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Title

Full-Scale Application of in-situ Automated Fiber Placement for the Production of a Fuselage Skin Segment

Authors

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Abstract

The CleanSky II multi-functional fuselage demonstrator is the world's largest known aviation structure made of thermoplastic composites. The Center for Lightweight Production Technology (ZLP) in Augsburg together with Premium Aerotec, supported by Aernnova and Airbus was responsible for the delivery of the 8 m long upper half shell. The first step in the upper shell production is the skin placement which is done by means of in-situ automated fiber placement (in-situ T-AFP). The process is a lean, single-stage additive manufacturing process for thermoplastic CFRPs. In order to ensure a sufficient quality in the laminate the ZLP has worked intensively on dedicated design principles for the process, material quality requirements and an optimization of process parameters. Major advancements on the way towards a full-scale fuselage have been displayed in the past by the manufacturing of a scaled demonstrator. This paper presents the evolution to the recently manufactured full-scale component with a total length of 8 m, a diameter of 4 m and a composite part design that includes reinforcements for the door cut-outs and two different welding interfaces. The latter will be leveraged for the joining of two half-shells by means of thermoplastic welding. In this work the methodology for a scale up to an actual airplane geometry and the associated challenges are emphasized. Critical aspects of the scale up and potential mitigation of future issues for in-situ process are discussed with regards to design, process and manufacturing. Finally, a way towards industrial, full-scale productions by means of in-situ AFP is proposed.

Keywords: Aerospace, Fuselage, CFRP, Manufacturing Technologies, AFP, Thermoplastics, in-situ consolidation, Scale-up

1. Introduction

In order to reach a more sustainable aviation, the status quo of aircraft manufacturing and operation is challenged on various levels, like for instance by new energy storage systems and more efficient engines. Lightweight design has always been a key enabler to reduce mass and thus the energy consumption in flight. Broadly speaking, aircrafts are optimized in terms of mass, drag and expense. For a conventional single aisle aircraft, such as the Airbus A320 both major and incremental optimization has been going on for about four decades.

In order to compete with an already very effective and efficient solution is hence demanding.

Still, the multi-functional fuselage demonstrator (MFFD) funded within the European CleanSky II research program aims to do just exactly this. A holistic approach trying to establish a new optimum taking all disciplines of production into account, i.e. systems, cabin and structure with a disruptive all-thermoplastic composite fuselage, which has the great potential to revolutionize the major component assembly by means of dustless welding. This means for instance, that the bottom part of the fuselage may be equipped with system installations, a floor and seats with full accessibility for workers and robots before adding the upper shell with its head-racks and cabin monuments in place. With a conventional aluminum build this would not be possible as metal chips produced by drilling and bolting might harm the installations.

Such a switch of material needs to prove its benefits on the system level, i.e. on a full-scale aircraft barrel, where new challenges often only arise and manifest during scale-up.

As for the upper shell, DLR chose to apply in-situ consolidation for the production of the skin. Avoiding vacuum bagging and related tasks may reduce lead time compared to standard thermoset designs – such as the twin-aisle A350 – by up to 40%. This was calculated by a KPI-analysis conducted by PAG and Airbus. However, the part quality has to be demonstrated when avoiding secondary consolidation. Especially, high-performance thermoplastic composites have a strong heritage – ever since the invention of poly-aryl-ether-ketones in the late 1970's - but to date could not find their way into high-rate production of primary structures.

Equally, in-situ consolidation of thermoplastic composites is a subject of research but still needs to robustly deliver high quality parts. This highly transient process in which tows of fiber-reinforced tapes are placed track by track and hence build up the final part needs to assure heat up above melt temperature just before the compaction roller and then cool down and consolidation beneath the same. Establishing a proper processing window is thus a challenge for a multitude of trades, from mechanical engineering, to material sciences, control technology and simulation. Another known key factor is the quality of the as-delivered material. As void removal beneath the compaction roller is limited, its quality strongly influences the final part quality.

As part of the CleanSky II multi-functional fuselage demonstrator the ZLP has matured an in-situ automated fiber placement process from small panels to a fullsize demonstrator. This helped to identify fields in which future actions need to be taken in order to utilize the in-situ AFP technology for large aeronautic structures

2. Experimental Setup for Full-Scale Manufacturing

The validation of the in-situ AFP technology has been done on a test shell with full-size radius, but reduced length [1]. However, the demonstrator was not designed as a flying component. For the final demonstrator the design has been adapted to a realistic fuselage skin that also incorporates interfaces for later assembly. Additionally the size was increased from approximately one to eight meters [2]. Adjustments were necessary to account for the more complex design as well as the size of the demonstrator. Changes to the design, the hardware and the software chain will be presented in the following.

