

ANTISTATIC – DEVELOPMENT OF AN ANTISTATIC COMPOSITE PIPE SYSTEM FOR AEROSPACE APPLICATIONS VIA PULBRAIDING

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Summary

The pultrusion process, although well-established for manufacturing endless fibre-reinforced composites, is not widely used in the aerospace industry. The AntiStatic project aims to enhance its application in the aerospace sector by developing a composite fuel pipe system for aircraft. The straight pipe sections are manufactured with PulBraiding, a continuous and cost-effective production process for profiles with a tailored composition of layers and continuous off-axis reinforcement.

Composite pipes made of glass fibres and epoxy resin offer significant advantages due to their high corrosion resistance and lightweight properties. To enable the use of these composite pipes for fluid transport applications, a certain level of electrical conductivity must be achieved. This is accomplished by incorporating conductive fillers based on carbon nanotubes (CNTs) into the epoxy resin, thereby allowing the conductivity to be adjusted to the required range.

This paper investigates the potential of the PulBraiding process to manufacture antistatic fuel pipes for aviation, targeting key aerospace specifications such as pressure resistance, impact tolerance, and specific resistance. Through comprehensive testing, the study emphasizes the pipes' impact tolerance, static and dynamic pressure resistance, and chemical and temperature resilience to meet stringent aerospace specifications. Prior research confirmed the achievement of necessary specific resistance and surface roughness properties. Additionally, pressure tests and chemical resistance assessments yielded excellent results, further supporting the pipes' suitability for aerospace applications.

Keywords

PulBraiding, pultrusion, continuous reinforcement, braiding, composites, antistatic, aerospace, pipes

1. INTRODUCTION

In recent years, composite pipes have increasingly been adopted in technical and infrastructure applications due to their advantageous properties. Glass Fibre Reinforced Plastic (GFRP) pipes are primarily used in the oil and gas industry, offering superior weight, specific strength, and corrosion resistance compared to steel, asbestos, and concrete pipes [1,2]. In aviation, media transport pipes are traditionally made from aluminum, steel, titanium, or PEEK [3], but especially for the metal materials there are drawbacks such as higher weight and high electrical conductivity. To address these challenges, GFRP pipes present a promising alternative [4]. GFRP pipes can be manufactured using various techniques. A major technology is winding, with wet winding being the current state-of-the-art for producing GFRP fuel pipes in aviation [5, 6].

The second is PulBraiding, which combines braiding and pultrusion and is investigated within this study. PulBraiding incorporates unidirectional (UD) and off-axis rovings to improve mechanical properties for various load scenarios. Braided composites are preferred for their high shear strength, damage tolerance, and toughness due to the off-axis orientation of the rovings. PulBraiding facilitates a continuous and efficient manufacturing process with high production capacity, allowing for the creation of pipes in adjustable lengths and diameters [7], providing an improvement compared to the current state of the art of wet winding.

Glass fibre-reinforced composites are commonly non-conductive, therefore being susceptible to the built-up of electrostatic charges. This is especially important to consider when using GFRP pipes as fuel pipes within the aviation industry.

Static charges occur when electrons transfer from one object to another, leading to an uneven charge distribution [8]. Conductive materials can quickly balance these charges, while insulating materials, like GFRP, tend to accumulate them due to low electrical conductivity [8]. This accumulation increases the electric field, which can cause electrostatic discharge, like sparking [9], if it exceeds the insulating properties of the environment [10].

Therefore, the conductivity of GFRP fuel pipes must be adjusted to a specific range to dissipate static charges effectively and avoid sparking, while still providing electrical insulation against lightning strikes [11]. By incorporating antistatic or conductive fillers, such as nanoparticles or nanotubes, the conductivity of the GFRP can be modified to allow for rapid dissipation of static charges, preventing electrostatic discharge in the form of sparks. [12,13] Similar to wet winding, the resin system's conductivity and specific resistance in pulbraided pipes can be adjusted to meet these requirements [6].

This paper builds on previous findings [14] concerning the surface roughness and specific resistance of pulbraided antistatic GFRP pipes for aviation, which are crucial for efficient fluid flow and electrical conductivity. Earlier research demonstrated that the pipes consistently maintained surface roughness values below the rejection threshold of $1.5\ \mu\text{m}$. Specific resistance measurements confirmed the pipes' antistatic properties, with the optimized filler content at 0.15 wt.-% to achieve a required resistance range that balances static charge dissipation and electrical insulation against lightning strikes.

