SAMPE Europe Conference 2019 Nantes - France

A FIBRE-REINFORCED THERMOPLASTIC PRIMARY STRUCTURE FOR SOUNDING ROCKET APPLICATIONS

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ABSTRACT

This paper presents work done at the German Aerospace Center (DLR) to realise a primary carbon fibre-reinforced PEEK (CF-PEEK) structure for use in the ATEK sounding rocket mission programme. As part of the programme, one of the metallic primary structures has been substituted with an anisotropic ($[45,0,-45,0]_{S3}$) CF-PEEK component produced using entirely in-situ Automated Fibre Placement (AFP) technology at the Institute of Structures and Design in Stuttgart, Germany. Having passed all necessary test phases, the component is now ready to be integrated into the main system, with launch scheduled for early 2019.

1. INTRODUCTION

The implementation of carbon fibre-reinforce thermoplastic (CFRP) composite structures in the aviation industry is now a widely accepted and celebrated practice. This trend began with Fokker’s development of PEI ribs in the 1990s [1] and is represented today by a variety of large and small-scale components, from the PPS wing leading edge of the A380 [1] to the PPS and PEEK clips used extensively in the A350 XWB [2,3]. The use of thermoplastic components in the space sector has been much more gradual in comparison, though as the pursuit of launch mass reductions intensifies, stoked partially by the advent of privatised rather than state-funded space programmes, these materials are being investigated in greater earnest. The 2015 launch of NASA-JPL’s Soil Moisture Active/Passive (SMAP) satellite saw an aramid fibre and PEI matrix structure assume a mission-critical role in the form of the deployable AstroMesh Lite reflector [4]. With next-generation projects such as the Black Upper Stage (BUS) seeking to develop primarily or exclusively composite launch vehicle structures, the task at hand is to transfer CFRP material advantages from the laboratory into demonstrator and flight-tested components.

The first generation of these space-focused components has been centred around pressure vessels and other cylindrical or axisymmetric structures. When considering these shapes as well as the sheer scale of spacecraft structures, it follows that fibre winding or Automated Fibre Placement (AFP) have been selected as the preferred manufacturing methods [5-7]. While both processes take advantage of the high strength-to-weight ratio of unidirectional (UD) thermoplastic pre-preg material, AFP provides greater flexibility with regards to the placement of material, allowing purely axially aligned fibres and hence greater tensile/compressive strength.

A relatively young technology when compared to its thermoset counterpart, thermoplastic AFP has often been combined with subsequent autoclave consolidation following tape placement to reduce void content and improve bonding between plies [8,9]. While this two-step process can be used to improve mechanical properties, it nevertheless represents additional costs which increase steeply with increasing part size. In order to offset the higher material costs associated with CFRP material, a single-step (or "in-situ") manufacturing process is preferred.

These guidelines have been used to design, manufacture, test, and implement a thermoplastic primary rocket structure at the German Aerospace Center (DLR). Developed within the ATEK (Alternative TEchnologien für Kleinträger) project, the advantages of UD CFRP material and AFP technology were combined to produce an anisotropic CF-PEEK replacement for an aluminium primary structure in a VSB30-class sounding rocket. This part was produced entirely in-situ and subsequently qualified as flight-ready following compression and bending testing. The work presented in this paper focuses on the manufacturing of the part using AFP, with details of the qualification testing being the subject of a separate study.

1.1 The ATEK Programme

The ATEK programme at DLR aims to decrease space programme costs by promoting reusable rocket components. These include propulsion unit components as well as those responsible for vehicle structural integrity and monitoring. Sounding rockets therefore prove an ideal platform with which to flight test parts and subsystems on a reduced scale.
The vehicle of choice for this programme is the VSB-30, a two stage rocket which has been used at DLR since 2004 to conduct experiments at altitudes of up to 270 km [10]. The payload stack of the ATEK rocket, shown in Figure 1, is constructed of variable-length aluminium modules with an outer diameter of 430 mm. It is one of these modules which has now been replaced with CF-PEEK through the work presented in this paper.

