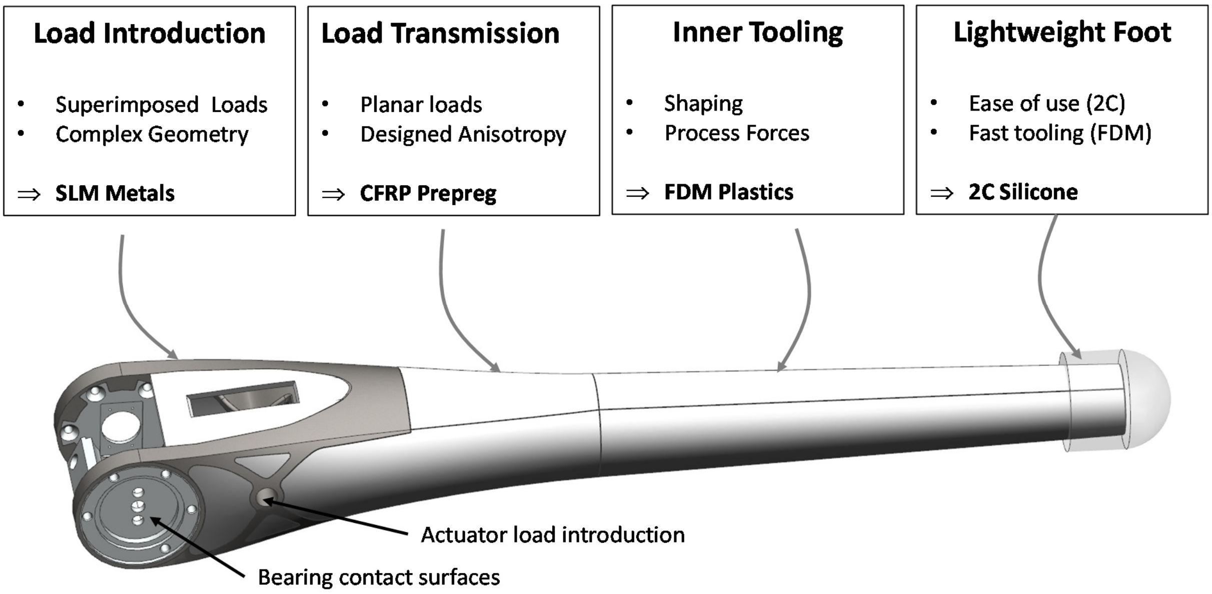

Figure 5. Design concept of the lower HyQ leg with AM and CFRP

The leg is dimensioned for the *walking trot* load case. Even though the load case is dynamic, the dimensioning of the CFRP is conducted for the static load case with the value of the maximum load being equally to the one in the dynamic load case. This approach is conservative and valid, if the strain in the CFRP does not exceed 0,4% (Schürmann, 2007). To fulfill this requirement a very conservative layup was calculated with the Classical Laminate Theory. Beginning from the top, two plies of twill weave with fibers oriented at ±45° to the main leg axis absorb shear, followed by four UD plies for normal stresses and finishing with two weaves oriented at ±45°. The layup can be summarized as: $[\pm 45_w/\pm 45_w/0°_{UD}/0°_{UD}]_{sym}$. The materials used are SGL Prepreg CE 8201-200-45 Twill Weave Fabrics layers with an aerial weight of $364 g/m^2$and 3K Carbon Fibers and SGL CE 1007-150-38 CF-UD Prepreg with an aerial weight of $150 g/m^2$, a fiber volume fraction of 60% and 12K carbon fibers. The SLM part is dimensioned according to the equivalent von Mises stress. The load introduction is made of CL 20ES stainless steel with a tensile strength of $650\ N/mm^2$.

3.2.2 Design Analysis Results

A static FEM analysis using Siemens NX 8.5 was carried out of the new design for the walking trot load case (Figure 4, right). Figure 6 shows the von Mises stresses of the SLM part (left) and the strain in the fiber direction of a selected UD ply (right). Von Mises stresses up to 136 MPa are observed in the bars-like structure responsible for transferring the load into the composite structure. The critical points are the radii in the area of the bearings. The maximum stress is 328 MPa, which is about half of the tensile strength of the material, resulting in a safety factor of around 2 for the SLM part. The FEM analysis showed that all ply strains are under 0,4 percent and range in the area of 0,01 percent for unidirectional layers and 0,1 percent for the weave. Compression is observed in the top, tension in the bottom (Figure 6, right).

