ADDITIVELY MANUFACTURED SANDWICH STRUCTURES FOR AEROSPACE APPLICATIONS

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Keywords: Additive manufacturing, Composites, Aircraft structures

ABSTRACT

Fibre-reinforced plastic (FRP) parts are commonly produced in Small and Medium-sized Enterprises (SMEs) using conventional processes like hand lay-up or vacuum-assisted resin infusion. However, these processes are limited in flexibility and ability to service orders for prototypes and small series due to the need for expensive moulds. Additive manufacturing can increase production flexibility by allowing the production of FRP structures without the usage of moulds, resulting in lower costs and higher flexibility. Additive manufacturing approaches for FRP parts include the printing of negative moulds, direct printing of FRP, and printing of textile semi-finished products. In this paper, a wing segment of a glider with a printed foam core is developed according to the VDI 2221 standard [1], with simplifications made based on the symmetrical wing structure. The aim is to avoid the use of negative moulds in the production of the wing section by printing a shaping core structure onto the reinforcing textile. A dry carbon fabric is clamped into a 3D printer and printed with a rigid foam at defined points. Once the fabric is released, it can be formed into the wing structure around the printed core without the need for further moulding tools. Different core cross-sections are evaluated considering challenges associated with 3D printing accuracy and distortion due to porosity. As various materials can be used for production, e.g., different fibre materials and printable foam cores, a concept is developed for producing an aerofoil cross-section using foam printing on textile. The requirements for mouldless FRP production can be met with a simple truss-like structure, which can be further refined using bionics-inspired lattice-like designs. Conclusively, we show that additive manufacturing using foam printing on textile has the potential to increase production flexibility and reduce costs in the production of FRP parts for aerospace applications.

1 INTRODUCTION

Due to the tools required for hand lay-up or vacuum infusion (e.g. usually expensive moulds), many SMEs are severely limited in their flexibility and ability to service orders for prototypes and small series [2]. To increase production flexibility, additive manufacturing can be used which allows the production of manufacture load-path optimised structures from FRP without the moulds needed in conventional production processes. In this way, both material and production time can be reduced, resulting in lower cost and higher flexibility [2]. Therefore, within this paper, we present a theoretical approach to use additive manufacturing for the production of composite structures for small aircrafts such as glider wings. The core material is applied directly to the textile by foam printing. The textile is then draped around the core. In this way, no mould is required for the production of the FRP part. This process can be transferred to other structures made of fibre-reinforced plastics. Different variants of the same components can be created without costly negative moulds for each modification.

2 STATE OF THE ART

2.1 Moulding process

Moulds for the series production of FRP aircraft parts, such as wing shells, are nowadays produced in several separate work steps as standard. First, a master model is created, which originates from a CAD model and is milled out of a solid material such as a polyurethane or aluminium block. This model is post-processed in several steps, ground and finally polished to a high gloss before the actual impression process begins which involves the application of various layers of resin and fibres that are necessary to create a rigid mould. This process is repeated for the production of all necessary moulds. Each component variant and components of each size require a separate negative mould.

In addition, larger moulds are usually reinforced with a framework of steel tubes so that the inaccuracies caused by twisting are minimised. The mould surfaces created in this way are polished again to a high gloss after the moulding process. Not until then can the first FRP part be produced with these moulds.

2.2 Small aircraft in FRP design

A closer look at the classic cross section of the wing reveals that this slender structure is made in a half-shell construction. This is done by placing the outer fabric layers on top of the gelcoat previously placed in the moulds. After the resin impregnation of these layers, the sandwich core material is inserted, for example using a rigid PVC foam that is cut from sheets. This is followed by the inner fabric layer as the top layer of the sandwich, which is also impregnated with resin. The procedure for producing the second half-shell is analogous.

After assembling the previously manufactured spar structure, consisting of two spar chords and the spar web, as well as the assembly of the control mechanism, the joining of the two half-shells follows. For this purpose, "beads" of resin, which is usually thickened with cotton flocks or comparable materials, are applied to the joints of one half-shell. Since the bonding is a so-called blind bonding, the amount of resin must ensure that the two components are bonded together over as full an area as possible. For this reason, there must be an excess of resin, which may be pressed out of the joints during the closing of the moulds.

