Innovative Manufacturing: Highlighting Technology Bricks for Automated Production of Fiber-Reinforced Composites in Helicopter Structures

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1. Abstract

The increasing demand for lightweight, high-performance materials in aerospace applications has driven a heightened focus on the automated manufacturing of fiber-reinforced composite structures. However, current manufacturing processes - often labor-intensive and requiring extensive manual intervention - pose significant challenges in terms of cost, quality consistency and scalability. The integration of advanced single part manufacturing processes and joining technologies holds great potential to overcome these barriers. As part of the NEUTRON joint project, relevant technology bricks for the manufacture and assembly of a generic helicopter engine deck structure were investigated in varying degrees of detail. To date, state of the art helicopter engine decks with conventional architecture have not allowed the use of fiber composite structures for reasons of fire resistance. An innovative, functional-differential approach developed by Airbus Helicopters [1, 2] makes it possible to manufacture the engine deck structure from carbon fiber-reinforced plastics and enables the maturation and demonstration of the developed technology bricks.

A fully automated pick-and-place system with intelligent, autonomous ply location and shape detection enables high-precision fiber lay-up of complex carbon fiber preforms, ensuring consistent fiber orientation and ply contour, critical for mechanical performance. Additional quality assurance is achieved through in-process fiber angle measurement using optical sensors enabling a continuous tracking and documentation of relevant quality characteristics. An adapted automated diaphragm preforming process introduces integrated binder activation via combined resistive and hot-gas heating. The overall process is designed to allow for a stepwise preform binder activation and considers the need for intermediate compaction of thick-walled textile preforms. The process is therefore designed for higher production rates with less manual work and fewer tool changes. Additionally, the integration of thermoplastic polyetherimide patches onto the fiber-textile preforms via an optimized infusion process is presented.

For component assembly, an adapted out-of-oven interdiffusion joining process, termed Assembly Interdiffusion Joining (AIDJ), enables pressure- and temperature-activated diffusion joining at moderate temperatures. This eliminates the need for post-curing under vacuum bagging while maintaining structural integrity, offering a scalable, energy-efficient solution for assembly lines.

Throughout all manufacturing stages, process as well as quality assurance data is systematically recorded and stored in a data management system called “shepard”, enabling the generation of a digital part description.

With this work, the potential in aviation part design, manufacturing and assembly are shown by the combination of manual and automated manufacturing of subcomponents combined with the help of a data driven process and quality assurance, and optimized usage of material combinations for dust-free assembly.

2. Introduction

The NEUTRON (New Technologies for Eco-Efficient Helicopters) collaborative project aimed to reduce CO_2 emissions from helicopters. As part of the project, concepts for implementing hybrid-electric propulsion systems were to be developed, and the initial technological components required for this were to be developed and implemented. The combination of different propulsion systems can lead to an increase in weight due to additional components. This effect, which runs opposite to the goal of CO2 reduction, was to be counteracted by a new, weight-optimized design for structural components. The engine deck, as the interface between the propulsion systems and the helicopter airframe, is the primary focus. Building on a new architectural concept developed by Airbus Helicopters Deutschland (AHD) [1, 2], the DLR aimed to realize a design for an engine deck using a new construction method based on carbon fiber-reinforced plastic (CFRP). In addition to the conceptualization and design of the structure, a partially automated, quality-assured manufacturing process was to be designed and implemented. This includes both the manufacture of individual components and their assembly into the final sub-assembly. The aim was to demonstrate practical processes for helicopter production that could also be used for small batch sizes and a variety of components. The application of the manufacturing process was demonstrated through the production of a full-scale demonstrator, which its CAD model is shown in figure 1.