2.1. Technical Infrastructure

Hardware changes were necessary compared to the manufacturing of the previous demonstrator in order to manufacture the more complex features such as the stepped longitudinal joint area or the reinforcements. Additionally, a change of the robotic cell was necessary in order to facilitate manufacturing of the full-scale part.

2.1.1. Tooling

The chosen material for the tooling is Ni36 Invar. This was done in case secondary annealing would be needed to ensure laminate quality for subsequent processes. Otherwise, in-situ consolidation could also be conducted on a simple steel tooling which would reduce the investment cost of such a tooling to about 30%. Its total weight is 19.4 tons. The surface was measured for geometric accuracy and showed that most of the surface deviations are within the tolerance. A local higher deviation of 1.3 mm from the nominal geometry occurs in one of the corners. This is acceptable since the area is outside of the engineering edge of part (EEOP). The tooling together with the surface deviations is depicted in Figure 1.

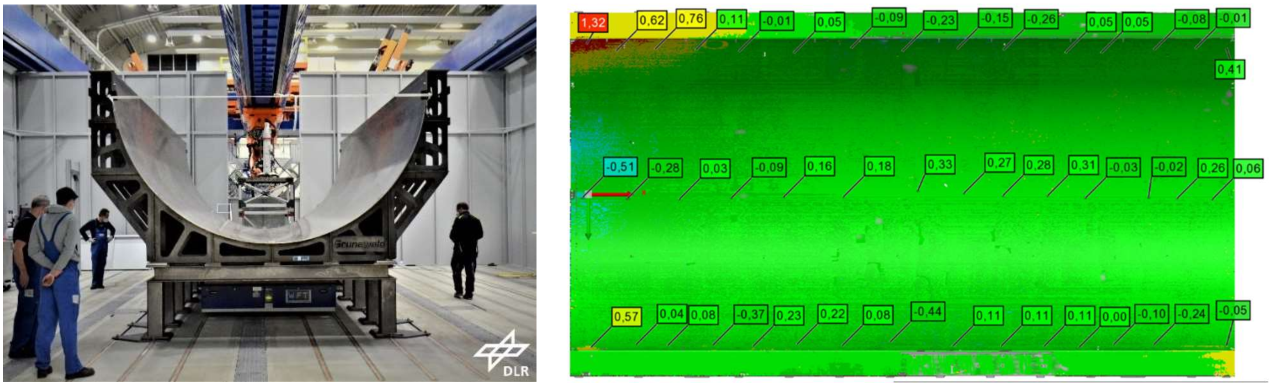

Figure 1: Design tooling (left) and as-built accuracy measurements (right)

One key difference compared to the previous tooling is the integration of a system of vacuum suction points on the surface. A total of 20 connection points is evenly distributed across the surface of 55 m². Two axial piston pumps TRIVAC D65B supplied by Leybold are used as vacuum generators. Each pump has a maximum pumping speed of 78 m³/h.

2.1.2. AFP Machine

The AFP machine used for layup is the Multi Tow Layup Head by AFPT. The head can place three ½” tapes in parallel. The placement machine was customized in order to enable a single tape cut. The robot used for the demonstrator build is a ceiling mount KUKA KR270 R2700 on a rail. This setup allows the working envelope to enclose the entire part. An enclosed setup ensures laser safety.

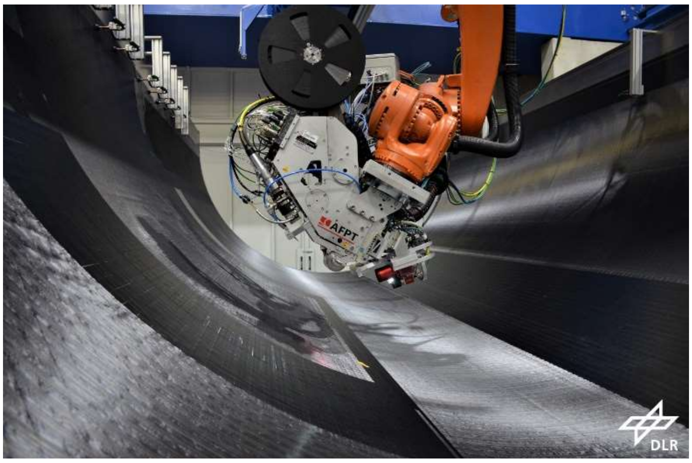

Figure 2: AFP machine on the robot during production of the demonstrator

2.1.3. CAD/CAM Process Chain

The software workflow included ply design, path planning, offline programming of the robots, process simulation and collision analysis. The composite design was defined in CATIA V5s CPD work bench. Subsequently the data was exported to the offline programming tool Vericut Composite Programming (VCP) supplied by CGTech. Afterwards, the generated programs for the machine were simulated to verify their accuracy and check for collisions. Two software tools were used: RoboDK and an inhouse developed tool called CoCo [3]. Table *1* gives an overview of the used software and their respective tasks in the CAD/CAM process.