The main mechanical loads are taken up in a double T-spar in the wing, which is produced in separate moulds and positioned in the wing before the joining process. Further reinforcements can be integrated as stringers in the fuselage or ribs and webs in the wing area (Figure 1) [3]**.** Today, small aircraft are almost exclusively made of FRP. For this purpose, in addition to the wings, the fuselage is also made from half-shells in two large negative moulds before they are joined with a material bond.

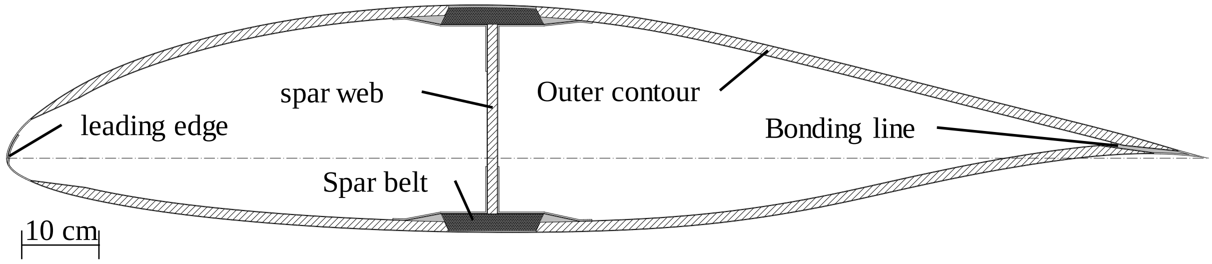

Figure 1: Cross section of a glider wing

2.3 3D printing in the production of FRP

Various approaches have been established for the additive manufacturing of FRP parts. One of the processes is the printing of negative moulds. Instead of the conventional process, moulds can be produced additively in large-scale printers.

For the 3D printing of moulds, at first the CAD models of the moulds are converted into a printable G-code using slicer software. The most common used printing process is the so-called fused deposition modeling (FDM) process. Polymer granulate or filament is melted in an extruder and fed to the printer nozzle. This is guided by a portal or a robot arm and builds up the mould structure layer by layer on the heated print bed. Depending on the geometry of the mould, support structures are required which have to be printed additionally. Currently, printers are available with installation spaces in the range of several cubic metres, allowing the production of component lengths of 6 metres and widths of over 3 metres. The printer frame, which gives the system the necessary rigidity, has a major influence on print quality. For this reason, printers cannot be enlarged at any size. Another challenge is the surface quality of the printed shapes. The layer-by-layer structure creates small steps that are transferred to the component surface of the FRP structure. Printed moulds are usually reworked in milling processes to avoid this undesirable effect. In addition, a compromise must be met between layer thickness and printing time. Large layer thicknesses enable the fast production of moulds, but cause poorer quality surfaces. With small layer thicknesses, the component quality increases, but so also does the time required. Several approaches to additive manufacturing of molds have shown potential to date. Additive manufacturing can be used in both direct tooling and indirect tooling. Today, molds for helicopter rotor blades, diving objects or even boat hulls can already be manufactured additively. In this study, we consider a process that is intended to substitute the need for molds. Therefore, mold construction by using AM will not be considered in more detail here. [4–9]

The second option to produce FRP parts additively is the direct printing of FRP. So far, this process has mainly been used for the production of small and structurally highly stressed parts. Until today, very different approaches have been pursued. For example, granules with short fibers from the injection molding industry can also be used for 3D printing. This allows a significant improvement in mechanical properties compared to unreinforced polymers. With increasing fiber length, the mechanical properties improve up to a certain level, above which the increase in porosity has a strong negative influence. This results in a decrease in interfacial adhesion in the component. Table 1 shows numerical values from tests according to [10]. [10–12]

	GP-ABS	CF-ABS
Fiber content [Vol.-%]	3	3
Porosity [%]	9,45	13,7
Tensile strength [MPa]	24,3	32,2
Young's modulus [GPa]	0,55	0,85
Yield strength [MPa]	13,7	20,7

Table 1: Characteristic values of the graphite particles (GP) and acrylonitrile-butadiene-styrene (ABS) and carbon fibres (CF)-ABS samples according to [10]

FDM printing offers the opportunity to integrate fibres into the polymer printed (Figure 2). Different fibre materials and fibre lengths can be used depending on the requirements. Compared to components made of unreinforced thermoplastics, the components produced in this way have higher strengths and stiffnesses, especially in the planes of each layer. Due to the influence of the fibres on the interfacial adhesion, there is a strong anisotropy in the layered printed components. In addition, the cost for the printable raw material is very high due to the usage of fine reinforcing fibres. Polyamide reinforced with continuous carbon fibres, for example, currently costs between 300 and 350 €/kg.