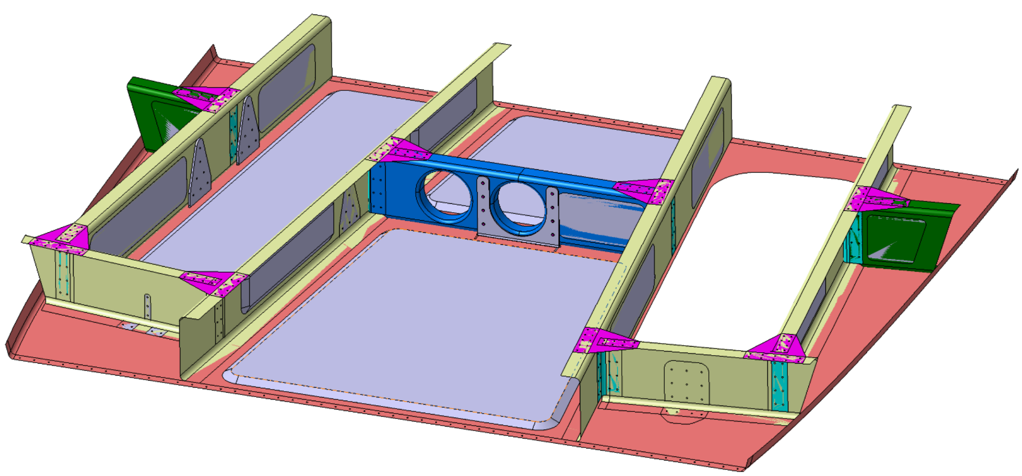

Figure 1. CAD surface model of the engine deck demonstrator assembly

Based on the defined manufacturing route and the selected individual processes, a semi-automated manufacturing process and a quality assurance strategy were defined for the engine deck. The approach here involves a division between manual and automated process steps, or between manual and automated sub-steps within a single process step, as well as the implementation of flexible automated processes. The goal is to identify processes applicable to helicopter manufacturing that can be used even for small production runs and for components that differ in type but are similar in size and structure. An overview of the implemented process is shown in figure 2. In this work the processes for preforming, quality assurance, draping, binder activation, vacuum bagging, infusion and assembly will be highlighted.

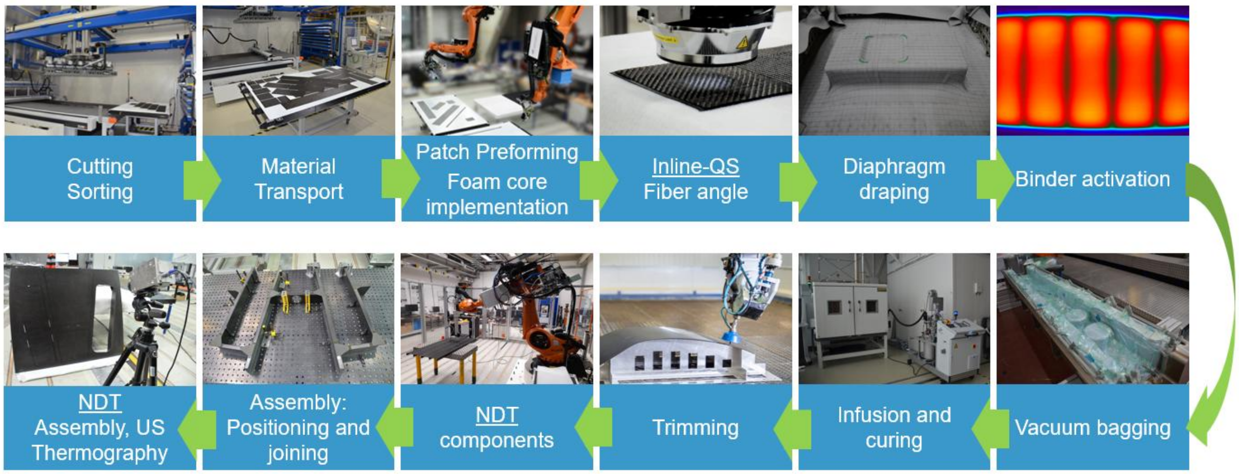

Figure 2. Manufacturing process chain of engine deck demonstrator

3. Process developments

3.1. QA Data management with database shepard

To fully document the production processes, the DLR developed data management system “shepard” was used and further refined for use in the project. Shepard consists of an application programming interface (API) and a web interface for managing data. However, both are designed to be very generic. The manufacturing process implemented in the project involved a mix of automated, semi-automated, and manual processes. In particular—unlike in standard industrial automated processes—there is no overarching process control. Therefore, a graphical user interface (GUI) called “Process Wizard” was developed, which enables a graphical definition of the production workflow. Additionally, it is possible to specify which data must be recorded for each production step.

Using the graphical interface, the necessary structures for data collection are created in shepard similar to the process flow shown in figure 2. An interactive wizard is then available that queries all relevant data step by step and saves it in the correct locations. Here, continuously recorded data can also be graphically assigned to time series with date/time stamps, making it easy to later evaluate all data from a process step.

Figure 3 shows a section of the created data structure using the process step “Infiltration” as an example. Since the software interface to the infiltration system does not yet exist, the recorded data series can be manually assigned to components and processes via the GUI and uploaded.

With this setup all process and quality assurance data were stored manually or automatically by the individual process steps in shepard, including cutting shapes, fiber angles, temperatures during binder activation, pressure and temperatures during infusion, temperatures during joining as well as down streamed NDT data.