This study emphasizes detailed testing procedures for pulbraided pipes, assessing their impact tolerance, static and dynamic pressure resistance as well as their chemical and temperature resistance to adhere to stringent aerospace specifications. It begins with a comprehensive description of the manufacturing setup, materials, and testing procedures, followed by the testing results.

2. EXPERIMENTATION

The PulBraiding trials are carried out using the Px500-10T pultrusion machine from Pultrex. The machine is equipped with two alternating clamping grippers, with clamps adapted to the geometry of the pipes, and a caterpillar. The die used in the pultrusion process is made of a chrome coated steel. The resin impregnation is achieved using an injection chamber, which is directly connected to the die. The double ring braider RUh 2/60/84-120 by August Herzog GmbH & Co. KG was used to produce two braid layers. Figure 1 illustrates the setup of the PulBraiding process.

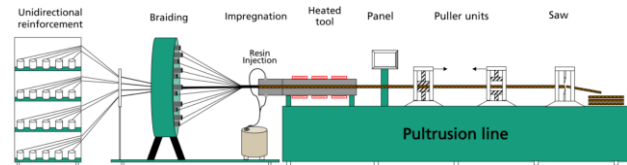


Figure 1: Schematic depiction of the PulBraiding process [14]

Within this study, two different pipe geometries according to requirements of the aviation industries are considered: Profiles with an outer diameter of 38.1 mm (equals 1.5") and a wall thickness of 2 mm and profiles with an outer diameter of 63.5 mm (equals 2.5") and a wall thickness of 1.44 mm were manufactured. To achieve the different wall thicknesses, the braid layers were varied as well as the content of UD fibres along the core.

For the 38.1 mm pipe two different injection chambers, a conical and a teardrop shape, and their influence on the PulBraiding process were investigated.

2.1. Materials for PulBraiding

Within this study, as described in [14], HiPer-tex™ W 2020 rovings manufactured by 3B were used. The rovings are specially sized to provide optimal adhesion to the epoxy resin system. The density of the rovings is $2.58\ \text{g/cm}^3$. The epoxy resin system used is the resin Araldite® LY556, the hardener Aradur® 917-1 and the accelerator DY080 (all Huntsman Advanced Materials GmbH). In order to achieve the conductive properties of the resin system the Araldite® GY40100 (Huntsman Advanced Materials GmbH), consisting of the Araldite® LY556 with 2 wt.% MIRALON® pulp, was used for this study. MIRALON® is a conductive additive, consisting of macroscopic sheetlets with a nanostructure based on long and interconnected carbon nanotubes. The internal release agent IC-25 (ChemTrend GmbH) is added to the mixed resin.

2.2. Characterization

The properties and the requirements of the pipes are determined using various testing methods. To ensure a safe use of the pipes, static and dynamic pressure testings with previous impact damaging are conducted and evaluated as well as temperature and chemical resistance measurements.

2.2.1. Impact testing

To conduct the impact testing a rig (Figure 2) is used, resulting in the formation of a 'Barely Visible Impact

Damage' (BVID), defined as a mechanically induced plastic impression on the exterior surface of the pipes. The purpose of this procedure is to ensure that any surface damage that may occur during the installation of the pipes is considered when assessing their technical suitability. A drop tower was specially designed and constructed for the test, allowing a punch with a defined geometry and flexibly adjustable mass to slide downwards on a movable carriage and hit the longitudinally placed pipe (see Figure 2). These included adjustments to the mass of the punch and the drop height, in order to achieve a circular plastic impression of 0.3 mm depth. This was measured using a calliper. This was achieved with a mass of 1 kg and a height of 1 m; the potential energy was therefore 10 J. In this configuration, all pipes were pre-damaged, i.e. a plastic impression was created in the centre of the pipe, after which the tests were carried out to further characterise the technical properties.