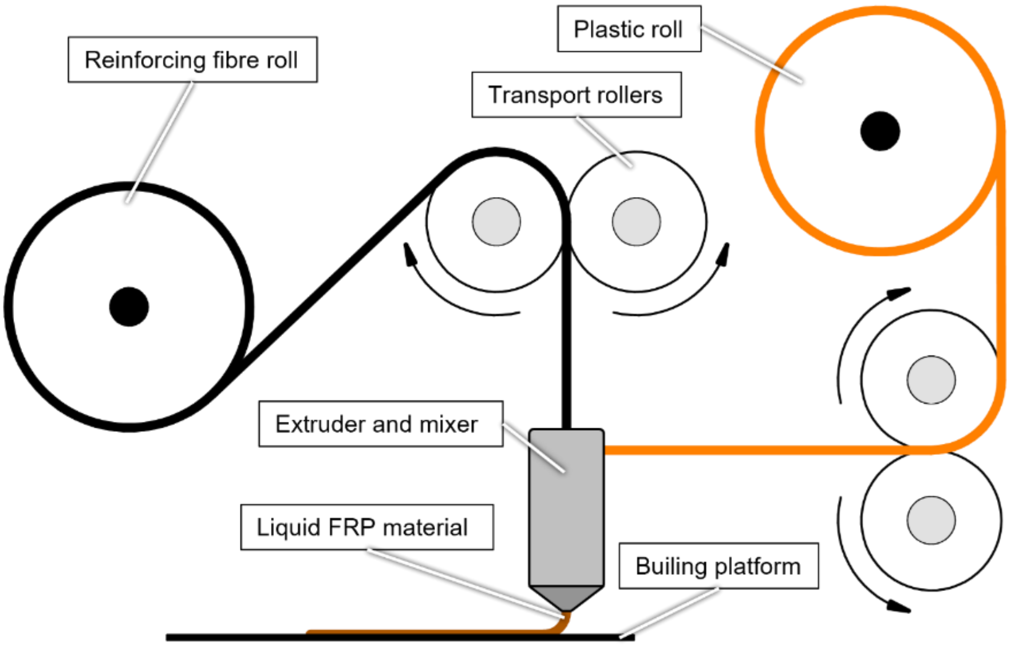

Figure 2: Principle sketch of the fibre integrated FDM printing process

The third variant is the printing of textile semi-finished products. In addition to 4D textiles, which can be functionalised through printing, composite production can also benefit from this. For example, a light and hard foam structure made of HDPE filled with up to 60 % glass micro balloons can be printed. For this purpose, a textile ply is clamped in a printer and printed on with foam. The foam can be - at least partially - form-giving for the flexible textile and substitute the negative forms. In a previous work at the institute, various material combinations of core and cover layer were investigated for the production of an FRP sandwich. Applied fiber materials are glass and carbon fibers. Woven fabrics with canvas and twill weave are tested. The core is printed onto the textile either as a honeycomb, a gyroid or a square made of polylactic acid PLA, polyethylene terephthalate glycol PETG or thermoplastic polyurethane TPU. Here, an infill of 10% for the cores or 5% for the gyroid structure is selected. A CFRP sandwich of aramid honeycomb and carbon face sheets serves as a benchmark for the mechanical tests. The thickness of the honeycomb is 8 mm and a honeycomb size of 3.2 mm. The cover layers are each made of one layer of twill fabric with a weight of 200 g/m^2. The fiber orientation is along the 0°/90° direction. The best results in the four point bending test were achieved by the structures made of carbon fabrics and cores made of PLA, as well as the benchmark structure made of aramid honeycomb and carbon face sheets. Within the scope of this paper, a concept is created how a wing structure of a glider can be generated by 3D printing of foam cores. [5,13]

3 METHOD

The wing segment with printed foam core is developed according to the VDI 2221 standard [1]. After determining the requirements, simplifications are made based on the symmetrical wing structure.