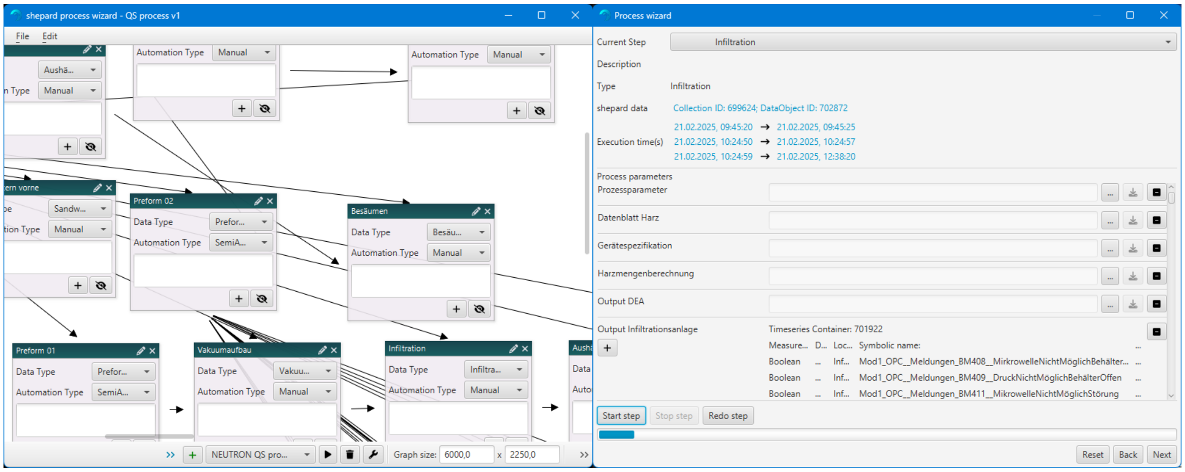

Figure 3. Shepard Process Wizard (left), Data description of process step "Infiltration" (right)

3.2. Preforming station

The focus during the development of the preforming station was on ensuring the widest possible range of applications for the production of various component preforms. In addition, the results obtained in preliminary tests of diaphragm draping were taken into account in order to achieve fiber-friendly draping without introducing defects. Based on a reachability and collision analysis in CAD, a suitable height and position for the fixture was determined for the production environment in the multifunctional robot cell [3]. The station consists of a base plate for mounting the components and is fixed to the rail span of the robot cell on a truss of aluminum profiles and also contains target plates for robotic calibration and is shown in figure 4.

Figure 4. Preforming station for diaphragm preforming of patch preformed carbon fibers

The membrane is stretched using a frame made of aluminum profiles. This frame is mounted on two synchronized linear axes with a vertical pneumatic stroke to enable the membrane's feed movements over the stacked semi-finished layers. A scissor-lift mechanism was designed and built beneath the base plate; this mechanism drives the forming punch into the membrane and counteracts the forces exerted by the membrane—which increase with stretching—using the relative motion of the scissor principle. The positive molds are mounted on the extending and retracting base plate in an interchangeable manner using fixed stops, thereby eliminating the need to re-calibrate a new mold. The advantage of this design is the implementation of complete patch preforms before draping. To enclose the scissor lift kinematics in a vacuum-tight housing, a steel box was designed. Due to the large surface areas and the resulting forces on the walls, the box was analyzed in FEM for stresses, deformation, and buckling.

A pneumatically adjustable wooden box that can lower onto the membrane to enclose the preform was initially used to heat the preform and activate the binder by hot air. However, to achieve a higher level of efficiency, an electrical surface heating system for the mold was implemented as an alternative.

A square-mesh fabric (DIN 1.4301/AISI 304) with a mesh size of 0.09 mm and a wire diameter of 0.04 mm was used as the heating structure to minimize its impact on the component's final contour. This was secured to the mold using PTFE Virginal foil 0.25 V AD, which was intended not only to secure the position of the square-mesh fabric but also to ensure sufficient electrical insulation from the electrically conductive preform, as well as improved sliding friction properties between the preform and the mold. Due to the reduced drapability of the square-mesh fabric, as well as its surface application on the tooling, a "best-fit" solution was developed, taking into account a wide variety of electrical circuit configurations, to ensure maximum coverage of the single-curved tool geometry with homogeneous heating over the longitudinal beam.

Figure 5 shows the AISI 304 heating structure in a partially integrated state, including embedded Type K thermocouple sensors for temperature monitoring of the device, as well as the completed mold after application of the PTFE Virginal film.