Table 1: Overview of CAD/CAM Process Chain

CATIA V5	**Vericut (VCP)**	**RoboDK**	**CoCo (DLR)**
▪ Design ▪ Definition of ply boundaries ▪ Definition of layup surface	▪ Path definition ▪ Motion planning lay-up ▪ Manual editing of tracks ▪ Motion planning for link-ups ▪ AFP parameter setup ▪ Post-processing into KRL programs	▪ Motion simulation ▪ Reachability analysis ▪ Identification of obvious collisions	▪ Final collision analysis ▪ No simulation of cable chain

2.2. Full-Scale Thermoplastic Design

The full-scale design for the upper shell of the fuselage has a total length of 8000 mm. The outer diameter of the part is 3950 mm. Cut-outs for door and window integration are part of the design. These areas are reinforced systematically which leads to a complex design around these areas. The thickest part of the design is the door corner support area which consists of a total of 68 plies in thickness direction resulting in a total thickness of roughly 12.6 mm. The thinnest areas of the skin are found in the non-reinforced, so-called farfield. The farfield has a minimum of 10 plies which results in a thickness of 1.9 mm. The most challenging features of the part are the longitudinal edges. For the purpose of joining the upper and lower half of the full fuselage, the edges are designed to be joined by a subsequent welding process. Both joining areas are designed as a stepped structure on the edges in order to transfer the mechanical loads between the two fuselage shells. A Principle sketch of the proposed longitudinal joints are shown in Figure 3. The green structures are the direct joining partners for the placed skin. The left picture shows the concept of the butt-strap and the right picture shows the direct joining with the lower shell. Red areas indicate the welding zones. These steps are challenging to manufacture, mainly due to two reasons: Firstly, a stepped structure must be present in the formative tool which complicates the tool design. Thus, the deposition of material in the tooling requires an absolute rather than a relative accuracy. Secondly, a step size of in this case 30 mm requires single tows to be cut, since the perpendicular cut results in a sawtooth pattern in ±45° layers. If all three tapes are cut simultaneously the height of the sawtooth is greater than the step size which is not acceptable for the design.

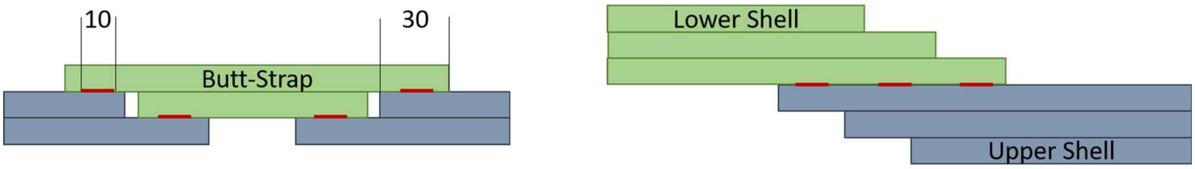

Figure 3: Schematic of the two types of proposed longitudinal joints

The final design was estimated to require 53000 m of tape resulting in a weight of 213 kg for the skin only. Figure 4 gives an overview of the CAD design, with the door reinforcements in the middle, the reinforced buttstrap on the top and the antenna patch on the bottom of the illustration.