3.1 Mechanical requirements

The structural design is based on the half span of a glider wing. The airfoil under consideration is an Eppler airfoil of type E603, which was used in gliders such as the Grob Astir CS. The wing geometry of the Astir looks as follows seen from above (Figure 3)

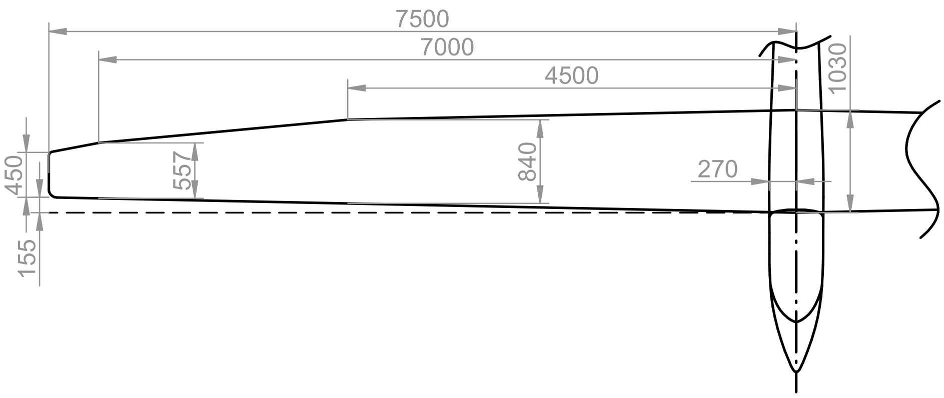

Figure 3: Geometry of the Astir wing [mm]

The design load case considered here follows from the currently valid EASA regulations for gliders. The Astir is certified as a normal glider, which today corresponds approximately to category U (Utility). According to this, the structure must be able to safely bear a load factor of n = 5.3 g at the manoeuvring speed (VB = 170 km/h) with a safety factor of j = 1.5. For the complete structural design, some further load cases must be considered, which are mainly decisive for individual areas of the wing.

3.2 Structural design

The most important mechanical loads are calculated from the above assumptions. The structure of the Astir wing is evaluated on the basis of these and the new construction is designed. From the known geometric data of the wing and the known mass of the non-structural parts, which according to the assumptions is evenly distributed over the wing surface, the course of the applied lift force is calculated. The transverse force curve follows from the integration of the force curve over the span. With a further integration over the span coordinate y, the bending moment curve in the wing is calculated. The basic formulae for this are [14,15]:

$$d^2/(d*x^2)*(E*I_y*d^2w/dx^2) = -d^2M_{by}/dx^2 = -dF_{qz}/dx = q_z \tag{1}$$

$$E*Iy*w'''' = qz. \tag{2}$$

Accordingly, the fourth derivative of the deflection w multiplied by the bending stiffness EI_y is equal to the load q_z and equal to the second derivative of the bending moment M_{by}. The mechanical system for calculating these loads is shown in figure (Figure 4). The dimensions correspond to those in Figure 3. To calculate the structure, a statically determined basic system must be available. For this reason, two knots are placed at the points where the transverse force of the fuselage is introduced. The outer of the two nodes is clamped tightly, the second node, on the other hand, remains without support reactions. However, a negative point load is introduced which corresponds exactly to the transverse force of the wing at this point. In the original wing of the Astir, the so-called shear force pins are located at these points, which are integrated into the root rib and introduce the forces into the fuselage structure.

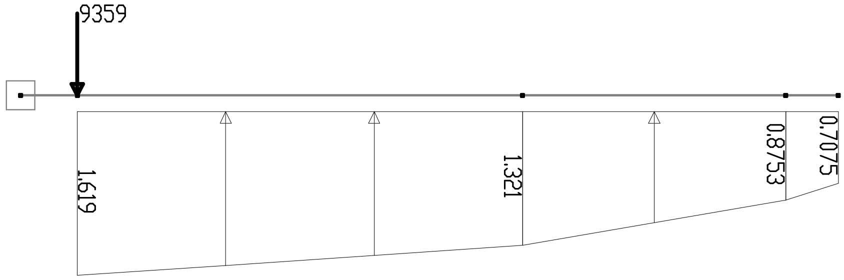

Figure 4: Mechanical system of the wing load: line loads [N/mm]; point load [N].

