Final Report

Short name of project	LEEToRB
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1. Introduction

Commonly used resin transfer molding (RTM) tools made from steel show a poor performance in terms of environmental and economic aspects within the context of rotor blade manufacturing. This is mainly due to their high weight and therefore bad manageability, the intensive energy consumption for heating during the process, a high ratio of scrap when cut from solid material and high-energy expenditure for the production of raw material in the first place. Furthermore, the weight of the molds result in undesired deflections that have to be eliminated by additional material usage for stiffening the tools. On the contrary, the use of composites in tool manufacturing is known to be a solution for the above stated problems but is not yet capable of satisfying the strict requirements for RTM processing within aerospace. The project LEEToRB comprises the development of "**L**ightweight, **E**nergy-**E**fficient **T**ooling for the Manufacturing **o**f **R**otor **B**lades" within the Framework of the Green Rotorcraft (GRC) programme of the EU research project Clean Sky. Carbon fiber reinforced polymer (CFRP) molds are utilized in combination with a novel heating system introduced by the consortium partner Qpoint Composites GmbH to provide the cabability of manufacuring of CFRP parts with complex geometries including highly varying cross-sections in an energy-efficient way. To do so, four major topics are adressed within the project: The manufacturing of the CFRP RTM prototype tools is carried out by Qpoint Composites GmbH. Development of process technology as well as curing simulation is accomplished by the Technische Universität München. Finally a life cycle assessment is made by the Fraunhofer Institute. The target application of the work conducted is provided by Airbus Helicopters.

2. Process technology and tool manufacturing

2.1. Overview

Within LEEToRB a new tooling technology of a closed mold CFRP tool with integrated heating layers has been developed. Using CFRP as a tooling material gives several advantages over metallic tooling: equal thermal expansion in comparison to the part, lighter weight and quicker heat up due to the shell structure and lower costs compared to invar tooling. The integrated heating layers designed according to the locally required heat input allow homogeneous temperature distribution in the laminate independent from lay-up changes. Chapter 2 covers the topics of process technology and tool manufacturing.

The development of the CFRP RTM tools started with basic investigation of tool surfaces and exposed areas such as edges. Sealing concepts were developed and tested in test-tools. A long term test was run with two different surfaces that reproduced the entire loads acting on tools such as thermal loads, local indention and demolding loads. Furthermore a test has been developed that determines the strength of different composite edge concepts. An edge is locally loaded until failure, determining the load and displacement. Different edge concepts, e.g. short fibers applied at the edge or an elastomeric edge, have been compared.

Based on these results a simplified demonstrator rotor blade and an according CFRP RTM tool has been designed. The tool was developed utilizing a stand-alone concept and has the dimensions of 1000mm by 800m. Eight simplified demonstrators have been manufactured with two different fiber layups. One layup representing a simplified layup, designed to reduce the manufacturing effort by displaying the critical rotor blade features at the same time. And another one given by the industrial partner representing the original layup in more detail.

The goal of the final work package was the transfer of the results from the simplified trials to the full scale geometry. A full scale CFRP RTM tool with integrated heating was designed according to requirements that were adapted to the new tool material. The final full scale tool consist of two CFRP molds attached to steel frames which are used to connect it to the rotor blade press. Two trials were conducted with the second one being successful. Thus, the main goal, the successful infiltration of a full scale rotor blade with a new tooling technology, was achieved.

Chapter 2 is closed by the lessons learned from the full-scale infiltration trials and a quality control of the successfully infiltrated part.

2.2. Systematic design of tool features and evaluation of tool robustness

Within this chapter the systematic development of the sealing system, a test that determines the strength of different composite edge concepts and a long-term test, is described.

2.2.1. Sealing concepts for CFRP tools for RTM

The goal of WP 2.1 was the development of a sealing system suitable for FRP tooling. In a preliminary test, the functionality of a conventional O-ring sealing has been proven (see Figure 1). However a function analysis points out the malfunctions of a conventional sealing system in FRP tooling. The effects would be tool damage at sharp edges in sealing grooves, sealing damage due to resin in the sealing groove and increase of the clamping force due to sealing compaction. Based on those requirements three sealing concepts have been developed and theoretically evaluated. The best-rated system is a D-section mold seal that is supposed to be highly flexible and fills out the whole sealing groove. First trials with the simplified demonstrator tools with a medium D-section seal show the following results: vacuum and fluid pressure proof within the process boundaries, no resin film in the sealing groove and increase of the tool closing forces. In further tests the application of a softer D-section seal reduced the compaction forces by offering the same performance. Figure 2 shows a sketch of the D-section sealing and the application in the simplified rotor blade tool.

Figure 1: Sealing concept with conventional silicone cords.

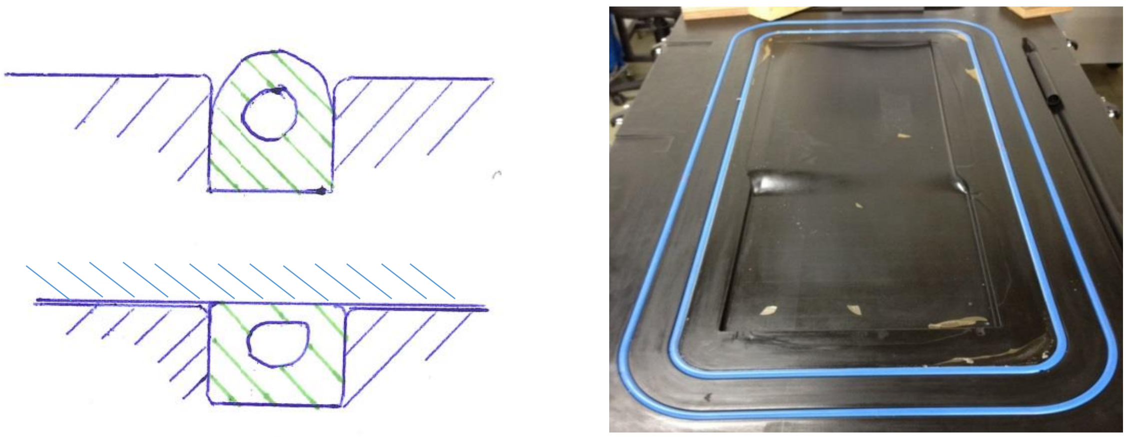


Figure 2: Sealing concept S1 with D-Section mold-sealing.

With the tested D-section sealing system the basic requirement for a sealing system - limiting the mass flow between two separate systems within the process boundaries - is fulfilled. Furthermore the shape of the sealing groove is designed in a more robust way accounting for the reduced edge strength of FRPs. Due to the higher flexibility of the D-section seal it fills the groove better leading to a lower amount of resin inside the groove, which results in less cleaning effort and higher durability of the seal.

A fragile part of CFRP molds are edges. Usually edges are avoided in composite design. But in mold design edges are sometimes necessary to reproduce the demanded part geometry or to create a continuous surface at the parting plane of for example light RTM tools. A main cause for damaged edges in CFRP tools is fiber pinching. Fiber pinching describes a fiber that is pinched in the parting plane during mold closure. The objective of this work is to investigate the influencing variables determining the failure of composite edges. Based on the results, guidelines for the design of composite edges can be derived.

Therefore, a testing procedure has been developed determining the quasi static strength of composite edges depending on the material layup and design based on the described application related load cases. The test is based on conventional hardness testing such as Vickers [2] and an edge test for brittle materials [3,4]. In the developed test a flat cylindrical indenter penetrates a composite edge until failure of the edge. Relevant measured variables are the indention depth [mm], the force at failure [N] and the overlap of the indenter [mm].

2.2.2. Mechanical performance of critical tool areas

The test developed needs to be relevant for the underlying problem of damaged tooling edges. Any occurring non elastic deformation of the tooling surface leads to an impression in the final part and therefore an undesirable deviation in geometry. Hence, the developed test needs to display a clear first failure of the composite edge.

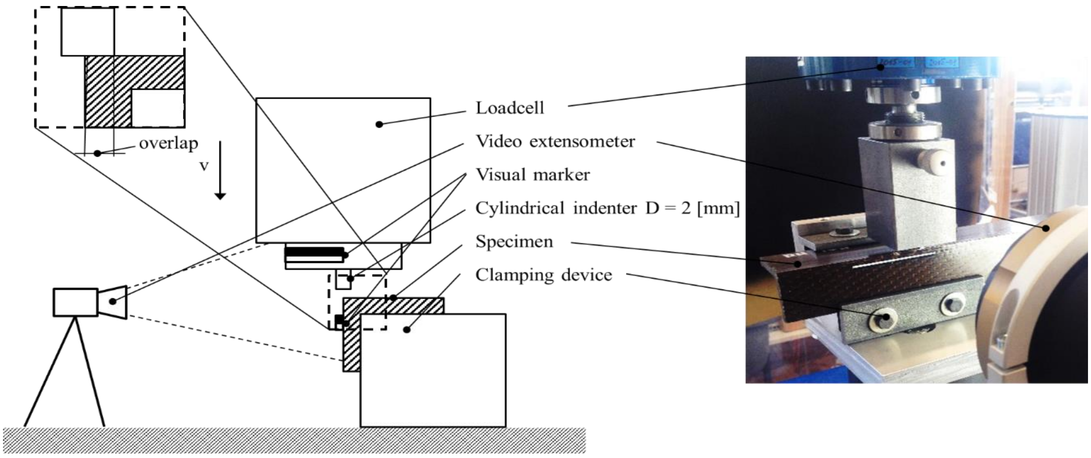
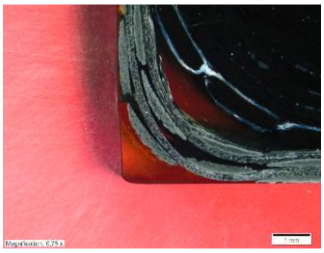


Figure 3: Test setup for quasi-static edge strength testing.