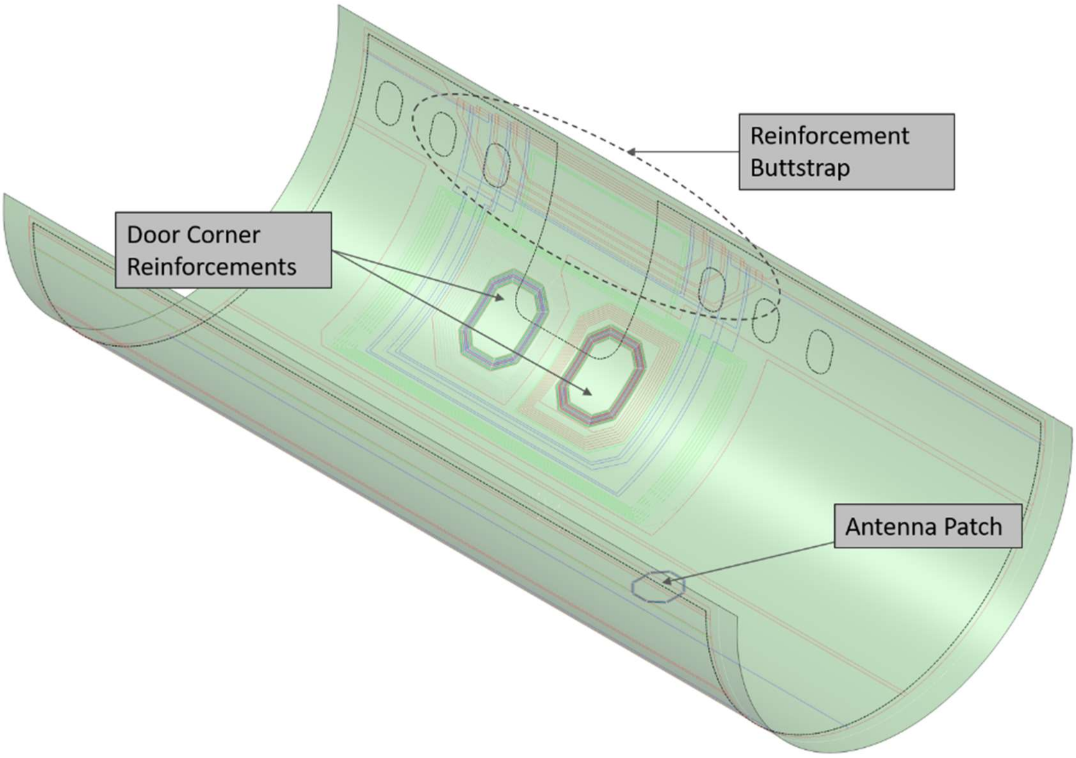

Figure 4: Overview of the CAD Design with notable features

2.3. Material Maturation for in-situ Processing

The chosen material is TC1225 from Toray Advanced Composites – a UD Tape with a T700 carbon fiber, a fiber areal weight of 194 g/m² and a nominal resin content of 34 %. The same material has been used for the optimization of the process and the demonstrators leading up to the final full-scale built. In the past LM-PAEK has shown a superior processability compared to other thermoplastic matrices [4]. In the course of the project the material was further developed together with our project partners. Single step in-situ consolidation showed material related problems. Issues were mostly ascribed to inhomogenous distribution of fibers and matrix within the tapes. This highly impacts transient manufacturing processes such as in-situ AFP due to the short times the matrix is above melting temperature and able to flow freely. Therefore, mechanical performance may vary significantly between batches or even locally within a batch. Figure 5 shows material of two different batches during production. The tape on the left side has an inhomogenous distribution of fibers and thus reflective fibers on its surface. Bright spots on the placed laminate as well as the incoming tape indicate areas of high reflection of the incoming laser radiation. In comparison, the right picture depicts the deposition of a faultless reference tape and identical process parameters.

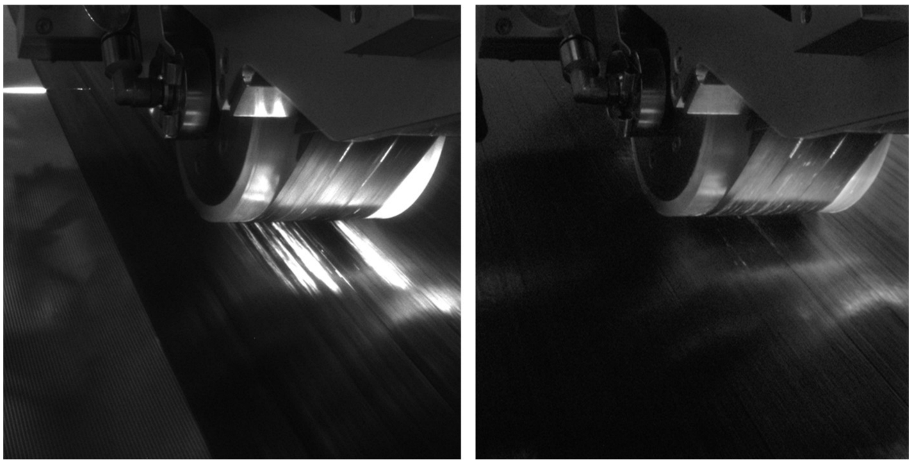

Figure 5: Comparison two different materials during the AFP layup – Corrupted Toray CF/LM-PAEK Batch (left) and Suprem CF/LM-PAEK (right)

Microsections of as-delivered tape show a highly irregular roughness on the surface of the tape and regular fiber avulsion. Furthermore, the overall distribution of fibers differs locally with a tendency of dry fibers on the surface and matrix rich areas in the center of the tape. An example of this is shown in Figure 6. Although microsections were taken from a specifically problematic segment, these observations were made over the entire tape batch.