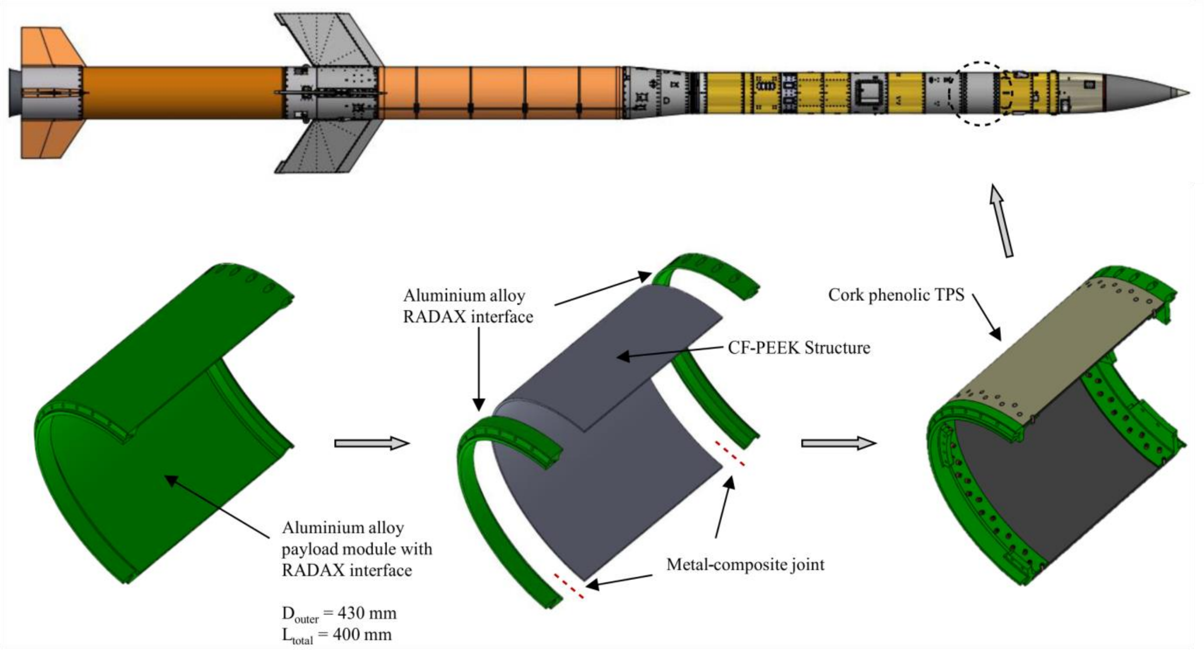

Figure 1 – ATEK rocket (above) and reference module in original and CFRP replacement form (below)

In order to qualify as flight-ready, the CF-PEEK module must sustain and endure compressive, bending, and shear loads of 36 kN, 18 kNm, and 4 kN, respectively, for a duration of 10 s. These loads, in addition to the aforementioned geometry, represent the constraints with which the primary structure has been developed.

2. EXPERIMENTAL FACILITY

The thermoplastic AFP facility at DLR’s Institute for Structures and Design in Stuttgart, Germany, comprises a 6 Degree-of-Freedom (DoF) robot, linear axis, 2 DoF planar tool, and rotating axis tool to facilitate the production of a variety of simple and complex part geometries. This facility, procured from AFPT GmbH and shown in Figure 2, features two AFP-deposition heads: the Single Tape Winding Head (STWH) and, more recently, the Multi Tape Laying Head (MTLH). As the MTLH was delivered after the manufacture of the rocket structure, the work presented in this paper is focused on the STWH. The MTLH and its potential improvements to the next generation of structures will be discussed in the outlook of this work.