Figure 3 illustrates the setup of the quasi-static edge strength test. The center of the test setup is the cylindrical indenter. The indenter is connected by an adapter to a 10 kN load cell which is further connected to the compression test machine. The specimen is fixed and held in position by an aluminum clamping device that is mounted on the bottom socket of the compression test machine. It is positioned in a way that half of the indenter is in contact with the specimen, resulting in an overlap of 1 mm. The sample is marked about 7 mm below the edge, the indenter 3 mm above its contact plane. Both marks are used as reference points for the video extensometer that determines the distance of both marks optically. With this setup, the penetration depth of the indenter can be measured independently from any deformation of the machine, all adapters or the clamping device, as well as independently from a movement of the sample in the clamping device.

The five different edge concepts, shown in Figure 4 have been manufactured and characterized by the developed test method:

a)



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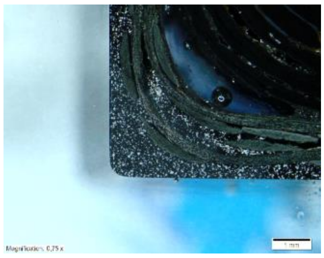

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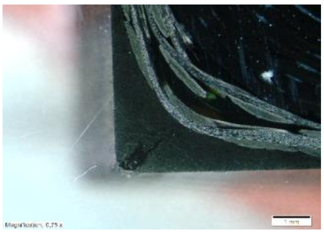

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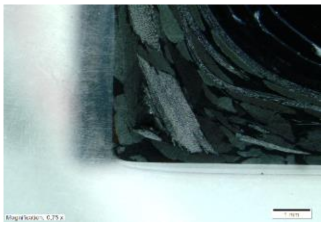

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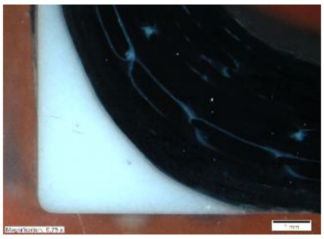

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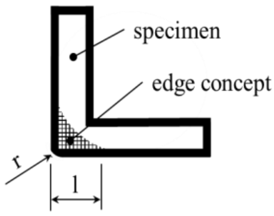

Figure 4: Micrographs of the specimen cross sections, magnification x 0.75: a) RH, b) GC, c) RV, d) SF, e) EE and f) illustrating the measured parameters (r: radius, l: leg length).

An edge filled with an epoxy resin (concept abbreviation PR), a gelcoat used as a surface reinforcement (GC), a fiber roving placed along the edge (RV), short fiber chops of 3 mm length distributed in the edge (SF) and an elastomer infiltrated in a defined area of the edge (EE). The tests show that fiber reinforced edges are stiffer and have a higher area load at first failure than the unreinforced edges. Furthermore the specimens with more homogeneous material in the edge show a smaller deviation of the results. The concept with the gelcoat applied (GC) and the pure resin edge (PR) show similar results.

a) b)

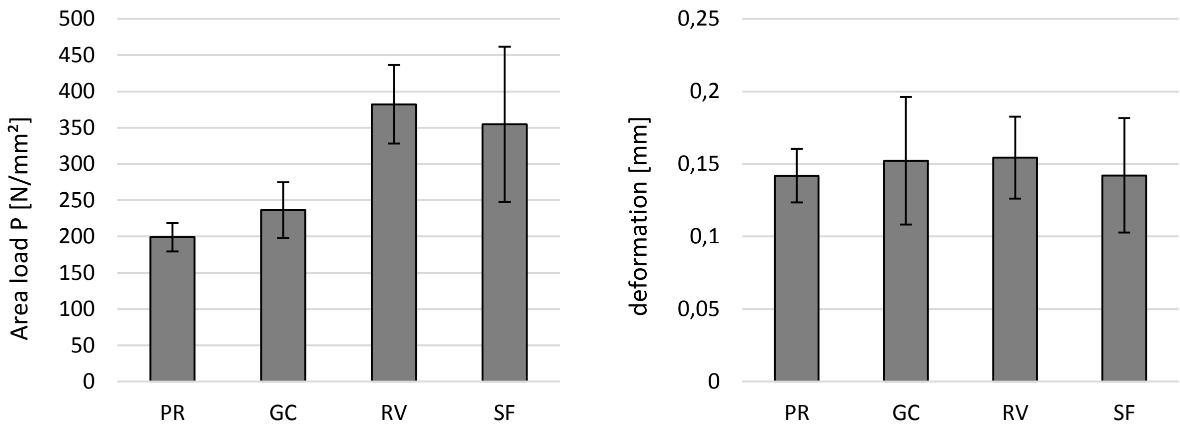

Figure 5: a) mean area load and b) mean deformation at first failure of the edge concepts.

Both edge concepts are based on epoxy. The comparison of gelcoat material in comparison to neat epoxy resin is the inclusion of hard filler materials that improve the abrasion behavior and surface hardness. According to the results, they do not influence the strength of edges significantly. In constrast, a very different elastomer resin system shows a much lower value for stiffness but doesn't fail at all up to a displacement of 1 mm. The choice of an edge concept for a CFRP mold finally depends on the requirements. A stiff fiber reinforced edge results in the best contour accuracy even at high loads on the edge. An elastomeric edge is a promising concept for robust edges with the drawback of contour deviations when loaded during process.

2.2.3. Long term performance of CFRP tooling surfaces

The evolution of tool damages and the vacuum tightness were determined throughout a high number of thermal cycles and a reasonable number of injections with a long term test. Figure 6 shows images of the two surface concepts (gelcoat and carbon paper) and the test rig that was used for infiltrations and cyclic heating.

15 injection cycles and 200 temperature cycles have been carried out with the closed mold. The mold with the Gel-coat surface doesn't show any damages on edges or the tool surface. The carbon paper shows a very rough surface with a number of break-outs at edges and within

the surface. After the last couple of injections, demolding the injected part ripped out small areas at the tool surface. The long term test shows that a gel coat surface withstands the thermal loads of 130°C for 200 cycles and 15 infiltrations without any damages, whereas the carbon paper surface is severely damaged and couldn't be used for any further infiltration without a repair. According to the results, the gelcoat gives a good tool surface that withstands a relevant number of thermal cycles and injections. Further tests that represent a relevant number of curing and demolding loads have to proof whether the gel coat is a sufficient tooling surface for infiltration numbers of up to 1000.

Figure 6: CFRP-tools for long-term surface tests with different surfaces: a) Gelcoat, b) C-Paper and the test rig the mold were implemented.

2.3. Simplified demonstrators: Design, tool and RTM trials

Within WP 3 the general functionality of a CFRP-RTM-tool with an integrated heating for the manufacturing of high-performance composite parts has been proven. The results generated show that there are still some challenges to face and that there are requirements that could not be tested yet.

The basic functions of RTM-tools are media integrity and the functionality of the heating. Vacuum tests demonstrated the unloaded media tightness, but the pressure tests showed resin leakage above 1.8 bars. A test run with 20 applied thermocouples in the empty closed mold showed a maximum temperature deviation of +4.9°C /-3.8°C at 130°C which meets the temperature tolerances.

In a following step, six parts have been manufactured. The first injection showed large flow marks over the whole part. The following five optimization runs were used to improve the surface quality.

Figure 7 a) shows the tool with an integrated preform. The preform consists of the carbon layers, the UD glass layers and the foam core. Adhesiveness was provided by a binder material,. A modified preform with a different fiber layout given by the industrial partner is shown in Figure 7 b). The additional wooden dummy simulates weight that is typically applied at the leading edge of a rotor blade.