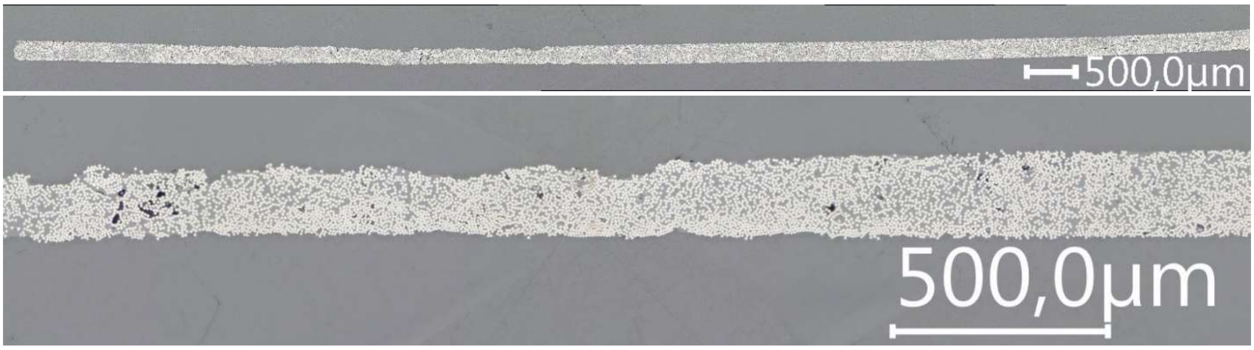

Figure 6: Microsection of Pristine TC1225 Tape from a presumed dry area

It needs to be stated, that laminates that were subsequently treated in a hot pressed showed the expected high mechanical values. Thus, the in-situ AFP process is especially sensitive to divergent quality in its wrought material, due to the short timeframe of heating and consolidation.

For this reason, a new batch of material was fully checked for mechanical performance, processability and overall homogeneity with regards to fiber distribution. Mechanical values were tested with a 3-point bending test according to norm DIN EN 2563 [5].

3. Full-Scale Manufacturing of the Skin

The process parameters were chosen as previously described by our colleagues in Schiel et al. [4], i.e. a lay-up speed of 125mm/s which yields an optimized ratio of productivity and mechanical performance.

Retraction movements of the robot and transfer between tracks roughly double the necessary manufacturing time. Material changes and general maintenance will further increase manufacturing times. Therefore, under optimal conditions a minimum manufacturing time of 90 hours or 11 workdays was estimated. Manufacturing of the full-scale part took place in December 2022 and January 2023 at the DLR facility in Augsburg within a total of 22 workdays and an average production time of 10h per day. With a typical learning curve during scale-up of production the lead time will briefly converge toward the theoretical throughput of 4.4kg/h, hence 48h lead time. Increasing the number of parallel tows by a factor of six, i.e. 18 tows would give an 8h shift per placed skin. A quality assurance sensor is mounted to the head to detect gaps and overlaps between tracks and tapes [6].

3.1. Manufacturing Challenges

Overall the Production of the skin was a success. The achieved surface quality and consolidation proved to be sufficient for subsequent manufacturing processes for the fuselage, such as ultrasonic and resistance welding. For the two different welding technologies used [7], the laminate proved to be more suitable and consistent compared to the scaled version of the demonstrator.

3.1.1. First ply adhesion layer

As part of the process development, a first layer with integrated lightning strike protection (LSP) was first tested in the scaled demonstrator [2]. However, the maximum sheet size of the LM-PAEK foil with integrated copper mesh is 1260 mm x 3100 mm since it was not available from a continuous process for this demonstrator. Thus, a total of 14 sheets needed to be joined in order to cover the entire placement surface. All plies were cut to their respective size including cut-outs for the longitudinal butt-strap joint, as shown in Figure 7.