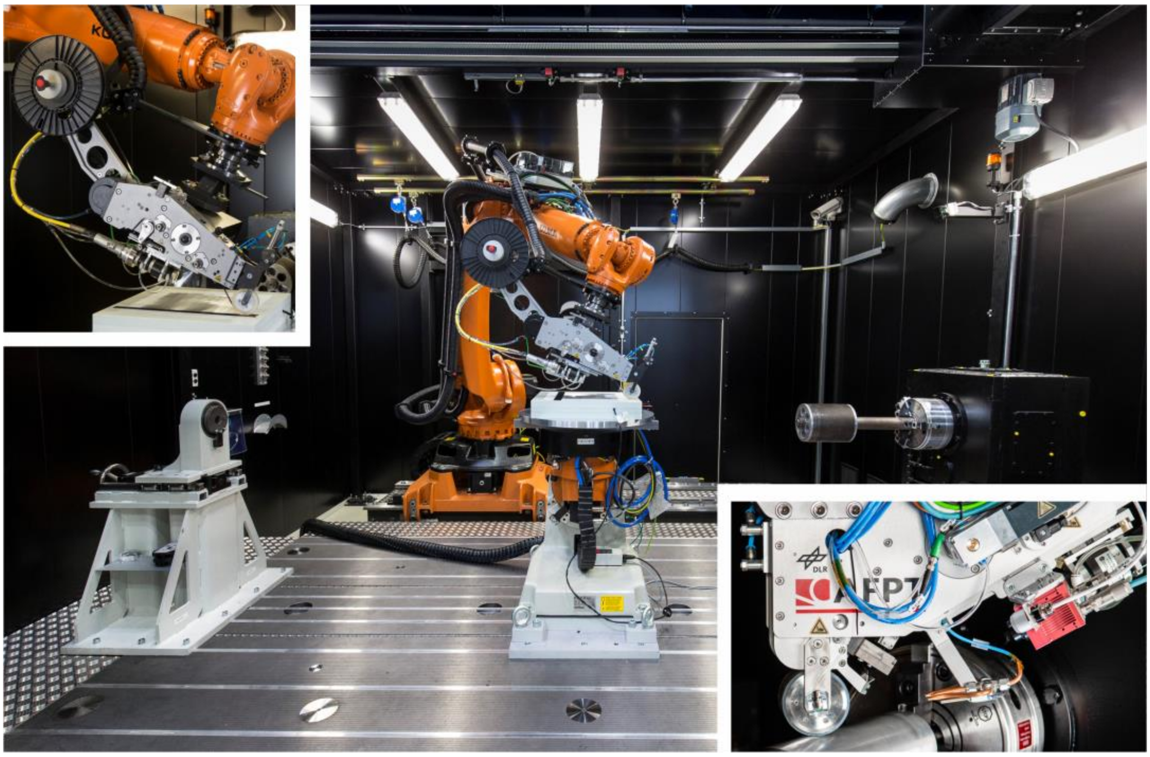

Figure 2 - Thermoplastic AFP facility in Stuttgart, Germany, with STWH (above left) and MTLH (bottom right)

The STWH combines a 6 kW diode laser with an air-cooled silicone compaction roller to facilitate the deposition of fibre-reinforced high-performance thermoplastic tapes (PPS, PEEK, PEKK) at high speeds. Within the enclosed cell parts up to 4 m in length and 2 m in height/diameter can be produced

Following preliminary trials with a scaled, tapered tooling, the decision was made to manufacture the rocket structure using a lightweight, collapsible tooling as shown in Figure 3. This tooling was developed with a lever mechanism, allowing a reduction in the outer surface area and hence easy demoulding of the finished part. The lightweight nature of this part also minimised inertial restrictions, minimising the load on the rotational axis motor to ensure high layup speeds were achievable.