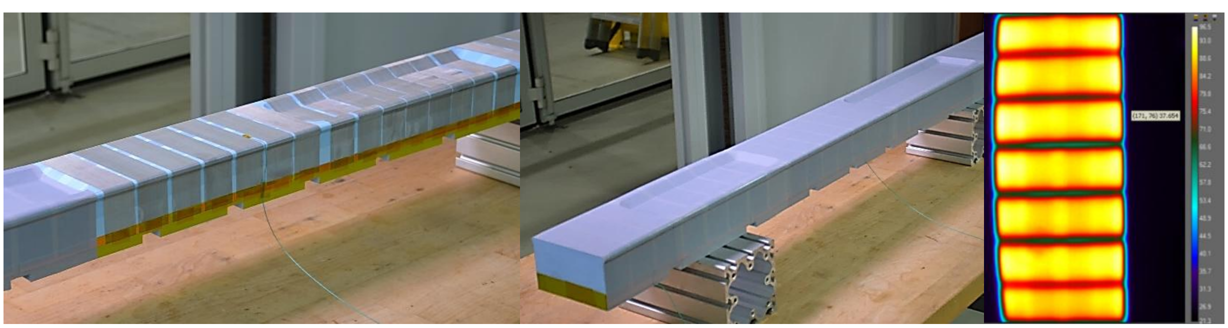

Figure 5. Applied metal mesh on mold (left), applied Virginal foil on mold (center),heatmap of mesh (right)

The existing infrastructure for electric resistance welding at DLR was used to validate temperature uniformity and define parameters for the electrical control of the heating structure. This confirmed both the temperature uniformity across the die and the correlation between the electrical design parameters from the preliminary design and the experimental results.

3.3. Automatic patch preforming for beams

The system developed at the institute is based on robotically guided end effectors to grip the cut pieces. In a preliminary test the feasibility of this system was analyzed and now further developed for the full preforming SAMPE CAMX 2024 [4]. To grip the correct cut pieces a module with a camera and flash unit is mounted on the preforming end effector. After an image of the blanks to be placed is captured, the blank contours are automatically detected and compared with the data in the component plybook. The software determines the next blank to be placed and generates a robot trajectory for picking it up and moving it to the placement point. This system was expanded for use with flexible robot teams, and the software was modularized to execute variable additional processes within the pick-and-place sequence. This enabled the implementation of the local binder activation of UD reinforcement layers with heating stamps and an inline fiber angle measurement with an optical measurement system from the company PROFACTOR. Additionally, an automated backup of all recorded data was implemented as part of the QA strategy within the Shepard software system used in the project.

Following the preforming process for one of the larger beams of the structure is highlighted. The first processing step for all components is the production of dry fiber blanks on a cutter and their sorting and placement on a blank trolley. The cart with the blanks is manually moved into the robot cell to a docking station. Thanks to the blank recognition system, any change in the position of the blanks due to induced forces during movement of the trolley is irrelevant.

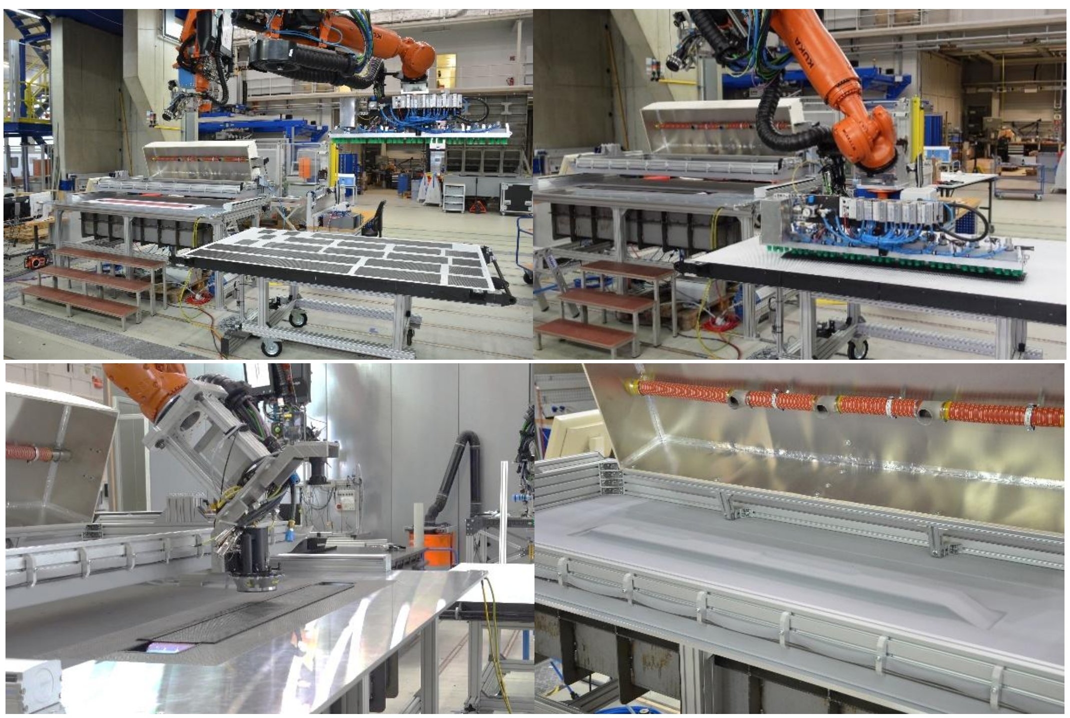

Figure 6. Detection of cut piece (top left), gripping of detected cut piece (top right), fiber angle measurement (center left), diaphragm draping (center right), foam core insertion (bottom left) and final preform (bottom right)