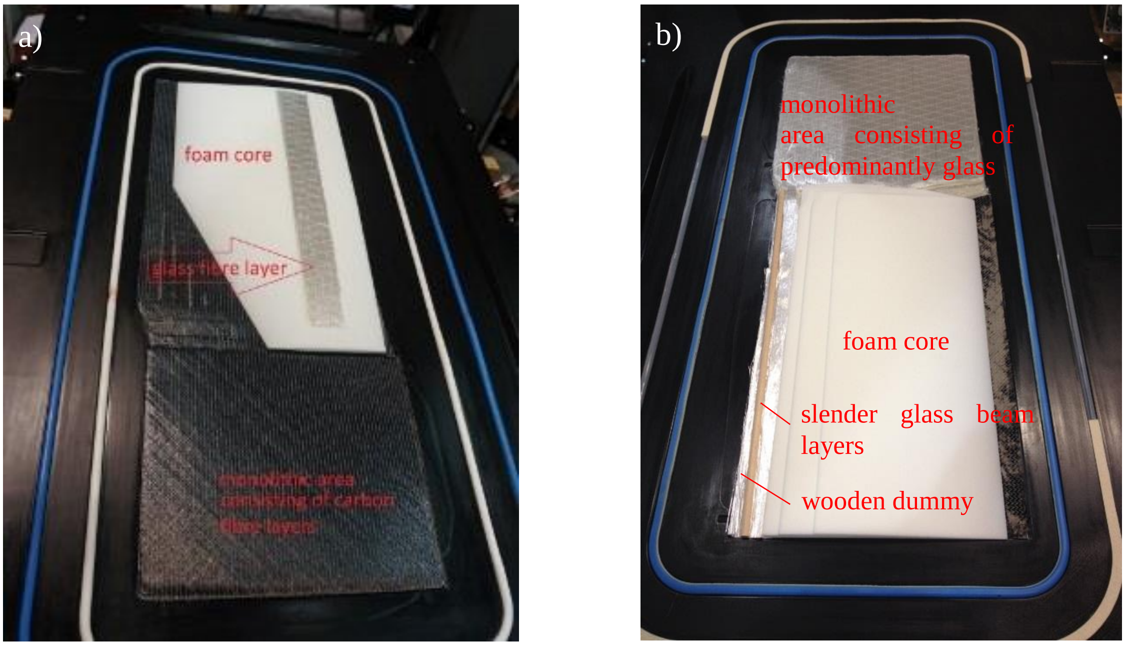

Figure 7: Preform integrated in the tool.

The prototypes manufactured were evaluated by visual inspection of the whole part and its cross sections (see Figure 8) and by a thickness measurement of the part. Furthermore, an optical analysis of the laminate quality was conducted. The part thickness measurements of the quality control show that the geometrical tolerances were just met by trial 4. Trial 2 and 5 were conducted without pressurization and are 0.2 to 0.6 mm below the required thickness. On the other hand trial 1, 3 and 5, which have been cured with pressurization, are 0.1 to 0.6 mm thicker than required.

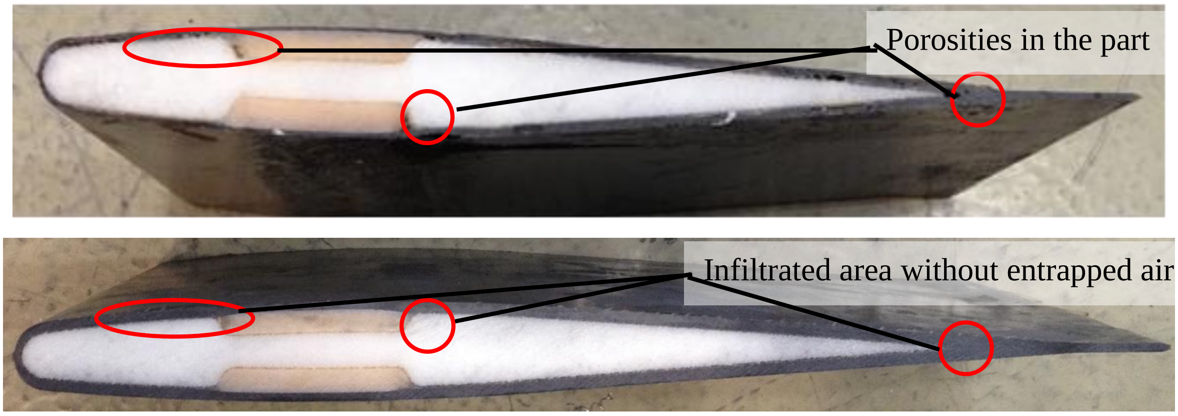

Figure 8: Comparison of cross sections of part 2 and part 3.

The results of the visual quality control of the laminate by microscopy are shown in Figure 9. In trial 1 and 3, the manufacturing process showed no incidents, high laminate quality was achieved. In contrast, the high void content of trial 5 indicates that the process was deficient.

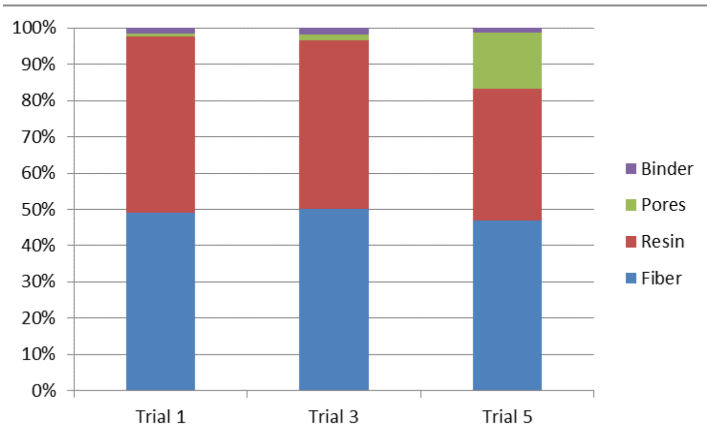

Figure 9: Analysis of the part quality by image processing.

2.4. Full scale CFRP tool for RTM processes

2.4.1. Full scale CFRP RTM tool

The developed CFRP RTM tool consists of two CFRP molds with integrated heating elements. Each mold surface is divided into 10 areas of separate heating elements. This offers the possibility of locally adaptable heat input according to the composite layup.

Figure 10 shows the bottom mold already placed on the rotor blade press. The CFRP molds are mounted on steel frames that build the connection between the mold and the rotor blade press. Two centering cones ensure the positioning of the mold towards each other.

Figure 10: Manufactured set of CFRP RTM tools with integrated heating.

Figure 11 shows both sides of the closed mold. On the one side the in- and outlets of the molds are positioned. All in- and outlets are entering the cavity through the upper mold. Copper tubes connect the in- and outlets to the connection devices at the steel frame. Teflon tubes connecting the injection device and the resin trap to the RTM mold can be passed through the connection devices until the mold surface. This way, the copper tubes stay clean during the injection and no drilling of the in- and outlets is necessary. On the other side of the tool (right picture) the connectors of the heating elements are placed.

The process steps preforming and lay-up were conducted according to the manufacturing guidelines of the conventional process.

The parameters of the injection process were set similar to the infiltration in the conventional metallic RTM tool. The tool was heated up to 80 °C and the temperature was held for 1.5 h. The resin was heated up to 40°C. Subsequently inlets were opened at t = 0, 6 and 8 minutes. The first resin at the outlet was observed t = 17 min after the infiltration started. All outlets were closed at t = 30 min. After the infiltration a pressure of 1 bar was applied in steps of 100 mbar.

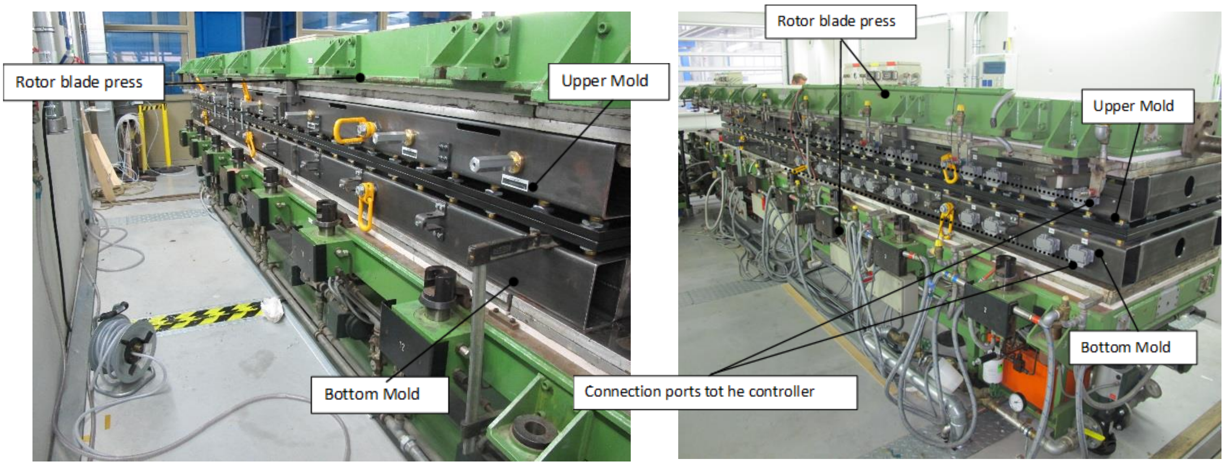

Figure 11: Tools integrated in the rotor blade press.

2.4.2. Full scale RTM trials

The first part was cured at one bar resin gauge pressure. Within the second trial, the resin started leaking at 800 mbar. Therefore, the resin gauge pressure was reduced to 300 mbar for curing. The curing cycle was applied according to the conventional infiltration parameters: heat up at 1.5 K/min to 125 °C, curing at 125°C for 90 min, cooling down below 60 °C tool temperature in 60 min. Figure 12 shows the bottom mold with the already integrated preform.

The right photo of Figure 13 shows the electrical controllers required for the integrated heating attached to the tool. The left photo shows the inlets connected to the injection device. The inlet tubes are reaching into the tool right to the mold surface. Thereby after curing the tubes and the cured resin within the tubes are removed without drilling or cleaning the in- or outlets.