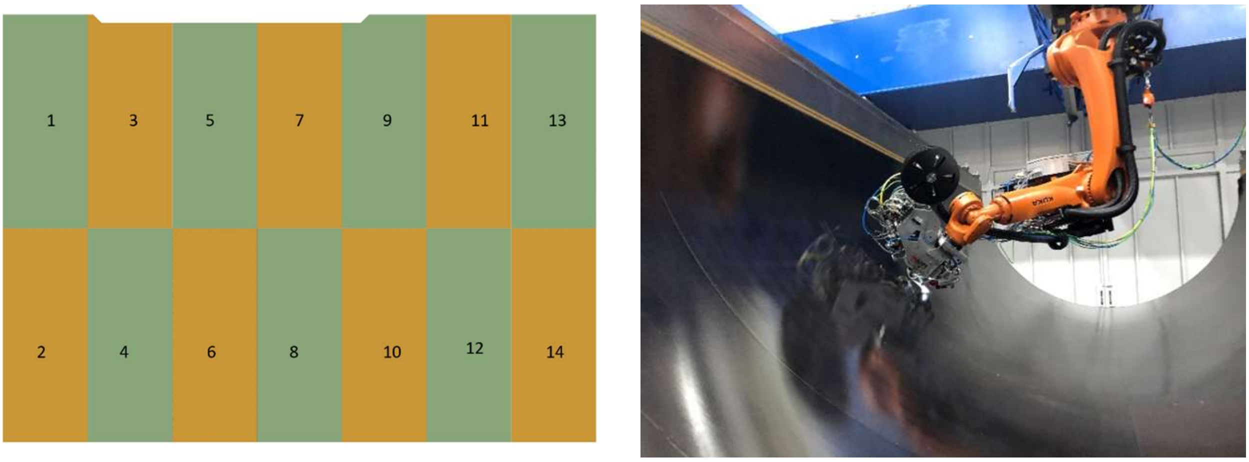

Figure 7: Lightening strike protection application

The joints were adhered manually with Polyimide adhesive tape. Since the LSP foil is rigid and cannot be sheared, joining needs to be accurate in order to prevent wrinkles. In addition, the overall size of 52 m² makes the application in the mold challenging. The most accurate results were met when the entire first ply was placed centered in the lowest part of the mold and subsequently rolled out towards the upper edges of the mold. The copper mesh cannot extend into areas of the longitudinal joints. All areas on the longitudinal joint are therefore equipped with double-sided Polyimide adhesive tape in order to hold down the edges of the CF/LM-PAEK tape and create a clean edge without trimming. The double-sided Polyimide adhesive acted also as seal for the vacuum. Minor repositioning after unrolling the foil was necessary in order to suppress wrinkles. It can be summarized that the first ply should be available in one piece in order to minimize the issue of wrinkles and application needs to be automatized for reproducibility and industrialization.

3.1.2. Spring-in of the Skin

The one-sided heating of in-situ AFP causes thermal stresses, that will result in forces that cause the skin to roll up. Within the project, FEM simulations were done in order to quantify the forces generated by residual stresses. Due to the inhomogeneous heating a significant displacement especially in the reinforced door area were to be expected [8][9]. The forces were anticipated to be compensated by the vacuum holding forces and thus not be problematic for the laminate. However, during production the vacuum seal was locally breached around this critical area around the door support. The laminate pulled inward as expected, further causing the skin to peel off the seal.

A displacement of roughly 30 mm was measured after the placement of approximately 75 % of the plies while the thickness in the respective area is roughly 3.7 mm (Figure 8 – left). The impact on the laminate quality is significant. At first the forces of the AFP machine were sufficient to counteract the displacement. However, the laminate is only temporarily pushed back into the tooling. This causes the laminate to become defective in this area. As a mitigation strategy, mechanical clamping devices were introduced to locally hold down the laminate and enable further production (Figure 8- right). Additionally, a second pneumatic compaction unit was used to compensate for the lower compaction force caused by counteracting the force from the laminate during manufacturing.

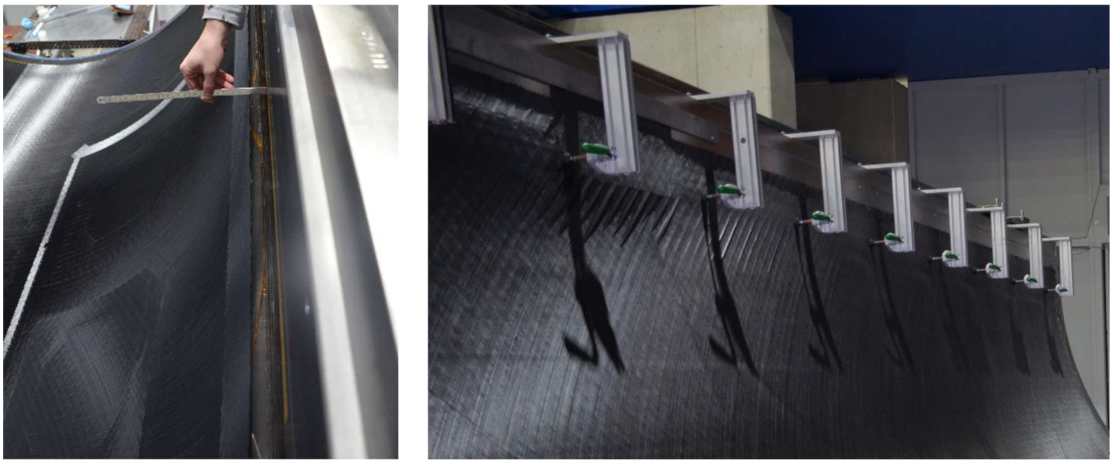

Figure 8: Local displacement of the laminate (left) and mechanical clamping for mitigation of spring-in effect (right)

3.1.3. Continuous Operation

The in-situ AFP process was developed by manufacturing small to medium sized components such as panels. The first instance of full-scale manufacturing with the in-situ AFP process at the DLR occurred during preparation for the MFFD skin with tracks as long as 6.5 m [2]. Signs of overheating of auxiliary material such as the compaction rollers were already experienced at those track lengths, despite active cooling in the roller. In the full-scale demonstrator, track lengths were even greater up to 11.5 m. Although the heat flux in the cooled roller unit was increased, the cooling was not sufficient to prevent degradation of the silicone due to overheating. This reduces the operational time of a single compaction roller to only a couple of tracks. Since this is not acceptable further actions need to be taken to enable continuous operations for the in-situ AFP layup. In order to mitigate degradation, a cool down time was implemented between each track and the silicon was changed frequently to ensure functionality. In total 58 silicon rollers were used for the production of the demonstrator.