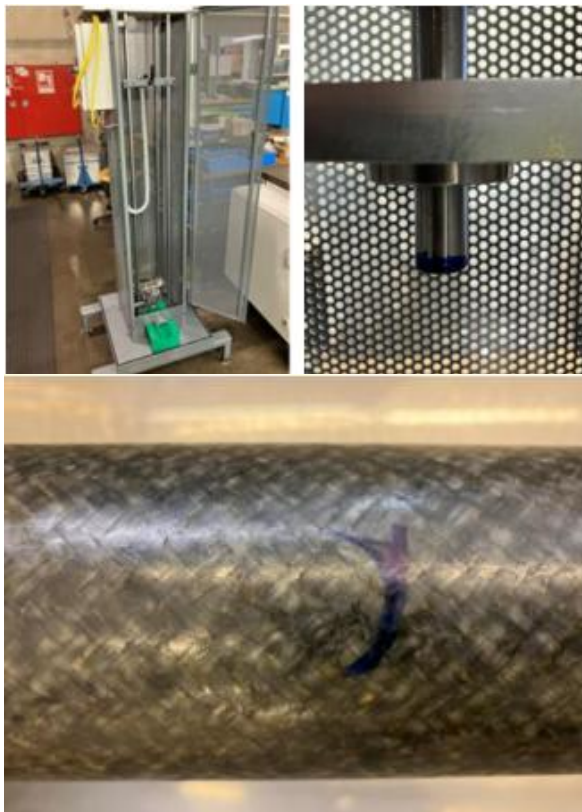


Figure 2: Test rig for impact testing (left and right, top) and pre-damaged pipe (63.5 mm) (bottom)

2.2.2. Static pressure resistance

In accordance with the specification, the pipes were subjected to a range of ambient pressures, from an internal pressure of 2.5 bar to an external pressure of 6 bar, and a range of temperatures, from - 55 °C to room temperature and 85 °C, respectively (compare Table 1). Silicone oil was used as the test medium.

To achieve a successful outcome, it was imperative that the stress on the pipe be sustained for a period of five minutes, without any loss of pressure occurring.

Table 1: Testing parameters for static pressure tests of the 63.5 mm pipes

Temperature [°C]	Pressure [bar]	Duration [min]
- 55	+ 2.5	5
- 55	- 6	5
21	+ 2.5	5
21	- 6	5
85	+ 2.5	5
85	- 6	5

2.2.3. Dynamic pressure resistance

In accordance with the specified test conditions, the 63.5 mm pipe is tested at varying external pressures of 1 and 3.14 bar, with a constant internal pressure of 1 bar. The 38.1 mm pipe is tested at alternating internal pressures of 1 bar and 11.85 bar, with a constant external pressure of 2.2 bar. One million load cycles are performed for each test. The test frequency is 1.2 Hz, and the ambient temperature is room temperature.

2.2.4. Temperature resistance

According to the specification, it is essential that the pipes have a defined temperature resistance. For the test (Figure 3), two test containers filled with oil are used. The temperatures in the test containers must be set at a constant 85 °C and - 55 °C, respectively.



Figure 3: Testing setup for temperature resistance measurements

The pipe to be tested is transferred from one container to the other within 15 seconds and held there for 5 minutes. The pipe is then transferred to the other container, where it is securely held. This allows for a total of 5,000 temperature changes between the high and low temperatures to be carried out in this way. The chambers of the test rig were filled with silicone oil, and the required temperatures were set using active heating and cooling. Due to the high number of cycles and to ensure high test accuracy, a gripper robot was used to transport the tube from one container to the other. The test was conducted on a pre-damaged pipe with an outer diameter of 63.5 mm. The test duration was approximately 36 days.

2.2.5. Chemical resistance

As GFRP pipes come into contact with fuels and additives during technical use, it is essential to ensure that this does not cause any damage that could compromise safe operation. For this test, a 63.5 mm diameter pipe was placed in a container with a 50/50 mixture of water and Skydrol at a temperature of 50 °C for 1,000 hours. The pipe was then cleaned and inspected.

3. RESULTS

3.1. Impact of the injection chamber geometry on processing properties

In this study, the impact of the geometry of the injection and impregnation chambers on the processing properties of 38.1 mm pipes was thoroughly investigated. Two different chamber designs were examined: the teardrop injection chamber and the conical injection chamber. The teardrop injection chamber is characterized by a core with a consistent diameter whereas the conical injection chamber is designed with a conical core. The conical injection chamber, with its conical core, presented several challenges. The decreasing diameter of the conical core led to a build-up of braided fibres at the transition to the tool, resulting in tearing and inconsistencies. These geometric constraints made it difficult to maintain a high braiding angle and achieve a stable processing environment. Additionally, the congestion and displacement of rovings within the tool compromised the surface quality and process stability. The fibre volume content (FVC) achieved is insufficient to ensure an even resin distribution, further preventing the attainment of a uniform wall thickness. The braided fibres were often displaced, forming an uneven braid, which detracted from the overall quality of the final product.

On the contrary, the teardrop design facilitated the achievement of an even braid, high process stability, and superior impregnation of both braided and unidirectional (UD) fibres. Consequently, for all pipe tests conducted within this study, the teardrop injection chamber was utilized due to its favorable processing attributes.