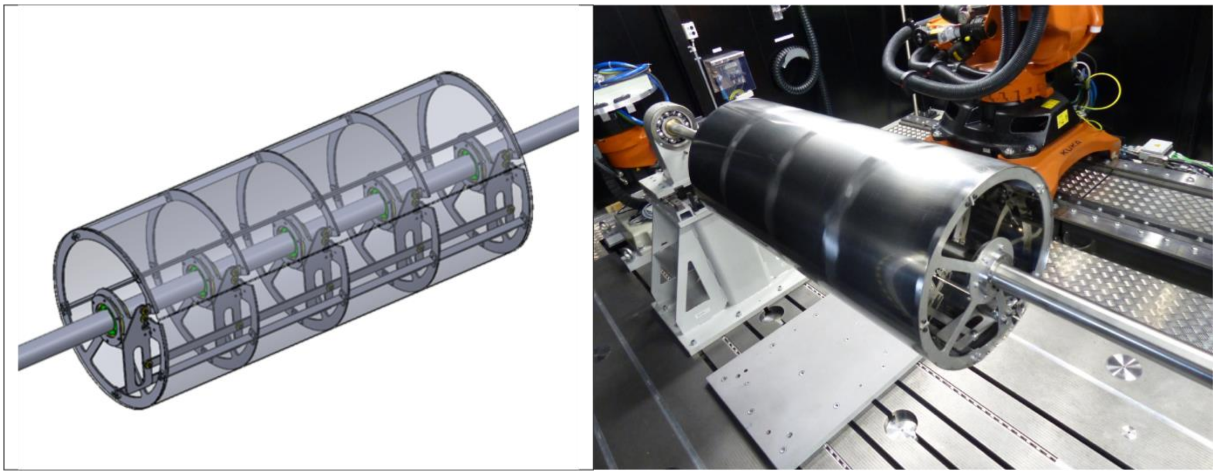

Figure 3 - Collapsible tooling used for module manufacturing

3. MANUFATURING PROCESS

This part was produced using UD CF-PEEK tape composed of PEEK-150 matrix from Victrex and Hexcel AS4 fibres. This tape featured a fibre content of 55% (by volume) and was deposited on the tooling as a 25.4 mm wide single strip. A summary of critical manufacturing parameters is listed in Table 1.

Table 1 - Structure manufacturing parameters

Parameter [Unit]	**Value**
Material []	AS4 CF-PEEK, 55%
b_{tape} [mm]	25.4
$T_{nip-point}$ [°C]	440
v_{layup} [m/min]	7.5
p_{roller} (input) [bar]	2

Due to the high axial compression and bending loads (36 kN and 18 kNm, respectively), an anisotropic layup was selected. This layup, consisting solely of 0° (parallel to the part axis) and ±45° plies, was optimised for the bearing stresses induced by the riveted lap joints. 90° plies were excluded from the construction in order to attenuate the difference in thermal expansion coefficients between the CFRP and aluminium alloy structures. The chosen layup makes full use of the thermo-mechanical properties of the continuous fibre tape by aligning the fibres with the flight-induced loads rather than distributing them evenly throughout the part volume. It is this approach which has the greatest potential to facilitate mass-savings in future aviation and space applications by providing part mechanical properties tailored to their application and environment. The final part was composed of 24 plies in a $[45,0,-45,0]_{S3}$ layup, resulting in a wall thickness of approximately 3,7 mm. This high ply-count was selected to safeguard the success of the ATEK mission, with the launch vehicle carrying several independent experiments and prototype components. Despite this ply-count, the final CF-PEEK structure still exhibited a lower mass than the standard aluminium module, thus signifying a net gain for the total vehicle. Based on the success of this first generation part, subsequent modules will be able to pursue more ambitious mass-saving goals.

While the anisotropic layup was advantageous for flight-loading, it also presented challenges during the manufacturing process. The production of many axisymmetric AFP components typically begins by applying an almost 90° ply to the tooling surface. This base ply ensures the contours of the tooling are closely followed and provide a substrate for subsequent plies to adhere to. However, as previously mentioned, the design requirements of this part did not permit any ply angles other than the 3 selected. Therefore, different manufacturing solutions were tested for their suitability.