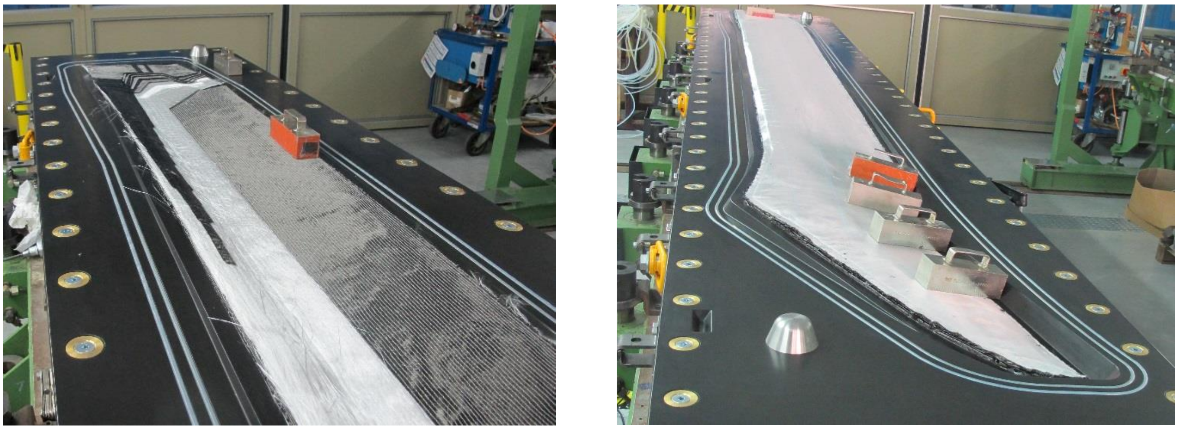

Figure 12: Layup of the full scale rotor blade.

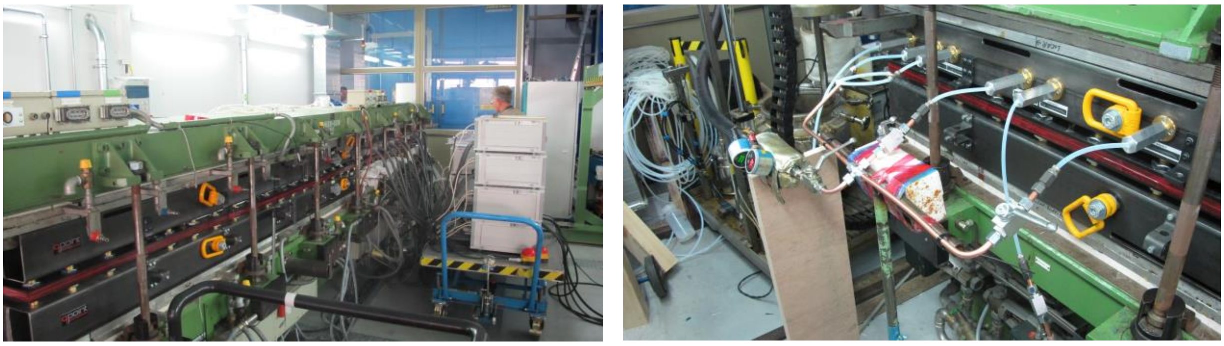

Figure 13 Closed mold with the controllers (left), resin inlet ports connected to the inject. device (right).

2.4.3. Rotor blade quality

The second manufactured rotor blade was fully infiltrated and didn't show any flow marks. On the surface of the rotor blade no dry spots or entrapped air could be determined. Figure 14 a) shows that there was still a gap between the two molds resulting in a resin film of 0.5 to 1.5 mm around the whole blade.

In an additional process step the rotor blade got trimmed to its final geometry and the erosion coat was applied.

An optical measurement of the rotor blade verifies that the mold was subject to deformation or was not closed completely during processing. The manufactured rotor blade is 0.93 mm thicker (mean value, with a standard deviation of 0.21 mm) as designed.

a)

b)

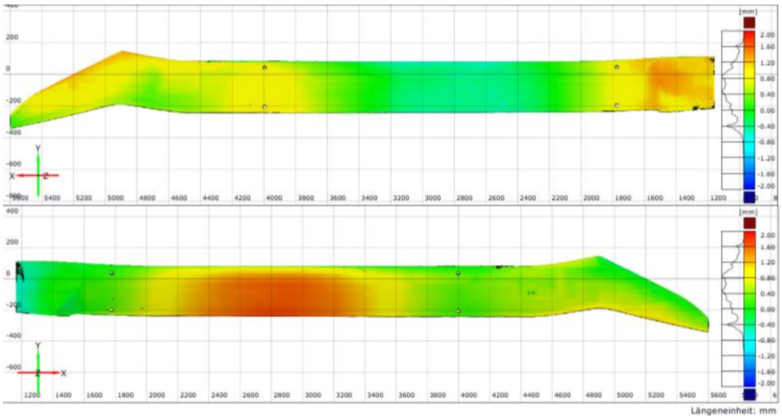

Figure 14: Manufactured rotor blade with resin film around the blade (a), results from optical measurement.

2.5. Lessons learned

In the following points the main findings of the full scale trials and the lessons learned from it are described.

2.5.1. Preforming

Closed CFRP molds have limits regarding tool design compared to solid metallic tools. For example, steady shearing edges can hardly be realized in tools made from CFRP. The full scale trials showed that having a tool without a shearing edges requires more effort in the preforming process. A more accurate preform that is pre-compacted to the final geometry would prevent fibers from getting pinched in-between the molds. Furthermore, the advanced preform would result in less compaction forces acting on the mold and deforming it.

- Suggestions for enhancing the preforming process are: Preforming of the skin layers
- Preforming of the whole rotor blade in 3-D
- Infiltration with erosion coat
  - Using the erosion coat as a infiltration and mold closing help

Lesson 1: An advanced preforming concept is key for the RTM process with CFRP tools

2.5.2. Layup and closure of the mold

Closing the mold was an issue during the full scale trials. Fibers getting pushed into the parting plane, resulting from the compaction of the preform and the compaction forces itself lead to a gap between the two molds. The resulting gaps were up to 2 mm.

The shearing edge concept worked well in the metallic reference tool. Instead of changing the preform, a different mold geometry could lead to an improvement of the closing procedure. Suggestions for shearing edges within CFRP closed molds are: replaceable metallic (e.g. invar) thermoplastic shearing edge. Besides shearing edges, additional feeders or chocks within the mold could be realized. Those parts are supposed to prevent fiber pinching in critical areas.

A central issue of the full scale CFRP mold is its stiffness. The bedding of the CFRP mold on the steel frame is far away from the sealing grooves. Furthermore the stiffening cross ribs are not fixed to the steel frame, which reduces their stiffening effect. The load introduction and the arrangement of the stiffening ribs results in a bending of the mold in transverse direction.

A effect from the gap between the two molds was the high vacuum leakage. The sealing was not compressed around the mold and locally didn't touch the upper mold. A different/softer sealing system e.g. the D-section sealing as used in the simplified demonstrator tool would reduce closing forces and allow a small gap in between the molds, since it sticks out of the groove for 4 mm. A D-section mold is an appropriate choice for "soft" CFRP RTM tools.

Lesson 2: Fiber pinching is an issue with a CFRP closed mold. Advanced preforming or a different tool geometry would help to avoid fiber pinching. The edge test developed within this project can give a trend for future edges in future composite tools.

Lesson 3: The stiffening structure and the load introduction need to be improved to increase the stiffness of the mold to compensate higher resin pressures.

2.5.3. Infiltration and curing

The final result of the second infiltration showed that the resin inlet positions that were copied from the conventional metallic tool as well as the outlet and new compression area worked well. To make the process more robust additional elastomeric flow stoppers could be applied in designated pockets.

A temperature measuring prior to the infiltration showed a homogeneous heat distribution along the whole tool. The final infiltration result showed that the positions of the heat elements as well as the heat input was sufficient. The measured energy consumption of the CFRP RTM tool was 85 % less than the energy consumption of aluminum tools in series rotor blade production.

An additional cooling system applied on the backside of the tools could accelerate the cooling down process and therefore reduce process times even more.

Lesson 4: The integrated electrical heating worked very robust and the heat distribution was according to the aerospace standards. A saving of energy of 85% compared to conventional tooling was reached.

2.5.4. Dimensional accuracy and tool surface

Manufacturing problems of the steel supporting frame lead to a very thin wall thickness of the frame. Within the first trials the steel frame was deformed by the closing forces that were needed for a resin pressure of 1.5 bars. As already mentioned in **Lesson 3** the tool needs to be designed in a stiffer way. The arrangement of the ribs and the connection between steel frame and mold need to be redesigned.

The tool surface roughness was in accordance to aerospace standards. The part was demolded without additional effort and the surface was easy to clean after processing. After the second infiltration defects at the tool surface could be detected. Tooling gel break-outs were located at the edges and at the resin inlets.

Lesson 5: The mold steel frame connection as well as the rib arrangement need to be redesigned to increase the dimensional accuracy.

Lesson 6: Further investigation on tooling edges need to be conducted to identify edge more robust edge designs with the capability to withstand the high loads such as e.g. the loads resulting from fiber pinching.