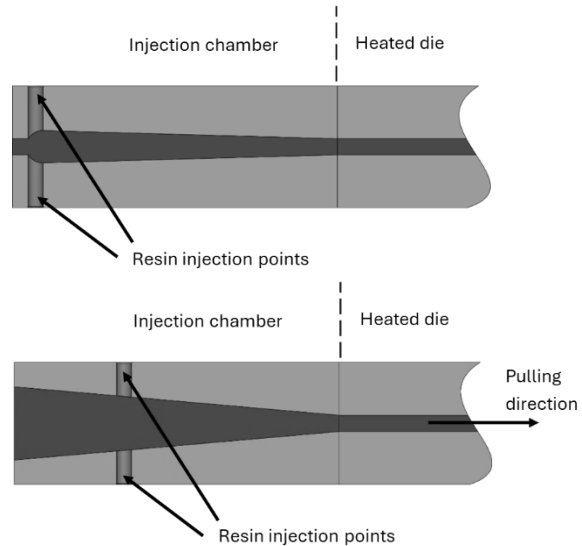


Figure 4: Schematic depiction of the two injection chamber geometries: teardrop (top), conical (bottom)

Through this comparative analysis, the teardrop injection chamber demonstrated superior performance in processing 38.1 mm pipes, underscoring the importance of injection chamber design in optimizing manufacturing outcomes.

3.2. Characterization

3.2.1. Static pressure resistance

In accordance with the specification, the pipes were subjected to different ambient pressures (compare Table 1). Silicone oil was used as the test medium. For a successful test, the stress on the pipe had to be maintained for 5 minutes without pressure loss. At a temperature of 85 °C and an external pressure of 6 bar, a pipe with a diameter of 63.5 mm failed in one case. The compression of the pipe produced a clearly visible plastic deformation and cracking in the longitudinal direction (compare Figure 5).



Figure 5: Damaged 63.5 mm pipe after static pressure testing at 85 °C and 6 bar external pressure

Computed tomography (CT) was used to evaluate the microstructural damage in detail, compare Figure 6. The CT scans initially show an interfibre breakage (matrix failure) in the UD layer as a result of the high external pressure. As a result, the failure of the matrix in the inner layer enables a localised relative movement of the outer braided layer. This in turn leads to delamination between the UD and braided layers. The delamination continues, weakening the local structure of the component and ultimately resulting in breakage of the outer braided layer.

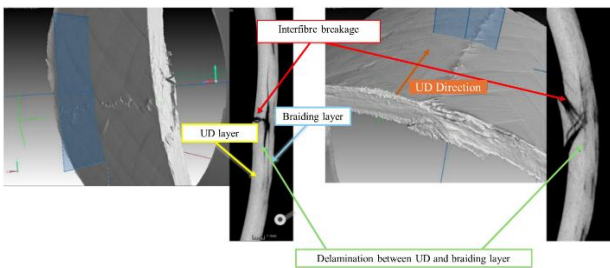


Figure 6: CT scan of the damaged pipe after the static pressure test with 85 °C and 6 bar external pressure

For a subsequent test, a test specimen was used that was heat-treated in a comparatively different way: Instead of allowing the adhesive between the tube and end caps to cure at 130 °C, a temperature of 140 °C was set. The heat treatment at a higher temperature has (within material-specific limits) a strength-enhancing effect on the adhesive and the braided GFRP pipe. The repeat test was carried out successfully without damage. This ultimately proved that the developed tubes are technically suitable for the test conditions defined in the specification.

3.2.2. Dynamic pressure resistance

After one million load cycles, no leaks can be detected during the dynamic pressure resistance measurements. Figure 7 indicates a stable performance, with no pressure drops observed, underscoring the pipes' ability to maintain integrity under dynamic conditions. No visual damage or plastic deformation is visible after the pipes were removed, meaning that the pressure tests for both pipe diameters are passed. This outcome highlights the pulbraided pipes' resilience, confirming their reliability for aerospace applications. Their ability to endure extensive cyclic loading without structural compromise is essential for aircraft systems, where dynamic pressures are frequent