The first approach involved applying tape to the tooling directly, with unreinforced PEEK foil used to assist bonding. While good bonding was achieved using this method, the unreinforced nature of the foil made it unable to resist shrinkage following tape deposition. This led to ply warpage and unacceptable part tolerances with subsequent plies. A second approach assessed the suitability of two distinct 90° windings, one at either end of the cylindrical tooling. This option provided a more robust fixing point for the first ply as well as an undisturbed region in the tool centre from which finished parts could be extracted. However, despite their close adherence to the tooling surface, the unsupported nature of these windings resulted in slippage and thus unacceptable final tolerances. Finally, a method of mechanically fixing these twin windings without obstructing the layup path was determined, yielding simple to manufacture cylindrical structures with the desired anisotropic layup. Images of the three layup methods investigated are shown in Figure 4.

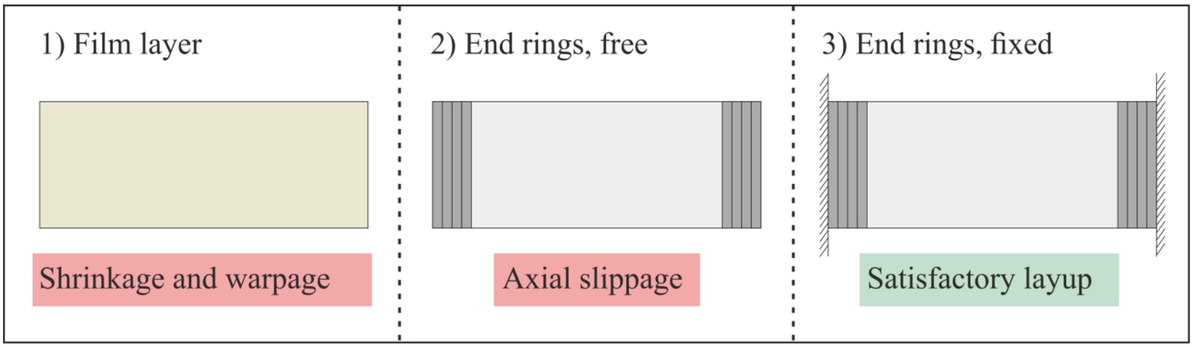

Figure 4 - Fixing methods investigated within this work

The combination of the chosen tape width, layup speed, tooling design, and fixing method resulted in a relatively low unit production time. A single cylindrical laminate, from which 2 modules could be extracted, required less than 1 day of active fibre placement, with demounting and trimming of the parts able to be performed in a matter of hours. With further optimisation of the respective production stages, or a scaling of the tooling itself, this production time per unit can be decreased still.