2.5.5. Future application of CFRP tooling at AHD

Small surface damage after the performed trials as well as tool deformation during processing due to insufficient stiffness are the critical results for this new RTM tooling technology. For future series application, this technology needs further development in these areas.

The high quality of the tool, the robust integrated heating delivering a homogeneous temperature distribution, the good infiltration result and the unique characteristic of a thermal expansion similar to the product makes this tooling technology relevant for other application as: Small series production, RTM prototype manufacturing and standalone preforming tool.

3. Simulation

3.1. Overview

The overall goal of process simulation is to gain an understanding for the processes and phenomena occurring inside the tool and part during the manufacturing process. Within LEEToRB, this understanding supports the part manufacture with feedback on setup variants in terms of temperature and material property distribution like glass transition temperature and degree of cure as well as the potential exothermic temperature overshoots. A novel location dependent heating system for the tool had to be included in conventional cure simulation, thus extending the commercially available cure simulation capability. The cure simulation package COMPRO[1] from Convergent was chosen, which can be included via a user subroutine bundle in the ABAQUS[2] environment. Four major topics were addressed within the simulation work packages of LEEToRB:

First, a material characterization was conducted to gather experimental data. Material models from literature were fitted towards this data by means of least square regression analysis. Validation of the assembled material card was made by cure of a 30 mm laminate coupon, manufactured with a vacuum bag on a self-heated carbon fiber reinforced composites (CFRP) plate provided by Qpoint Composites GmbH. Comparison of the temperature history of experiment and simulation showed a close agreement, thus confirming the material card applicability. Second, a simulation strategy was set up to incorporate the self-heated CFRP tooling within a cure simulation environment. The calculation of the arising tool temperature field with close to thermocouple accuracy was numerically verified and experimentally validated. Third, a cure simulation model of a 1 m generic rotor blade demonstrator was set up. It included the self-heated CFRP tooling and cure simulations were conducted to investigate the temperature and cure development within the tool. In-depth investigation of the results showed not only the potential risks regarding temperature overshoots, but also gave educated guesses on the origin of process technology issues such as apparent surface resin films. An improved cure cycle was set up and a part produced with this cycle showed significantly improved part surface quality. Fourth, an investigation regarding the influence of metallic inserts in the thermal and cure behavior was conducted. The study highlights the need of distinct heat patches and accurate heat patch placement, if high thermal masses such as metallic inserts are included in the part. With assistance of this study every apparent influencing feature on the thermal and cure behavior of the full-scale rotor blade was investigated, and simulation research was concluded.

[1] Convergent Manufacturing Technologies, Vancouver, B.C., Canada
[2] Dassault Systèmes, Vélizy-Villacoublay, France

3.2. Material characterization

Two different CFRP material systems and their material properties were required for the investigation: Only the thermal material properties in fully cured state as a function of temperature are relevant for the tool material. In contrast, the material properties for the part are required as a function of degree of polymerization and temperature. Hence, characterization of the thermochemical properties were necessary. Additionally, the evolution of the polymerization of the part's resin at different temperature were measured, shown in Figure 15.

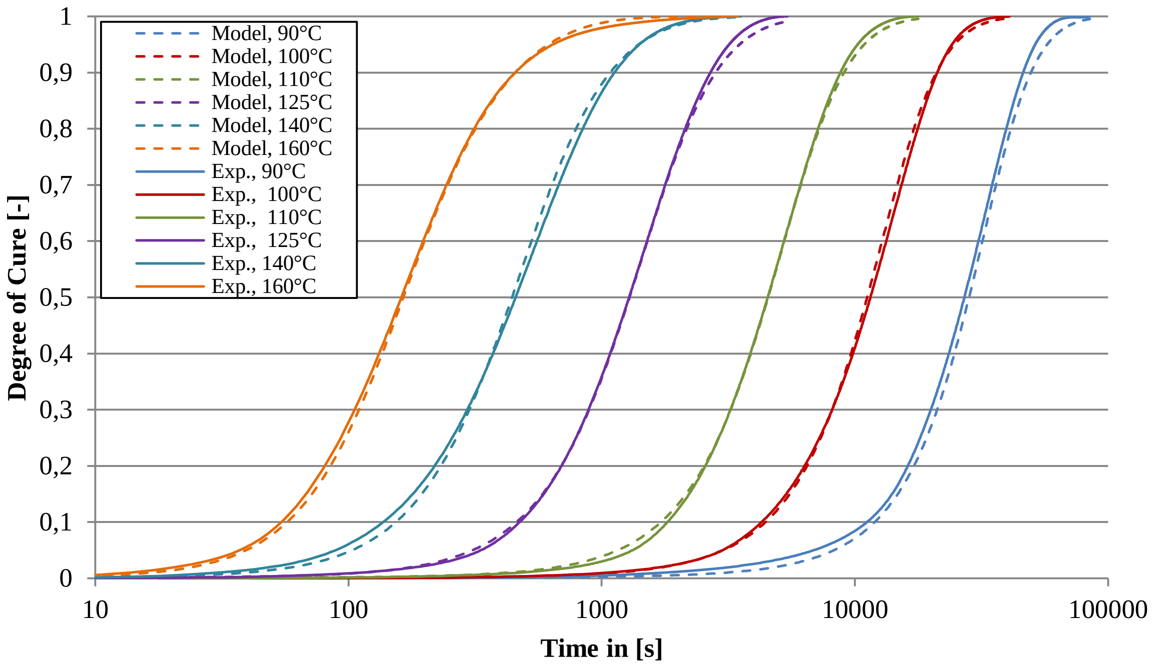

Figure 15: Evolution of the degree of cure at different temperatures[3].

The target application, a rotor blade demonstrator, incorporated a thick monolithic section of ~30 mm. Given that the chemical reaction of the curing resin is exothermic and the material has low thermal conductivity in thickness direction, it leads to a potential temperature overshoot and risk of material degradation, if fast cure rates are reached. Process simulation provides an understanding of the internal processes and, thus, provides a tool to predict and prevent those effects. On the other hand, higher cure temperatures lead to faster chemical reaction and, thus, to shorter cycle times favored by the industry. To identify the optimum, a controlled chemical reaction in a short cycle time, many simulations at different set point cure temperatures had to be conducted. Hence, simulation had to be capable of accurately predict

[3] Weiland, Hartmann, Hinterhölzl, Characterization and numerical investigation of an RTM cure process with CFRP molds and independent heat patches, Proceedings of the 20th ICCM, 2015

material behavior in a wide range of temperatures. The used material models had to be fitted to experimental data of a wide range of potential cure temperatures as well, as shown in Figure 15.

Overall, the following properties were determined experimentally by means of Differential Scanning Calorimetry (DSC), Nanoflash™ and Rheometer:

- Cure kinetics of the part's resin
- Thermal conductivity of the part's resin
- Specific heat of the part's resin
- Thermal conductivity of the tool laminate in thickness direction

The remaining properties of the tool resin as well as part and tool fibers were gathered from literature. Micromechanical models were utilized to determine the laminate behavior.

In a second step, the material models were validated with experimental data of the cure of a 30 mm laminate coupon shown in Figure 16.

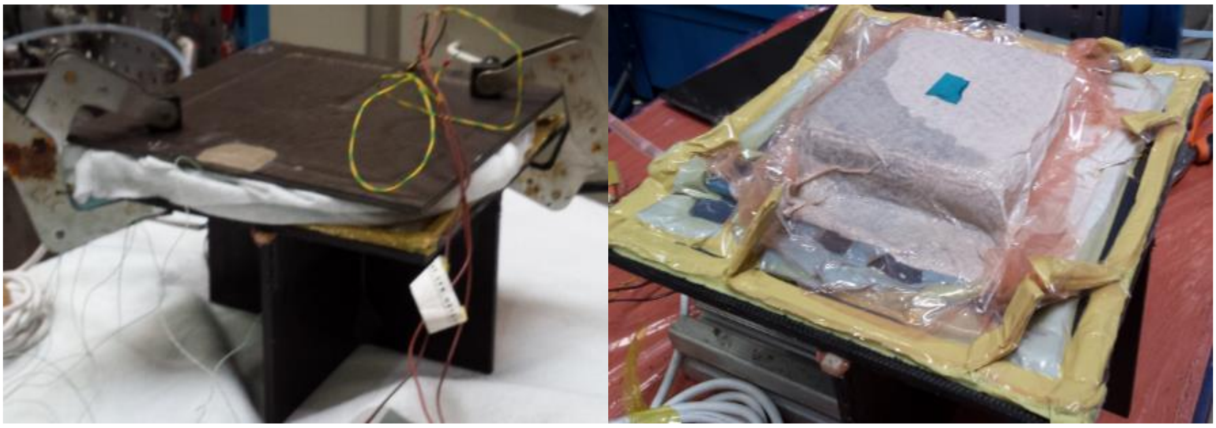

Figure 16: Experimental setup to validate the material models.

For the validation experiment, a simple manufacturing process with a vacuum bag was chosen. Energy was introduced by means of two carbon fiber reinforced composite (CFRP) plates with one included heating patch each. The plates were located at the top and bottom of the laminate (see Figure 16). Eighteen Thermocouples were positioned at the bottom, middle plane, and top of the laminate. The locations within those planes were either in the middle or with a 10 mm distance to an edge. The exact positioning is shown in Figure 17.