3.2. Summary & Lessons Learned

In general, the full-scale production was a success. The most challenging aspects of the demonstrator build proofed to work well with the scale-up. Specifically, the overall surface quality and the quality of the delicate stepped structure within the longitudinal weld zone is satisfactory. This was confirmed by subsequent welding processes which require a well consolidated laminate in order to perform well and with reproducible parameters. Positional accuracy is important for the production of the stepped structure in order to create a smooth edge. This was accomplished by using a standard industrial robot combined with high accuracy base measurements.
The stepped structure will be welded in the second half of 2023 executed by the Fraunhofer Institute for Manufacturing Technology and Advanced Materials (IFAM) in Bremen.

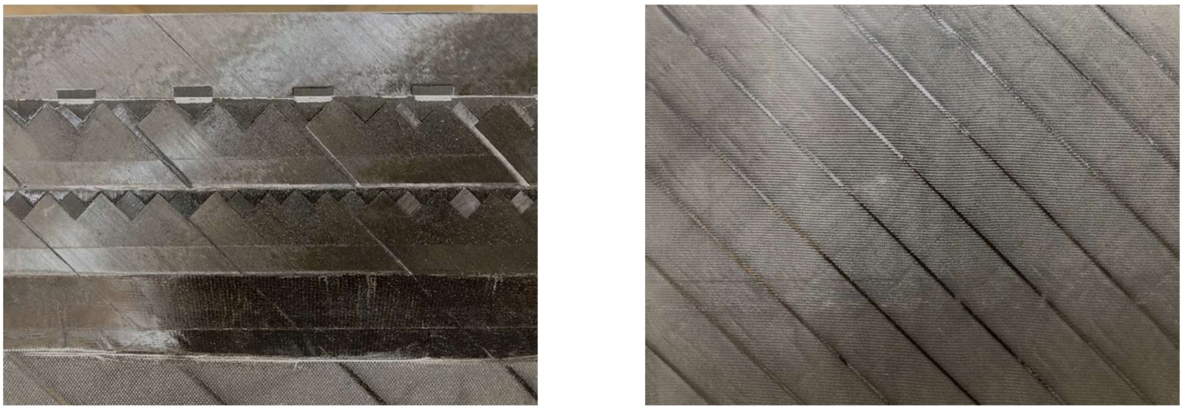

Figure 9: Outside/Tooling side surface details – Stepped Longitudinal Joint (left) and Fairfield (right)

The entire production was in-line inspected for placement accuracy as well as gaps and overlaps with favorable results. Additionally, the visual inspection of the demolded stepped structure was performed and showed that it is within the expected accuracy. This will be quantified in the upcoming work packages. An example of the stepped structures final quality is given in Figure 9 (left). The bottom side surface which is displayed in Figure 9 (right) has a rough finish after the removal of the glass breather which also served as protective peel ply. Removal of the glass breather/peel ply is a labor-intensive process step. It was found that the peel forces were highest were the glass layers had overlapped which led to local overheating resulting in matrix flow from the LSP into the peel ply. An alternative breather material that also provides a smoother surface finish after removal might be desirable. Additionally, visible marks along the edges of the placed tracks are seen. Presumably this is caused by a drop in the laser's intensity on the edges of the focal spot and a resulting drop in temperature on the edges of the tape.

Apart from the laminate quality the production itself was validated. The material was deployed with roughly 3.3 kg/h at machine uptime. The design principles for in-situ AFP that were established within the project proved to be applicable for the full-scale parts resulting in a favorable surface quality without additional post-treatments, like a vacuum consolidated heating cycle in an oven. The positional accuracy of reinforcements and other geometrical features is sufficient, even on the large tooling which can be challenging for the machine setup. The completed skin with indicated locations of some of the geometrical features is depicted in Figure 10.