4. POST-MANUFACTURING

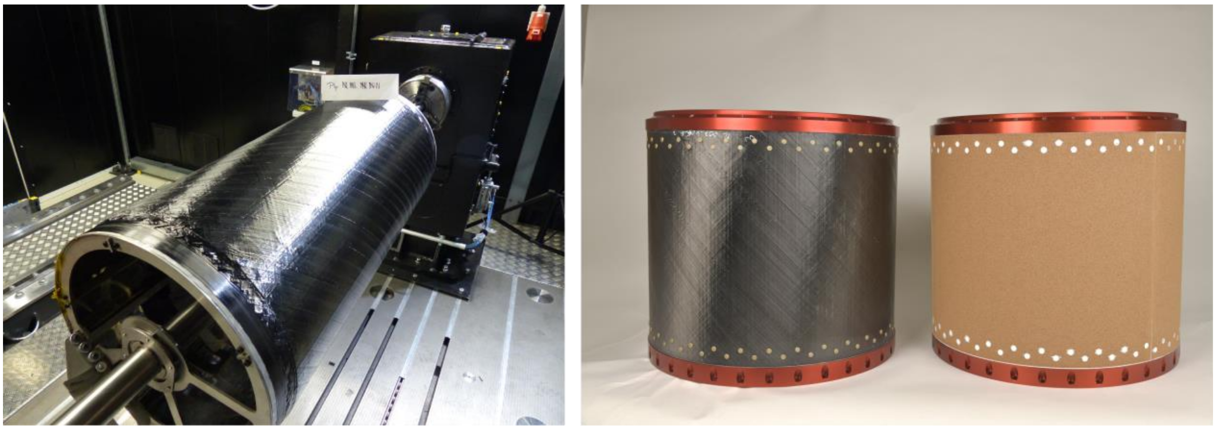

Figure 5 - CFRP structure after deposition of last ply (left) and in finished form (bare and with cork phenolic TPS, right)

Images of the final part before and after separation of the tooling are shown in Figure 5. A series of non-destructive testing methods (computational tomography, ultrasonic scanning, laser scanning, and infrared thermography) were used to assure the build quality of raw cylinder. Following being cut to the module dimensions, the CF-PEEK structure was drilled and attached to the aluminium Radial-Axial (RADAX) interfaces via a combination of adhesive and HI-LOK fasteners [12]. Following mechanical testing, a thermal protection system (NORCOAT® LIÈGE HPK FI [13]) was applied to the CF-PEEK surface to shield it from high temperatures during the flight path.

Mechanical testing under compression and bending loads was successfully concluded in mid-2018, with qualifications performed at the DLR facility in Stuttgart and University of the German Federal Armed Forces in Munich. Detailed results of the mechanical testing campaign are the subject of a separate paper and are hence not discussed in detail in this work. An initial launch date in November of 2018 was postponed, though as of the date of submission of this paper a launch is expected within the following months.

5. OUTLOOK

Manufacturing of this primary structure concluded approximately 2 years ago at a time when the thermoplastic AFP facility at DLR was still in its infancy. Since this time a significant amount of experience has been gained and with it a number of modifications made to the facility itself.

The MTLH was received at DLR in mid-2018 and represented a significant improvement over its predecessor. The MTLH is equipped with multiple material spools which allow the simultaneous deposition of 3 12.7 mm tapes or single tapes between 12.7 and 50.8 mm wide. The ability to deposit multiple narrower tapes is advantageous when fibre steering becomes critical, while the ability to use broader tapes can increase the total rate of part production. In addition to tape modifications, the MTLH is equipped with a water-cooled compaction roller with a thinner silicone mantle. The use of water cooling has been shown to increase the lifetime of the mantle as well as improve the surface quality of compacted material [14] while the reduced mantle serves to increase the force applied during consolidation. When correctly matched to the part tooling, the improvements are expected to yield increased mechanical properties and decreased production time for future components.

Lessons learned can also be drawn from the tooling used to produce this part, which emphasised demountability and a lightweight assembly. As has been shown in recent years, however, tooling temperature has a significant role to play in the mechanical properties of the final laminate or part [15,16]. By incorporating knowledge on this topic developed internally at DLR, as well as that of fellow research institutes, the performance of this part may be improved even further and significant savings (both mass and material) realised.

6. CONCLUSION

The work presented in this paper shows that fibre-reinforced thermoplastic materials have a role to play in the near future of space missions. By combining the advantages of unidirectional CFRP material with automated fibre placement, a flight-ready sounding rocket structure was successfully produced. The anisotropic nature of this part minimises unnecessary mass by orienting fibres in the required loading directions. Furthermore, the ability to manufacture this part in-situ, without the need for additional consolidation in an oven or autoclave, greatly reduces the unit production time and allows a high degree of process automation. Using lessons learned in the time since manufacturing of this part, future generations of sounding rocket structures can be made with greater mechanical properties and mass savings, paving the way for their implementation on larger spacecraft and launch systems in the future.

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