Although this experiment is easy to set up, it implies many variables, which are difficult to determine for the simulation: unascertained resin rich areas at the inlet and the outlet differ in the thermal behavior then the main laminate, the plates were subjected to natural convection and the foils have thermal insulating behavior.

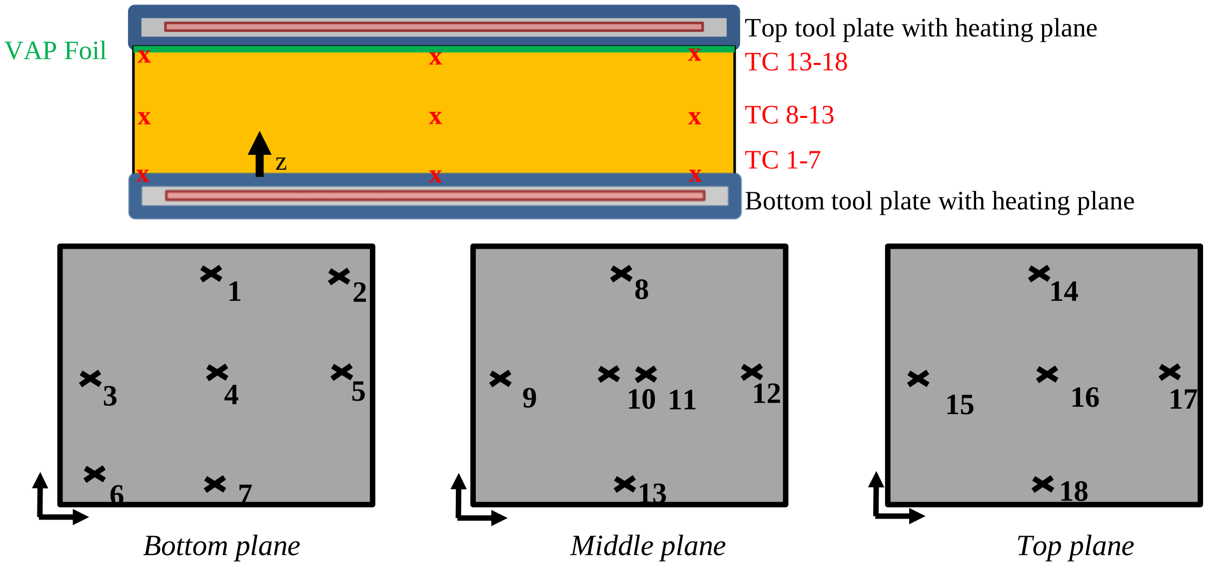

Figure 17: Positioning of the Thermocouples in the coupon test.

For a solid validation, it is important to ensure the comparability of the simulation and experimental results with a sole dependency on the modeled material properties. To satisfy this condition the measured laminate surface temperatures over time were interpolated and used a temperature boundary condition input for the validation simulation within ABAQUS.

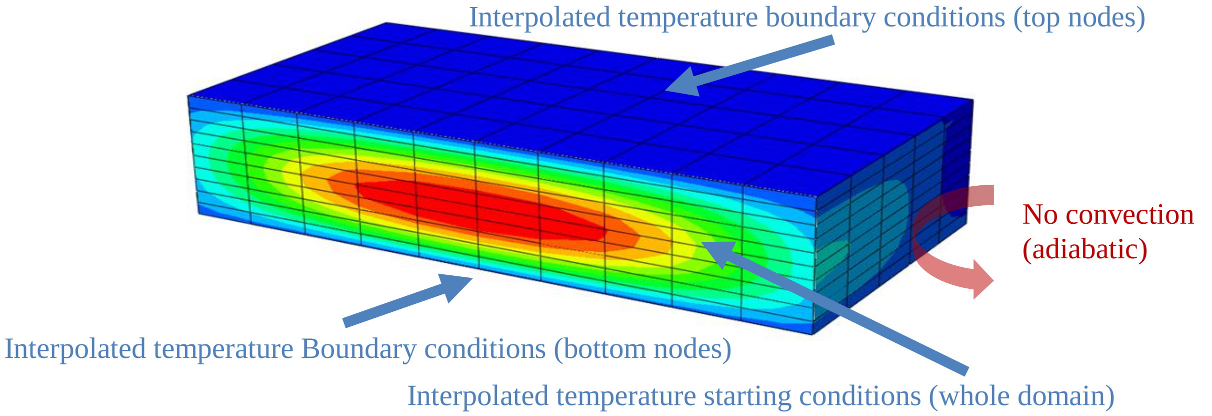

Figure 18: ABAQUS model of the coupon.

A similar procedure has been set up to interpolate and apply the starting temperature field. Although the sides were isolated in the experiments, several simulation runs were made with different convection coefficients at the sides. Small convection coefficients have negligible influence on the temperature development. Hence, adiabatic boundary conditions were applied in the validation simulation. The discretization was performed in such way that the real thermocouple coordinates coincide with a node. Figure 18 shows the model with the boundary conditions described.

A comparison of experiment and simulation temperatures of the internal thermocouples measurements within the laminate (see TC 8-13 in see Figure 17) validated the characterized material properties. Utilizing the developed method, all environmental or process influences could be negated within the validation. Hence, the material models of the curing laminate only were validated and the assessment of material model accuracy showed a close agreement between the Abaqus/Compro calculation and measurements, as shown in this Figure 19.

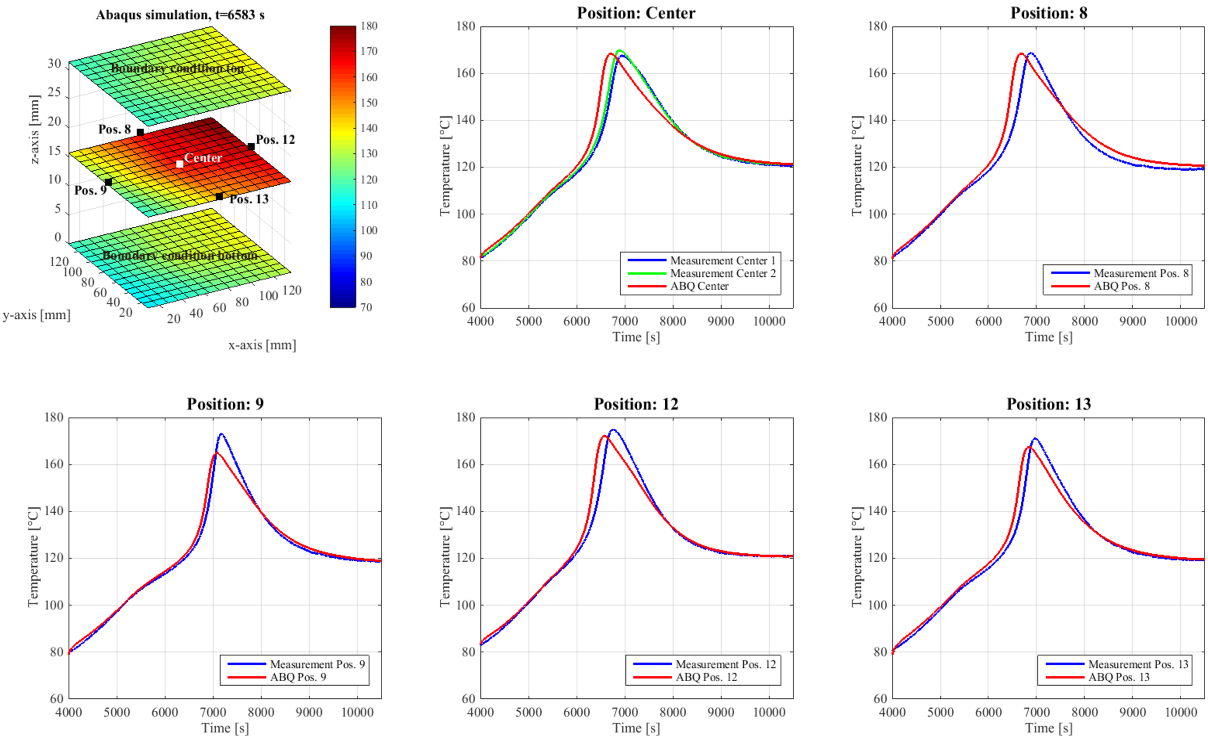

Figure 19: Material model validation[4].

3.3. Implementation of the heat patches within a cure simulation

To successfully implement a simulation concept that represents a location dependent heating system a series of studies have been conducted. The process requirements for the novel heating system provided by the project partner Qpoint Composites GmbH were the following:

- Maximum Power per Area: ~3kW/m²
- Temperature controlled electrical power input
- Maximum number of heating patches with constant power per tooling half:
  8 (Later within the project the increasing experience diminished this requisite)
- Smallest producible size of a heating patch: 50mm x 50mm

[4] Weiland, Hartmann, Hinterhölzl, Characterization and numerical investigation of an RTM cure process with CFRP molds and independent heat patches, Proceedings of the 20th ICCM, 2015

- Each heating patch has its own electric circuit

The last point implies the ability of controlling every heating patch separately in time. The heating patch allocation and sizing have to be defined in the manufacturing process. As the heat patches are incorporated within the tool laminate, they cannot be changed afterwards.