In the initial state, the positive mold is recessed within the preforming station so that its top surface is flush with the surrounding table surface. Using the blank detection (figure 6 top left) the prepared blanks are identified, gripped correctly (figure 6 top right), and placed on the top of the mold. Depending on the layer structure, individual preforms are pre-fixed here using heat stamps integrated into the end-effector. Subsequently, the fiber angle is checked at defined points using another robot with a separate end-effector (figure 6 center left). This process is repeated, depending on the number of layers, down to the layers below the foam cores.

At this layer, the membrane frame is moved onto the layer stack and a vacuum is applied beneath the membrane. The mold is moved vertically into the membrane with help of the scissor mechanics, and the semi-finished fiber sheets are draped to conform to the mold geometry (figure 6 center right). By lowering the hood and activating the hot-air blower and the surface tool heating, the binder is activated on the semi-finished fiber sheets. The membrane is vented, returned to its original state, and the mold is lowered. In the project, the foam cores were inserted manually (figure 6 bottom left). The described process is then repeated until all layers have been deposited and fixed by the final binder activation (figure 6 bottom right).

3.4. Cooperating robot preforming of cover plate

The process for manufacturing the cover plate is similar to that for manufacturing the beams, however, due to the project scope the draping and binder activation were performed manually. Since the cut pieces for the cover plate are much larger than the ones for the beams cooperating robots were needed. After the plies were delivered on the material carrier the detection system recognizes the ply and calculates the grip points for both robots (figure 7 top left). A collision free path to grip the cut piece, transport it fiber friendly and place it onto the mold is calculated and executed (figure 7 top right). This is followed by measuring the fiber angle at defined points (figure 7 bottom left). Manual draping onto the mold surface then takes place. The process is repeated until the layer below the foam cores is reached. Here, intermediate consolidation is performed using vacuum and the binder is activated in the oven After cooling, the vacuum bag is removed, the foam cores are inserted manually, and the subsequent layers are deposited automatically (figure 7 bottom right).

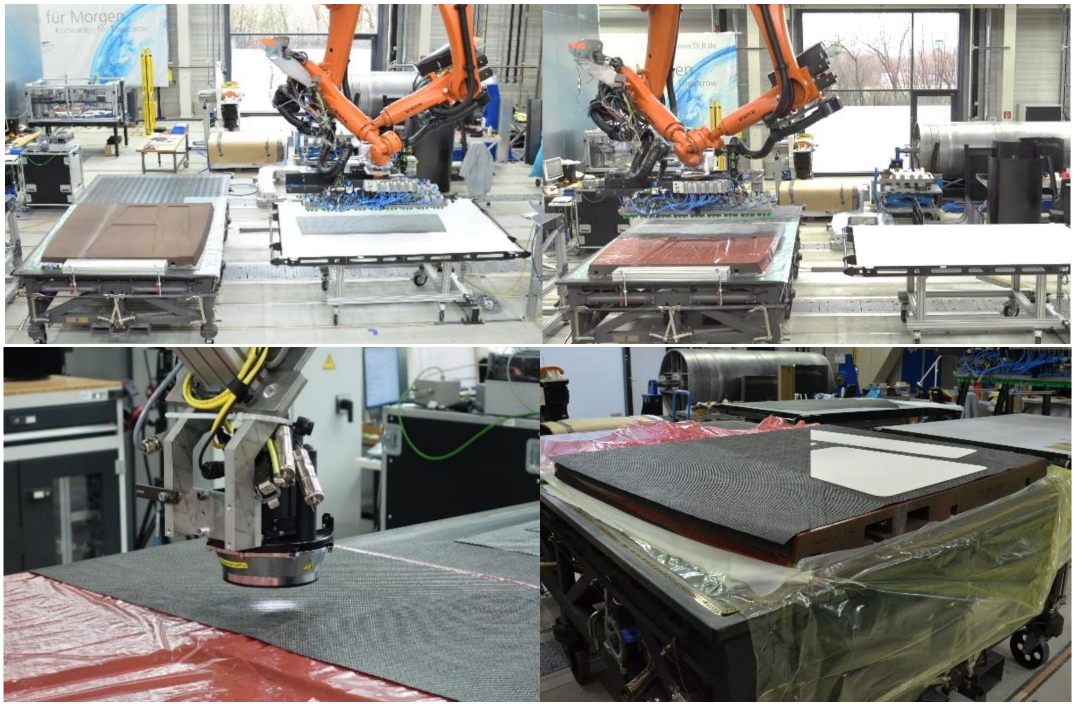

Figure 7. Cooperating gripping of cut piece (top left), cooperating transport and placement (top right), fiber angle measurement (bottom left) and foam core insertion (bottom right)