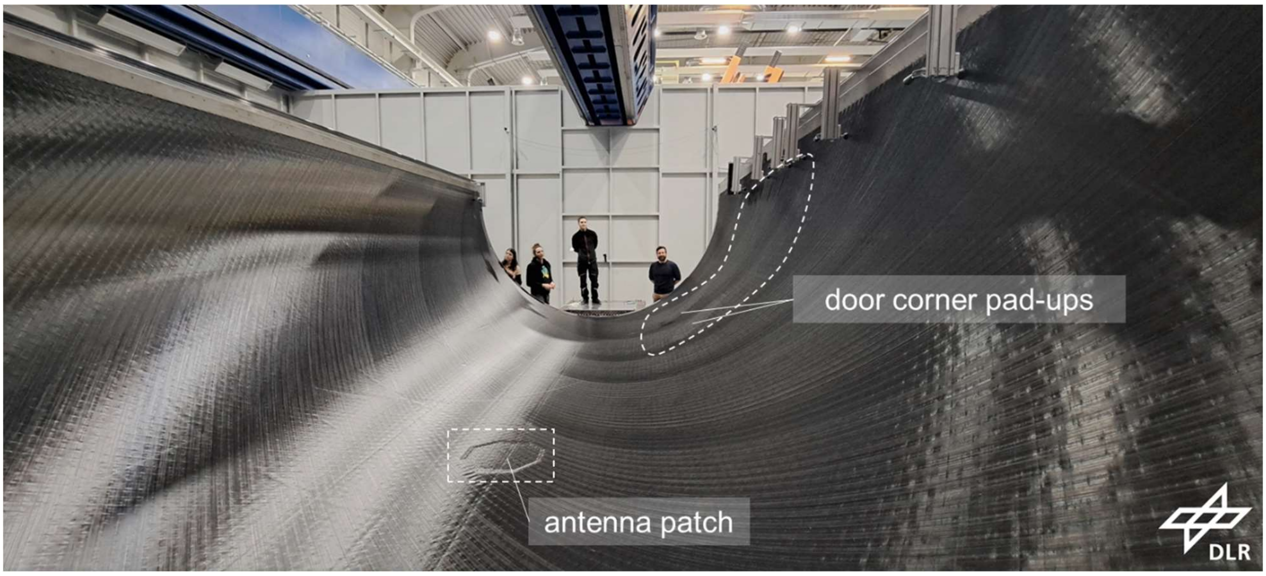

Figure 10: Completed Skin for the MFFD Demonstrator

Despite the overall success of the scale-up, there are several improvements necessary for an industrialized production of an in-situ consolidated part of this size. One of the biggest issues is the fixation of the component in the tooling via vacuum. The vacuum in our case was not sufficient to secure the part. The forces should have been sufficient to counteract the spring in. However, the distribution of vacuum was not homogenous over the entire area, resulting in local fixation around the suction points. These points were evenly distributed over the area of the tooling to average the area about each suction point (i.e. with 4 points oriented in 5 circumferential rows which were each approximately 1.5 m apart). However, the top row was located relatively far away from the edges, where critical peeling of the skin was induced by spring in forces consequently perpetuation further vacuum losses. Therefore, more suction points as well as an improved distribution especially towards the edges is recommended. After demolding we noticed, that the Gerster 15002 flow channel produced of knitted PES filament inlays, had partially fused to the glass breather and that the milled pocket produced a circular imprint on the skin (Figure 11).

Figure 11: Suction points with Gerster tape (left) and resulting imprint on the skin (right)

It is favorable to move the suction points in the area of the given window cut-outs closer to the tooling edges, where the skin laminate is later removed. Additionally, a more suitable breather material that improves vacuum distribution, surface finish and removal is desired to secure the first ply. Another aspect of the first ply that needs to be reworked for industrial use is the application of the LSP foil. Joining of several sheets and manual application is not feasible for large scale production.

Finally, the quality of the prepreg tapes for in-situ AFP is a crucial aspect of the overall performance of the single stage production. Matrix and fiber distribution in incoming tapes needs to be relatively homogenous without dry fibers being exposed on the tape surface, since the process is not providing enough time for substantial resin flow. The tolerance regarding widths of the tapes is also tight, due to the fact that gaps or not acceptable and the overall ply design depends on a reliable consolidated width.

4. Conclusion & Outlook

The fully automated manufacturing of a full-scale skin segment for a single aisle aircraft by means of thermoplastic in-situ AFP has been demonstrated. A total of 53000 m or 213 Kg of CF/LM-PAEK Tape have been placed at a deployment rate of roughly 3.3 kg/h. Conclusively, with the given setup a skin segment of this size can be produced within 65 hours with a continuously operating production. Higher rates are possible if the equipment is properly adapted e.g. by mean of more tapes placed in parallel. This demonstration concludes the latest development of the in-situ AFP technology at the ZLP. Quality issues of the AFP laminate regarding downstream processes such as resistance and cUS-welding were resolved so that consecutive assembly of the fuselage is ensured. However, inconsistencies regarding quality of the incoming tape are still unresolved and a specifically produced in-situ grade material is necessary to fully benchmark the capability of this method of production under the best conditions possible. The next steps in assessing the overall performance will be microsections of the laminate taken from cut outs from the windows and door with various thicknesses. The skin will be fully equipped with stringers and frames in the future and afterwards joining of the upper shell demonstrator with a lower shell is planned for the second half of 2023.

Acknowledgments

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Disclaimer

The results, opinions, conclusions, etc. presented in this work are those of the author(s) only and do not necessarily represent the position of the CAJU; the CAJU is not responsible for any use made of the information contained herein.

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