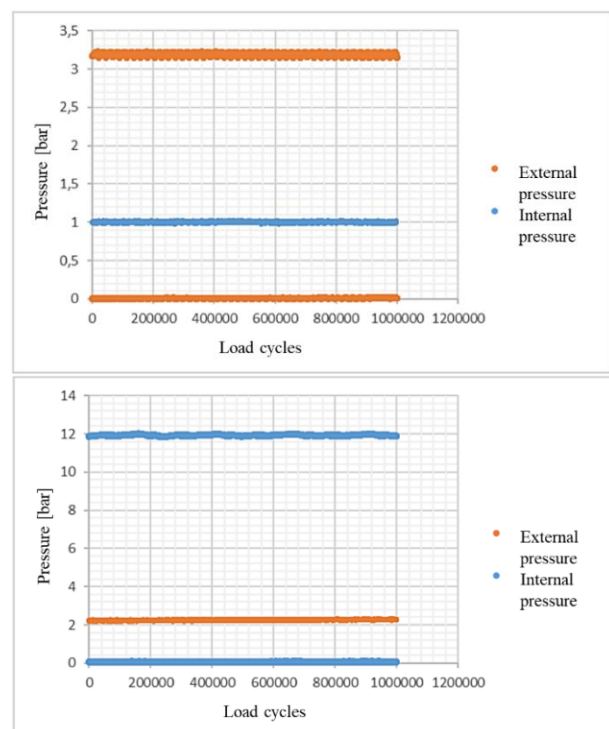


Figure 7: Dynamic pressure testing of the pipes with 63.5 mm diameter (top) and 38.1 mm (bottom)

3.2.3. Temperature resistance

Following the results of the long-term test, no optical defects were identified on the pipe; however, one end cap was found to be damaged. It appears that the issue was not due to inadequate thermal shock resistance in the PEEK end cap, but rather due to how the test was carried out. During the test, ice formed on the - 55 °C cold silicone oil-filled container. The end cap of the tube hit the ice during the immersion process, resulting in damage to the cap. Consequently, the damaged end cap was detached from the pipe after the test and a new end cap was adhered in its place.

The static pressure resistance was then tested and successfully passed. Following the test, no significant plastic deformation of the pipe could be measured. The pipe's temperature cycle resistance has thus been validated for the specified temperature range.

3.2.4. Chemical resistance

It is evident that there have been no discernible irregularities or alterations detected in the fibre composition of the pipe. However, it was found that the adhesive between the pipe and the end caps was attacked by the medium and partially dissolved (see Figure 8). This is not considered critical, as it is only a matter of attacked adhesive residues outside the joining zone. In the contact area itself, i.e. between the end caps and the pipe, the adhesive was not significantly compromised. The joint is still intact. It is not necessary to conduct an additional pressure test, in accordance with the specified requirements.



Figure 8: Pipe and end cap with damaged adhesive residues after chemical resistance testing

In addition, the electrical resistance was measured and an increase of 26 % was found. This increase can be attributed to the impact of the water/Skydrol mixture. As the electrical resistance of the pipe has a low value in the initial state, the subsequently measured increase is not critical. The electrical resistance is still within the required target range. It has been demonstrated that the pipe exhibits comprehensive chemical resistance.

4. SUMMARY

This study extensively examined the mechanical, thermal, and chemical resistance properties of pulbraided antistatic pipes, essential for aerospace applications. The integration of glass fibres and epoxy resin with conductive fillers successfully achieved the necessary antistatic properties. The investigation into

injection chamber geometry revealed that the teardrop design facilitated superior process stability and fibre impregnation, proving effective for maintaining uniform resin distribution and wall thickness.

Through rigorous testing, the mechanical robustness of the pipes was validated. Static and dynamic pressure tests confirmed their resilience under varied conditions, except for a single failure under extreme conditions, which was addressed through heat treatment adjustments. Temperature resistance tests demonstrated reliability across a wide range of conditions, crucial for aerospace environments. Chemical resistance tests ensured the pipes maintained integrity when exposed to fuel mixtures. Achieving Technology Readiness Level (TRL) 6, this study establishes the technical suitability of pultruded antistatic fuel pipes for aerospace applications. These findings underscore their potential for broader implementation, paving the way for innovative aircraft systems. Future research could focus on optimizing adhesive formulations and further validating the pipes under diverse operational scenarios.

5. ACKNOWLEDGEMENT

This paper expands on work conducted as part of the AntiStatic project (03LB2020) funded by the German Federal Ministry of Economic Affairs and Climate Action (BMWK) and includes, for the purpose of completeness, previously presented material at SAMPE Europe, 2024 [14]. The content has been significantly updated with new data and extended analyses concerning the characterization and validation of the pipes for this submission.

The test specimens were manufactured by Fraunhofer IGCV, while mechanical characterization and evaluation were mainly conducted by Otto Fuchs KG. We gratefully acknowledge the collaboration within the framework of the AntiStatic project.

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