3.5. Infusion of components

All components of the engine deck were manufactured using resin infusion in the Vacuum Assisted Process (VAP). Although the VAP process is certified for aerospace use, detailed planning and preliminary tests on vacuum build-up and infusion were necessary to achieve the desired high component quality. In addition to the infusion concepts, a detailed analysis of the vacuum setup was conducted. Pre-cut auxiliary materials were used to ensure high, reproducible component quality. The pre-assembly of the auxiliary materials was achieved by precisely cutting and joining the auxiliary materials to ensure the most accurate fit possible. The surface geometry is decisive for the number and position of the cuts by analyzing the surface curvature.

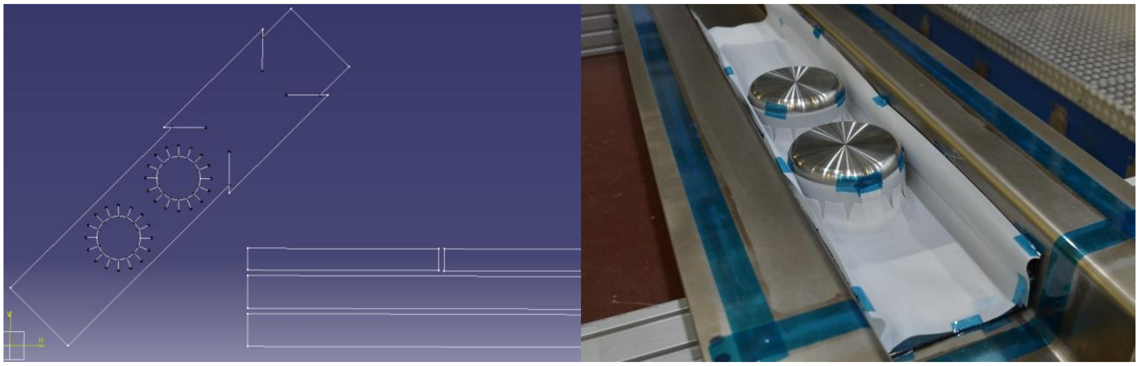

Figure 8. Auxiliary material preparation in CAD (left), applied peel ply (right)

Furthermore, the auxiliary materials typical for VAP (peel ply, perforated film, flow medium, semipermeable membrane, distribution medium, and vacuum film) and their general conformability were examined and analyzed in the context of the component geometries. Figure 8 shows the analyzed and cut materials in CAD on the left and applied to the infusion setup on the right, highlighting the accurate fit of the materials, guaranteeing high quality infusion.

To achieve a bolt-free joint between the components, thermoplastic PEI films must be incorporated into the components during manufacturing, and the incorporation process itself must already meet the requirements of the subsequent joining process (e.g., surface finish and positioning). However, the incorporation of these films must not have a negative impact on the infusion process. Different PEI films, optimized for the joining zone, were incorporated into all nine beams. Figure 9 on the left shows the incorporation of a PEI film on the inner side of a preform. Following infusion tests that yielded insufficient results, a sufficiently good joint surface quality was achieved by additionally applying pressure plates (figure 9 right).

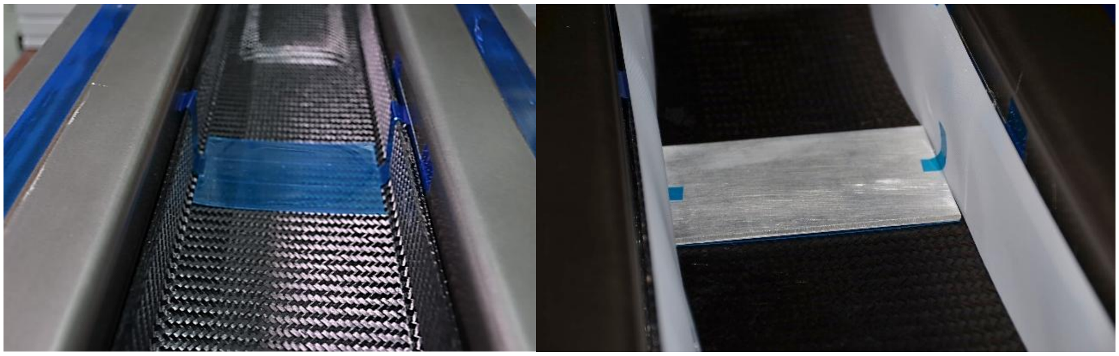

Figure 9. Applied PEI film on top of preform (left) and applied pressure plate on top of PEI film (right)