According to the physical behavior of the novel heating device, an energy control method was developed for cure simulations with the Abaqus/Compro[5] platform. Figure 20 shows a sketch of the thermal tool behavior.

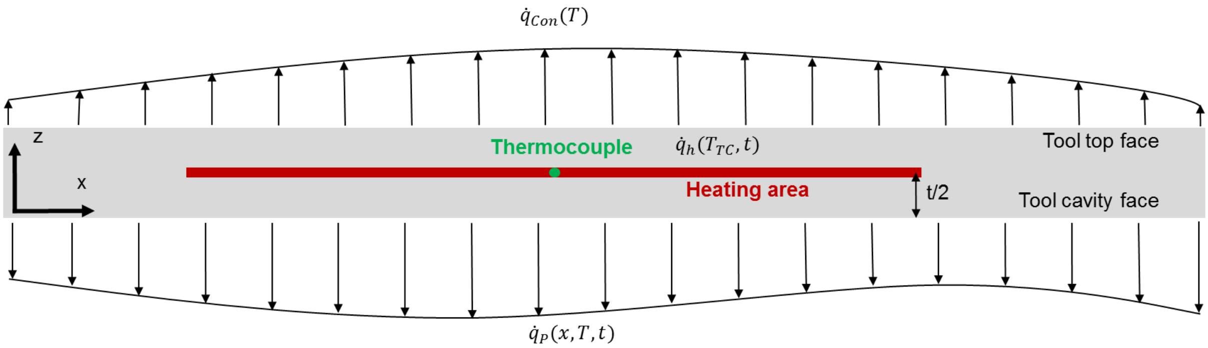

Figure 20: Sketch of the thermal tool behavior[6].

Whereas as to tool cavity face is subjected to a heat flow into the part during the heat up, the tool top face is subjected to natural convection only. The novel heating device developed by Qpoint Composites GmbH ensures a constant heat introduction in the heating area, located in the middle plane of the tool laminate. The amount of heat introduced is controlled in time with an external control system. A thermocouple is laminated within the heating area of the tool laminate and an external control device ensures set point temperatures at this specific location. According to the heat flow into the part and environment, tool temperatures can differ within one patch. A simulation strategy was developed within the project to calculate the tool temperature field with high accuracy within a cure simulation environment.

[5] All cure simulations within this presentation were conducted utilizing COMPRO/CCA from Convergent Manufacturing Technologies, Vancouver

[6] Weiland JS, Hartmann MP, Hinterhölzl RM. Cure simulation with resistively in situ heated CFRP molds: Implementation and validation. Composites: Part A 2016;80:171-181.

3.4. Generic rotor blade demonstrator

A finite element analysis (FEA) model of the generic rotor blade demonstrator was set up. The simulation discretization was made with 322821 linear continuum elements.

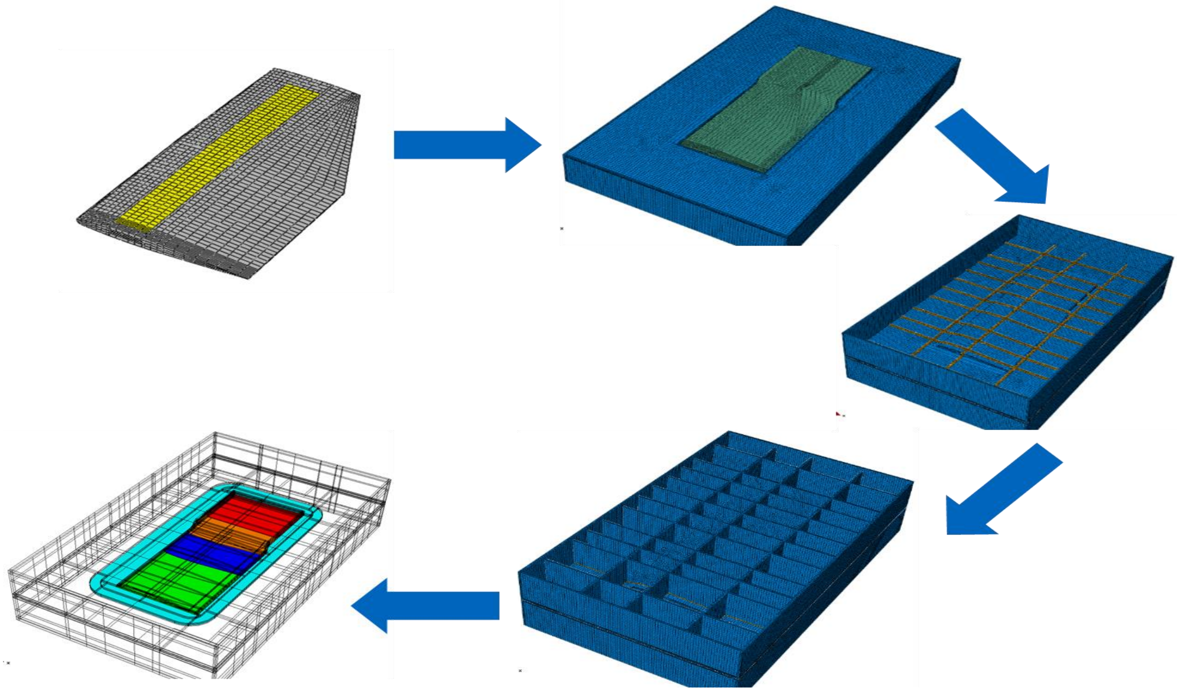

Figure 21: Finite element model development of the demonstrator part.

Figure 21 shows the development of the simulation model: starting from the sandwich core and the GFRP spar the generic blade was modeled. Subsequently, the CFRP tool including the thermal insulated ridges were included. Finally, the heat patch allocation was made in accordance to the developed tool at the institute.

The cure of the scaled rotor blade demonstrator was discovered to be inhomogeneous if the standard cure cycle is utilized. To give an accurate impression of the cure behavior of the part, the cure is shown Figure 22 at different simulation times. With this standard cure cycle, the exothermic temperature peak starts in the corners of the monolithic section as well as the close part of the transition section. The corners are subject to heat introduction from three directions instead of the one direction the center of the monolithic section is subjected to. Thus, their temperature profile including the exothermal peak is well ahead of the center.

The transition section between monolithic and sandwich section still has the same heat introduction as the center due the heat patch distribution, but a reduced thickness, hence a higher effective conductivity resulting in a temperature peak earlier than the center. Whereas the center temperature of the monolithic section is already above target temperature, the sandwich section is not subject to significant temperature overshoot.

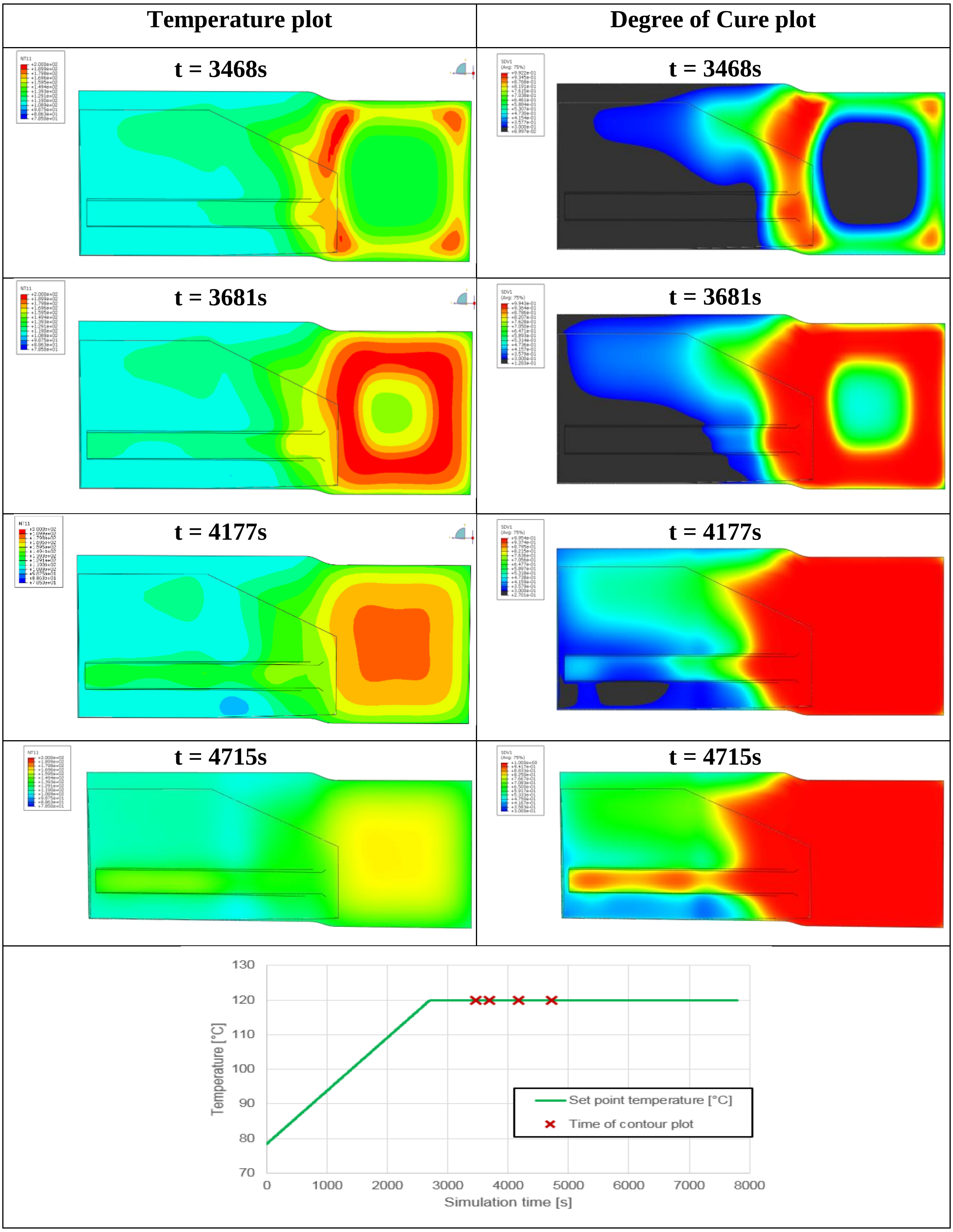

Figure 22: Temperature and degree of cure contour plots with standard cure cycle.