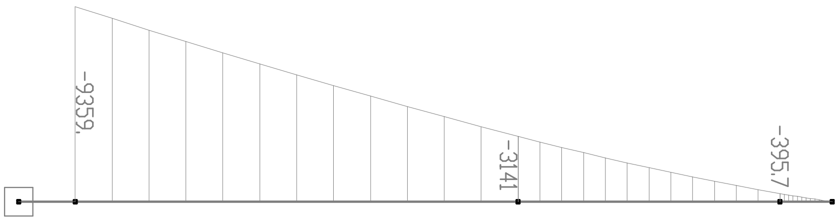

Figure 5: Shear force [N] over the wingspan

The numerical values shown for the line loads and the point load at the height of the fixed support result from the calculations of the wing geometry and the mass of the non-structural parts. The units of measurement are Newton or Newton per millimetre, whereby the line loads only have the specified value at the designated points. In the intermediate areas, the course is linear in sections. This load curve forms the basis for the calculations of the total mechanical loads. The resulting shear force curve is shown in figure (Figure 5). It starts at zero at the outer end of the wing and increases in three sections with quadratic curves up to the amount 9359 N at the level of the root rib. The largest bending moment is also in the area of the root rib (Figure 6).

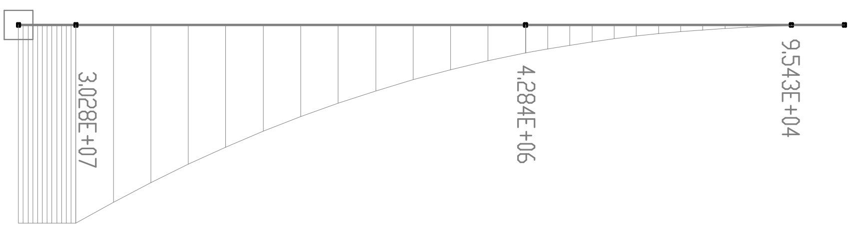

Figure 6: Bending moment [Nmm] over the wingspan

3.3 Development of the cross sections

Various core cross-sections are developed and evaluated for their suitability for use as a form-giving foam core according to the VDI 2221 standard. In order to design an optimised wing cross-section and to develop a suitable production method, the requirements that must be fulfilled in order to determine the suitability of the cross-section for aircraft construction are first determined. Furthermore, it is also a question of taking preferences into account. Requirements are, for example, mechanical properties such as strength and weight and the lowest possible complexity. The shortlisted cross-sections are then evaluated on the basis of evaluation criteria determined in accordance to the requirements. For this purpose, the various criteria are weighted with values between one and ten, where ten stands for "very important" and one for "not absolutely necessary". The sum of these values is then used to calculate a weighting in percent, which is used to evaluate the designs. In addition, points are assigned for the properties of the solution variants that reflect the fulfilment of the requirements. These points are then multiplied by the weighted requirements. By adding up the resulting number of points, a ranking of the individual solution variants is created.

The next step is the actual design of possible wing cross-sections for gliders that can be efficiently, reproducibly and easily produced using 3D printing. Different cross section configurations are considered and compared, with an optimisation based on a solid foam core as the shaping core structure. The materials considered are a carbon fabric with a weight of 93 g/m^2 in two layers and a polyethylene rigid foam. The basis of the development is the original wing design of the Astir, the cross-section of which is shown in figure (Figure 1). This construction is made in the classical way in negative moulds. The outer skins are of sandwich construction and have a sandwich core of constant thickness over the entire surface. The blind bonding of the half-shells is made with considerable excess resin. The spar construction is designed as a double-T structure that is stiff against bending.

On the one hand, the geometries must be able to be reproduced by printing and, on the other hand, they must be suitable for use in the wing. In addition to the challenges associated with 3D printing, accuracy and distortion due to the high porosity play an important role when printing foam.

Different materials can be used for the production of the parts. Various fibre materials, such as glass and carbon, are conceivable. The foam core can also be made from different printable materials. Prepregs can only be used to a limited extent due to the consolidation in the autoclave.

4 3D-PRINTED FOAM STRUCTURES FOR AEROSPACE APPLICATIONS

If possible, the production of the new design should be possible without using negative moulds (Figure 7). This means that the profile geometry must be printed by the 3D printer with a high accuracy (step 1). The first approach is to divide the cross-section along the chord of the profile and the spar axis, printprint the core as solid foam parts, join them afterwards (step 2, 3) and wrap them with fibre-reinforced plastic (step 4), Figure 7.