The institute's existing infusion system and oven were used for the infusion of the components. For the first time, the infusion system was connected to "shepard" allowing process data to be fed into the system in real time. This enabled more efficient data organization, analysis, and optimization of the infusion processes. Figure 10 shows the prepared preform of a long beam on the left, the applied vacuum bagging in the middle and the infusion setup of multiple parts in the oven on the right

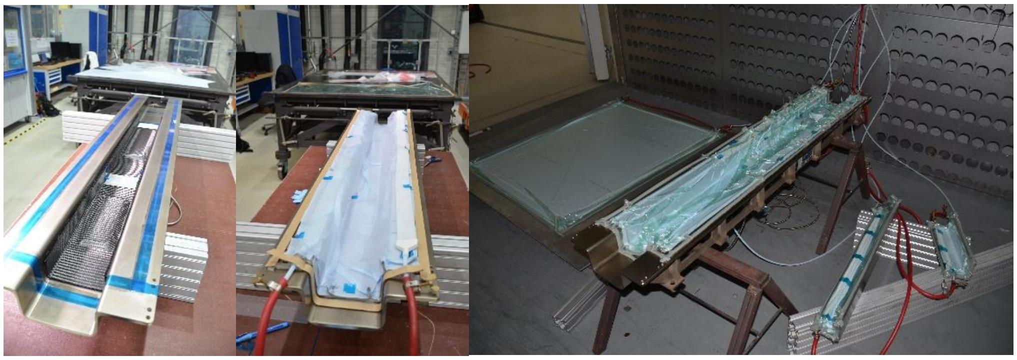

Figure 10. Prepared preform (left), applied vacuum bagging (center) and infusion setup in oven (right)

In total, nine beams with varying laminate structures, one cover plate, six clips, and six gusset plates were infusion-molded, demolded, and their joint areas prepared with PEI films for subsequent assembly steps.

3.6. Joining of components

In the aerospace industry, the traditional method of assembling differentially manufactured fiber-reinforced composite structures has typically relied on conventional bolted joints. Through efficient thermal joining processes, such as resistance or ultrasonic welding, thermoplastic fiber-reinforced composite structures demonstrate great potential for achieving bolt-free assemblies from low-complexity individual components. In contrast, joining duromer-based fiber-reinforced composite structures into a bolt-free, monolithic assembly requires the introduction of hybridization with help of PEI films on the top surface of the components like described in chapter 3.5. To join the components at these hybridized areas the Assembly Interdiffusion Joining (AIDJ) was used. In classic Film Interdiffusion Joining (FIDJ), one component is surface-hybridized and cured. This is then joined to another, uncured joining partner via co-bonding [5]. In the AIDJ process, the two components to be joined are already fully cured and hybridized in the joint area using PEI. To create a bond between the components, an uncured duromer prepreg (here: Hexcel HexPly M18 (G939) prepreg fabric) is applied to the joint area. The temperature increase and pressure application required for curing the duromer prepreg and forming the interdiffusion layer are achieved in the AIDJ process via locally applied, heated pressure pads.

For the assembly process of the subassembly, the individual components (longitudinal, transverse, and center cross members) had to be precisely aligned with one another and clamped securely to withstand the process forces. A fixture was designed and manufactured for this purpose (see Figure 11 left). This fixture is based on a standard welding table. The individual clamping units consist of aluminum base plates, which, using set screws, enabled an accuracy of 1/10 mm for the individual clamping units. Aluminum profiles were bolted onto these; to ensure a closed force flow during clamping, the profiles were connected with cover plates. These formed the basis for the low-pressure application via aluminum contour blocks. Additional clamping units with disc punches were attached to the sides of the profiles to bring the entire assembly into an approximate ideal position. Benefits of using the AIDJ process are its expanded capabilities for compensating manufacturing tolerances, as well as for simplifying tool geometry. External, localized pressure and temperature were applied using contour-following, self-heating pressure blocks.