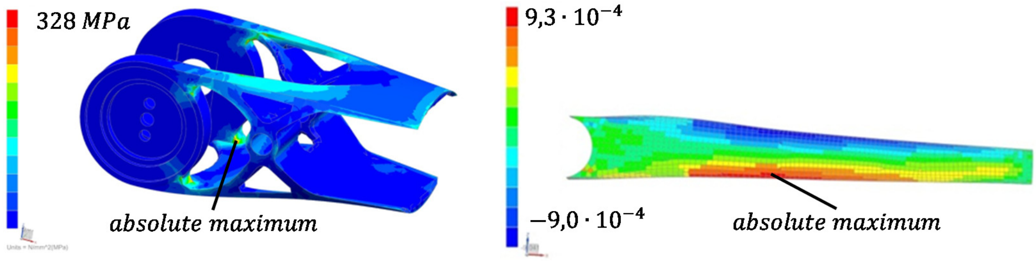

Figure 6. FEM analysis of the SLM part showing von Mises stresses (left) and strain in UD CFRP ply no. 4 of the leg structure (right)

3.3 Materials and Manufacturing

The SLM part and the composite structure are manufactured separately. The CL 20ES stainless steel SLM part has a volume of 38 cm³, a surface area of 299 cm² and weighs 303g. It is manufactured in a Concept Laser M2 Cusing machine with a 200 watt laser. The inner tooling is made of ABS plastics in a Stratasys Dimension Elite machine using the FDM process (Figure 7a). The composite part is manufactured with the method of hand layup and vacuum bagging (Figure 7b). The SGL E201/E202 epoxy resin system is selected as it allows curing at temperatures ranging from 80°C to 160°C and has a very good adhesion to metals. The prepreg plies are cut to the desired shapes and are manually deposited on the inner tooling. Then, the part is cured under vacuum conditions (pressure difference of 1 bar) for 23h at 80°C which is just below the deflection temperature. No autoclave pressure is applied. The final part is shown in Figure 7c.

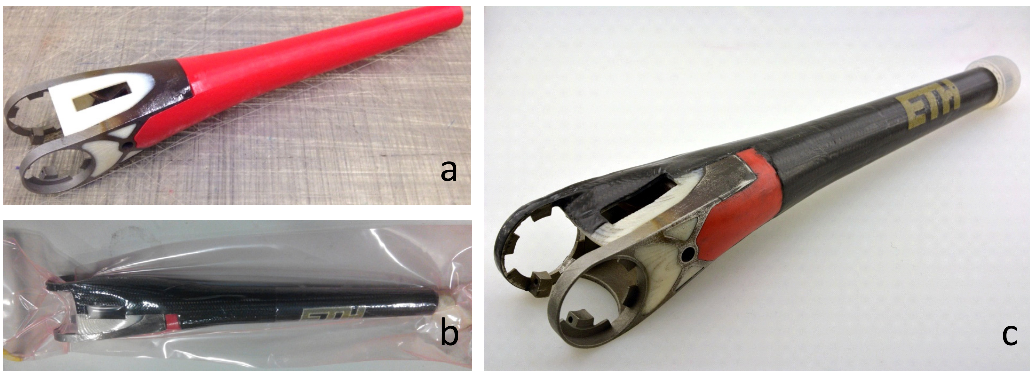

Figure 7. Manufacturing of the lower leg: assembled inner tooling with FDM and SLM load introduction (a), vacuum bagging (b) and cured part (c)

3.4 Testing

An isolated prototype is tested in a quasi-static 3-point bending (3PB) set-up to investigate the quality of the selected manufacturing process route for CFRP parts made with AM inner tooling. The results are compared with FEM analysis to verify the FEM model. The test set up is shown in Figure 8 on the left. The boundary conditions are chosen according to the degrees of freedom (DOF) of the robot's leg structure. The rotation around the hinge (knee) is allowed, all other DOF are constrained. The lower part (foot) is placed on a 1-point-support. The prototype displays of a load introduction made of ABS, three UD plies covering the tooling and is designed to fail at the maximum force of the actuator $F_{a,max} = 5000\ N$.

3.4.1 FEM Analysis

The FEM analysis (Figure 8, right) shows that failure occurs in the area of the foot, as ply strain amounts to $\varepsilon_{ply,FEM} = 0{,}66\ \%$ and therefore exceeds the critical value of $\varepsilon_c = 0{,}4\ \%$. The deflection in the load instruction amounts to $d_{a,FEM} = 2{,}18\ mm$.

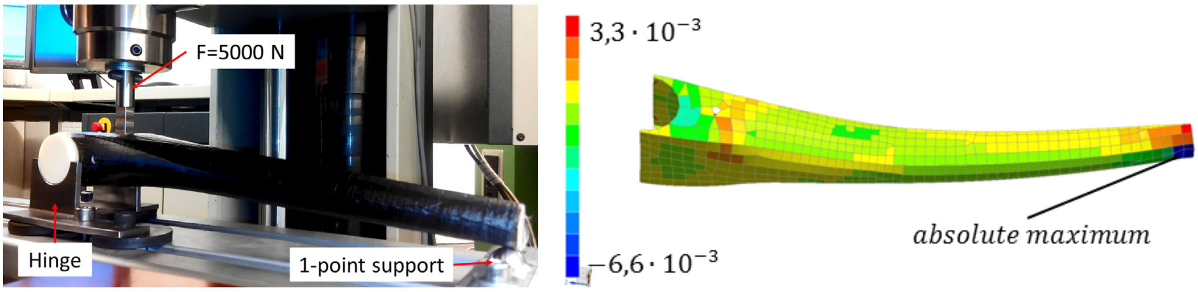

Figure 8. 3-Point-Bending setup (left) and FEM result showing ply strain failure at the foot