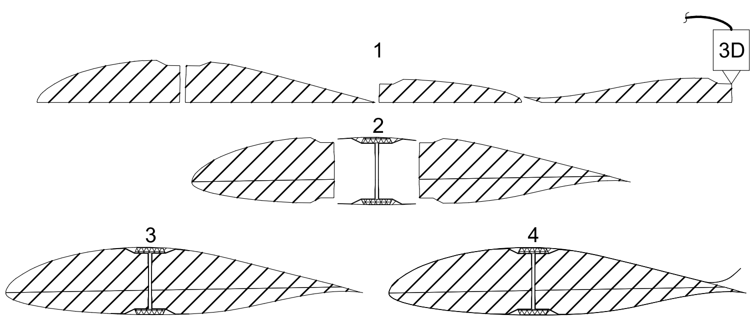

Figure 7: Procedure for producing the solid cross-section

Even though this construction is technically easy to realise, theoretical calculations show that it does not bring the desired success in terms of weight compared to the original Astir structure. For this reason, the approach is modified in a way that hollow spaces are incorporated into the individual foam parts so that weight can be saved (Figure 8).

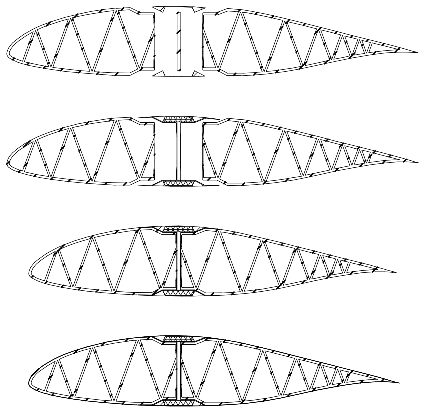

Figure 8: Procedure for producing the optimised wing cross-section

Although the aerofoil becomes narrower in the direction of the span (Figure 3), the changes to the geometry are so small that 3D printing can be used without introducing additional support structures, as there are no overhangs to support. In addition, work steps are saved during joining, as the wing cross-section is divided into fewer individual parts. With regard to the structure of the entire wing, however, this advantage is reduced again. As a result of the change in printing direction, the height of the printable space limits the size of the part. Thus, it is mandatory to divide the wing into several segments in the spanwise direction in order to represent a printable structure. These segments are butt-jointed, covered with the parts of the spar and wrapped with the required fabric layers (see also Figure 8 and Figure 9).

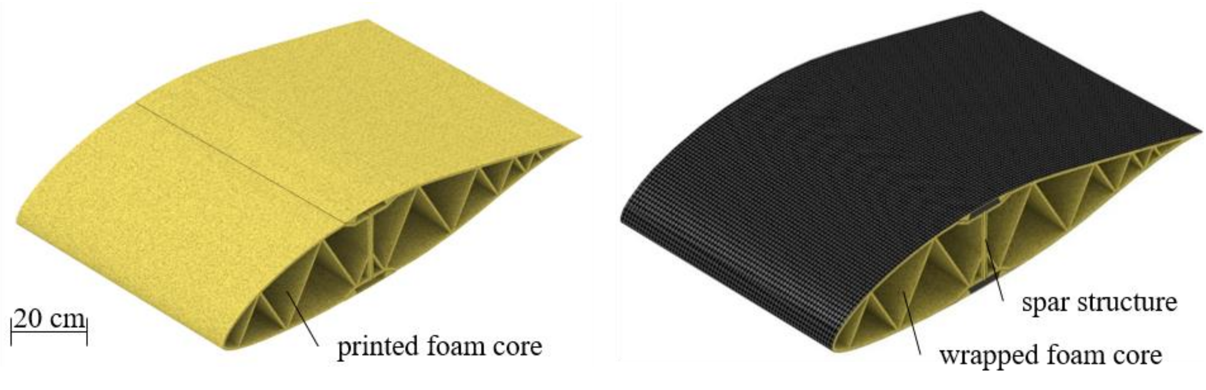

Figure 9: Foam structure of the optimised wing cross-section (left) and prototype component wrapped with carbon fibre fabric (right)

The struts of the so-called trusses are stressed exclusively by normal force due to their arrangement to each other. Similar structures that are mainly subject to bending and shear forces can also be found in nature, e.g., fibrous plant stems or sponge-like bone structures. Bones are made up of fine little tubes called trabeculae on the inside. Like truss rods, they are only loaded with normal force. However, bones are able to adapt to the direction of the load and to rearrange themselves accordingly. Since the trabeculae with a thickness of 150 μm are very fine, the transfer of this structure to mechanical engineering has so far failed due to the manufacturing possibilities. With the advantages of additive manufacturing, components with a bone-like texture can be produced. Transferring the bone structure to the wing cross-section of the astir results in a structure as shown in figure (Figure 10).