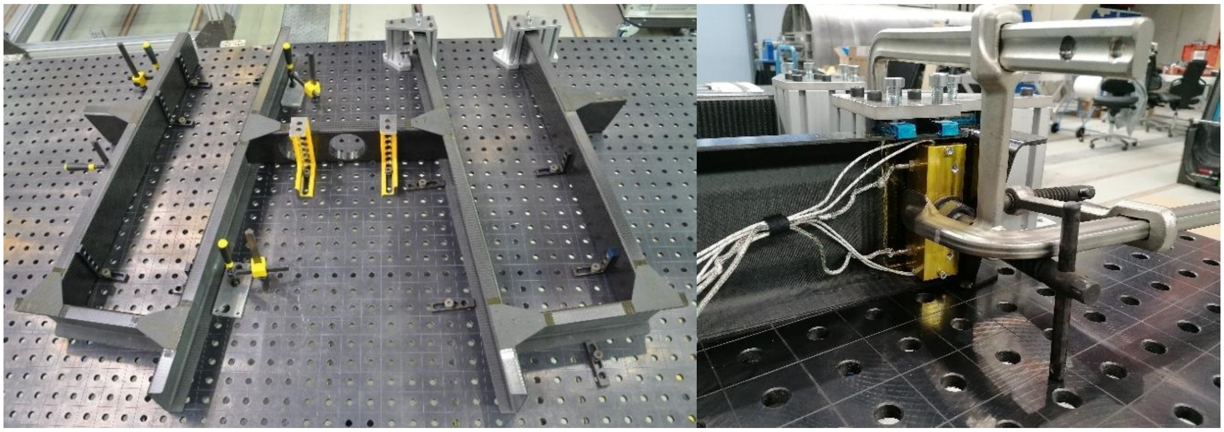

Figure 11. Fixed sub components on welding fixture (left) and AIDJ setup for joining (right)

The pressure blocks were electrically heated using heating cartridges controlled by a PID temperature controller (ENDA ETC2011). Two Type K thermocouple screw-in sensors integrated into the pressure blocks were used to measure the actual temperature for logging purposes and to serve as the reference signal for the PID temperature controller. All clips and gusset plates were integrated at a joint temperature of 220°C and a hold time of 30 min. Figure 11 on the right shows the technical implementation and the joined assembly. The final joining of the beam sub-assembly to the cover plate was performed using structural adhesive (3M Scotch-Weld EC-9323-2 B/A).

4. Results

The developed and demonstrated process chain resulted in a fully assembled engine deck. Figure 12 shows the assembled structure consisting in total of nine beams, the cover plate, eight gusset plates and eight clips. Also cut outs for further structural fasteners are already integrated.

Figure 12. Fully assembled engine deck in top and bottom view

The now individually more or less automated process steps introduced precise and repeatable methods of manufacturing these parts, which results in high quality, precise in geometry as well as further optimizable parts.

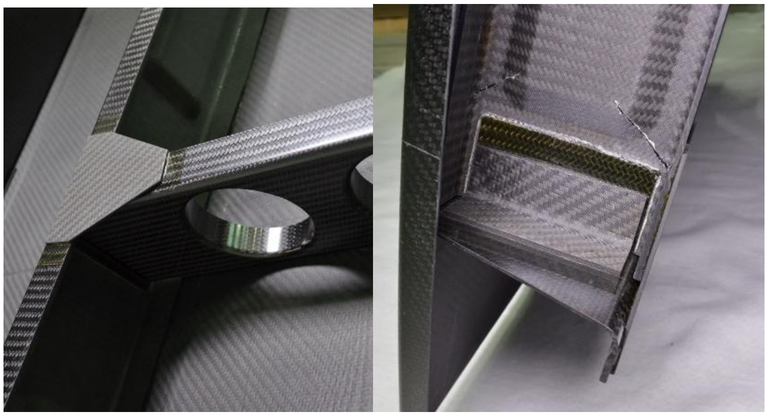

Figure 13. Joined gusset plate (left) and joined clip (right)

With help of the automated patch preforming onto the developed diaphragm preforming station, highly accurate preforms could be established. Combined with the optimized design of the auxiliary materials and infusion strategy the cured and trimmed parts showed high accuracy in geometry and enabled the further joining of the components due to the hybridization layers in the respective joining fixture. Figure 13 shows a joined gusset plate and clip and highlights that the introduction of the hybridization layers as well as the AIDJ joining method compensates manufacturing deviations to form rigid and resilient connections.

The introduction of the shepard database as well as the storage of in-line QA and process data as well as down streamed QA enables the generation of a digital part file for fully description of the structure and individual parts. This helps with future problems like repairs or maintenance.

The acquired fiber angles during the preforming steps showed that the highest deviation of fiber angles was 3.72° and is therefore lower than the set limit of ± 5°. This deviation is still high but is primarily due to the used materials, since the bindered weaves are generally worse aligned then uni-directional or unbindered materials.

With the achieved results in the project NEUTRON an innovative and highly automated process chain for helicopter parts manufacturing was established. The flexibility of the automated processes enables easier integration in existing manufacturing processes in the industry since investments and risks often outweigh the benefits of automation especially for small batch sizes like in helicopter part manufacturing. This shows that automation is a viable solution for helicopter structural part manufacturing that is adaptable to new difficulties like changes in propulsion and used materials.

5. References

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