3.4.2 Testing Results

The 3PB test is conducted on a Zwick universal testing machine, with a feed set at 5mm per minute, until complete part failure occurs. Figure 9 shows the force deflection diagram of the 3PB test. The deflection is measured at the load introduction. Setting effects and deflections of the ABS structure up to 2 mm are calculated out to ensure comparability with FEM. The observed linear force-deflection behavior is extended to the baseline, thus obtaining a residual deflection of $d_0 = 1{,}65\ mm$. Ultimate failure occurred at a maximal force of $F_{max} = 5362\ N$ at a relative deflection of $d_f = 2{,}35\ mm$ and is located at the foot. The relative deflection at $F_{a,max} = 5000\ N$ amounts to $d_a = 2{,}02\ mm$.

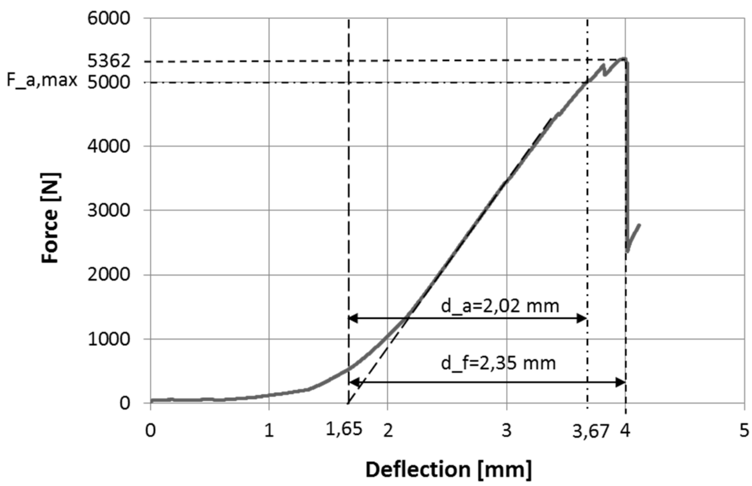

Figure 9. Force-deflection graph of the CFRP-AM leg structure in the 3-point-bending test

3.4.3 Testing Discussion

Simulation and test accord with the mode and location of failure being strength failure at the foot. However, the test outperforms the simulation in terms of ultimate failure. The deviation in percent between the simulation and the experiment is calculated with the following formula: $dev_i = |i_{test} - i_{sim}/i_{sim}| \times 100$. For the force leading to ultimate failure the deviation is calculated to $dev_F = 7{,}24\%$. The deviation of the displacement in the load introduction amounts to $dev_d = 7{,}34\%$. Both deviations are lower than 10 percent. Thus, the FEM model is in accord with the experiment, ultimately highlighting a manufacturing quality being sufficient for the production of load bearing parts made of inner tooling with FDM and CFRP Prepregs.

4 CONCLUSIONS AND FURTHER WORK

A novel lightweight HyQ robot leg structure was successfully manufactured by combining Additive Manufacturing with Carbon Fiber Reinforced Polymers (CFRP). The Prepreg was laid down on an inner tooling made with Fused Deposition Molding (FDM). The cured part was successfully tested under 3-point-bending. Results correlate with simulation and design calculations, thereby demonstrating the basic feasibility of the selected manufacturing process route, hence highlighting the potential of the process combination of AM with CFRP.
Future work related to the case study mainly focuses on dynamic testing of the leg structure on the testing facility of the Istituto Italiano di Tecnologia (IIT). Furthermore it is necessary to experimentally investigate the adhesion of the CFRP to the SLM part in order to verify the potential of the process combination for the load introduction. Ultimately, the redesign of the upper and lower leg with AM & CFRP is targeted.
The general concept of the combination of AM and CFRP still is in its infancy and therefore fundamental research is required. Many exciting research challenges for the design and manufacturing emerge from the case study. First, the fundamental mechanical behavior of the adhesion of CFRP and additive manufactured SLM parts for the transmission of high loads should be investigated to develop design guidelines for such load introductions. In terms of manufacturing, an autoclave process for AM and CFRP should be targeted as it is an industrial process delivering high quality parts. The applicability of AM materials for the autoclave process has to be considered in order to manufacture inner tooling for complex CFRP parts. Design guidelines for inner tooling have to be built up to ultimately produce high performing load oriented lightweight structures.

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