Highly stressed areas, such as the central part of the section, can be reinforced in the direction of the load as required. In addition, the spar structure can be redesigned so that the bending moment is not concentrated locally in a narrow double-T structure. The spar chords and web can be made wider, which increases the distance of the chord centre of gravity from the shear centre and the Steiner component in the moment of inertia calculation. This makes the structure 3-5 percent lighter.

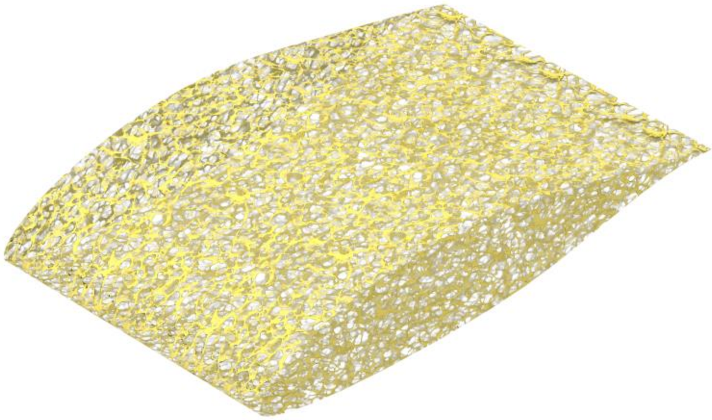

Figure 10: Innovative wing cross-section with bone-like foam structure

The bone structure can also be adapted locally to the requirements. For example, it is possible to print a finer structure in the area of the outer contour to generate a better joining surface for the carbon fabric. Thereby, a reliable adhesion of the fibre material is ensured.

5 CONCLUSION

3D printing has great potential to improve the production of fibre-reinforced plastics. In this paper, a theoretical concept of a wing structure for gliders was developed. Based on preliminary work in the field of 3D printing on textiles of reinforcing fibres, an innovative, printable core structure for a glider wing was developed. The final design of the cross-section presented in this publication is a bone like foam core wrapped with carbon fibre fabric (see Figure 10). It is intended to improve the original cross-section of the original Astir wing. After printing, the core is wrapped with fibre reinforced plastic, which gives it the required strength. The mechanical loads occurring during flight are largely carried by the spar structure. The spar structure is largely taken over from the original Astir wing. Only the fibre material is changed from glass in the original Astir wing to carbon fibre as the current standard for structures under high bending stress. Instead of glass fibres, carbon fibres can be used, which minimises the weight of the construction and results in higher stiffnesses and only slight geometric changes in the wing structure. Consequently, the possibilities of 3D printing can not only be used to reduce weight, but also contribute to the best possible use of the available installation space.

The use of negative moulds can be dispensed with in the production of the newly designed wing structure. By producing the foam structure using a 3D printer, the wing profile is mapped exactly, so that the carbon fibre semi-finished products are brought exactly into shape when wrapping the core. In addition, no blind bonding is required for production, which increases reproducibility and at the same time minimises the structural mass.

The requirements set can be met with a very simple truss structure. In the area of the spar structure, for example, a finer core geometry can be introduced, while the pores in the surrounding areas can be much larger. This structure can also act as a form-giving core and thus substitute the negative forms. Using bionics as a model, a wing structure, for example, can be redesigned and innovatively manufactured using additive manufacturing.

Figure 11: 3D-printed sample component of the concept wing cross-section

The picture (Figure 11) shows the printed truss-like wing core of a scaled model. It was printed from PLA and served to illustrate the concept. Further practical experiments are needed to verify and validate the theoretical considerations. Smaller structures can be produced for testing before large components such as entire wings are to be produced. The printability of foam materials using 3D printers and the accuracy of the manufacturing process must also be verified.

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