The degree of cure (DOC) is equal to the time integral of the cure rate, which has a high dependency to temperature. Higher temperature lead to a higher cure rates and, thus, to a higher increase in the degree of cure in a certain amount of time. The degree of cure contour plot look therefore similar to the occurrence of temperature peaks. To gain additional information on the state of the resin the colors of the contour plots of the pictures on the right hand side of Figure 22 were picked in such way, that the areas with dark grey coloring shows the areas where the resin is still in fluid state. All the other colors show solid resin in a gelled state. Advancing in time, the peak temperatures locations have evolved from the corners to the whole edges of the monolithic section and finally in the inner monolithic area. The GFRP spar as well as the sandwich section is well behind in the evolution of the degree of cure. Hence, the cure of the part is not only inhomogeneous in through thickness direction, but also inplane. This leads to residual stress build-up and is not favorable. At the end of the simulation time (7800s), the temperature distribution in the part is almost homogeneous again. Those areas, which were subject to significant exothermal peaks, namely the monolithic domain, the transition area and the GFRP beam have final DOC's at this simulation time of close to 1. The dominating final DOC in the remaining sandwich section is 96%-97%.

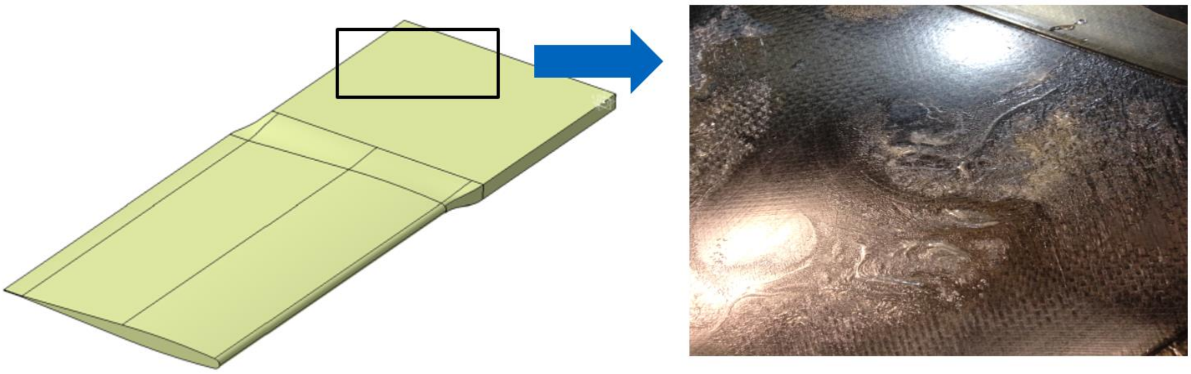

Figure 23: Flow marks on the monolithic section of the scaled rotor blade.

With the knowledge of the evolution of the degree of cure, an interesting conclusion for the process technology was possible: Figure 23 shows a manufacturing problem the LCC encountered during processing of the generic rotor blades. Flow marks were present on all produced parts with the applied cure cycle.

A closer look in the simulation revealed a feasible explanation for the occurring effect. Figure 24 shows the degree of cure state at the simulation time t=3541 s. The outside to inside cure behavior in the monolithic section led to an enclosed fluid resin domain (dark grey area). Whereas shrinkage effects on the side prior to gelation could still be compensated by a resin flow into the shrinking material, this was not possible in the entrapped fluid core. During cure, the shrinking core had the initial fiber and matrix ratio, in contrast to the sides, which had a higher ratio of resin material due to the compensating resin flow from the inlet. This led to different thicknesses at the sides and the center of the monolithic section, with the center possessing the lower value. Post infiltration pressure was subsequently assumed to lead to resin flow onto the center of the monolithic part instead into the part itself. Thus, post infiltration pressure was assumed to lead to the shown flow marks apparent in the middle of the monolithic section.

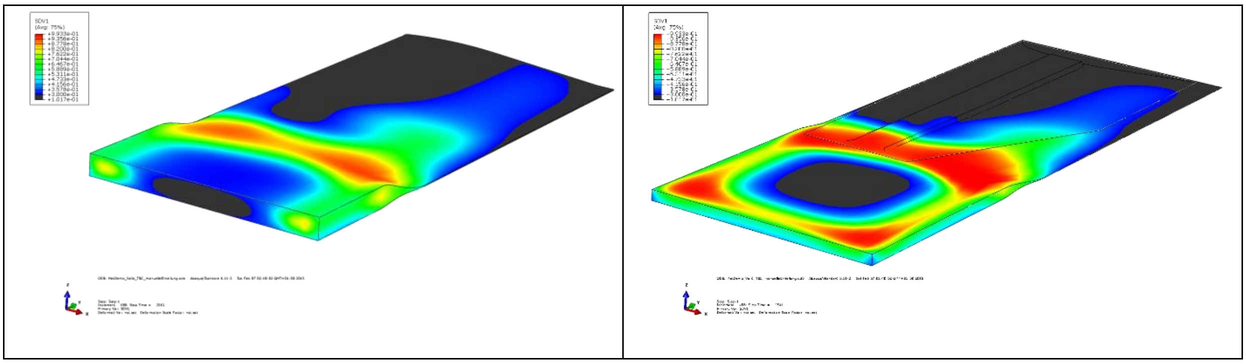

Figure 24: Contour plot of the scaled rotor blade at the simulation time t=3541s, left side: cut through the monolithic section in the xz-plane, right side: cut through the center in the xy-plane.

According to this theory, a solution to the problem was developed consisting of a more homogeneous cure in the monolithic part. This was realized by a new developed two-stage hold cure cycle. Simulation results showed that the new cure cycle led to a peak temperature overshoot reduction of ~75% and almost not additional required process time. The new developed cure cycle was applied in the manufacture of a part. A negligible amount of flow marks was observed in this experiment. Thus, it supported the theory developed by means of simulation.

3.5. Additional features apparent in the full scale tool

The generic rotor blade already incorporated most of the features influencing the thermal and cure behavior of the final full-scale part. Remaining features requiring investigation in the full-scale part where inserts of different materials, specifically steel. These inserts imply large local deviations in the thermal mass and conductivity. Hence, their heat up behavior differs from the surrounding part material. An investigation was conducted to investigate, if these features required their own heating area. The study showed that one heating patch for a steel insert embedded in sandwich material is not enough (see Figure 25). If this is embedded in the sandwich, and the controlling thermocouple lies within the tool laminate on top of atop the insert (thus leading to large amounts of energy introduction to heat up the steel), the sandwich material reaches degradation temperature. In contrast, if the thermocouple is located on top of atop the sandwich material (thus leading to small amounts of energy introduction to heat up foam core), the curing laminate on top of the insert will not reach full cure. Hence, those inserts requires their own heating patch, which is separated to the surrounding heating patch heating up the part sandwich.

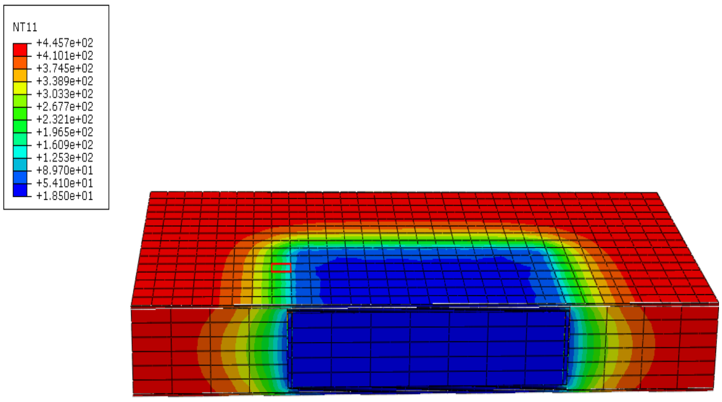

Figure 25: Insert study for the full-scale blade.

With this knowledge, an investigation of all apparent features in the full-scale blade was made and a process understanding of the phenomena inside the part was developed. Heat patch allocation and dimensioning of the full-scale blade could be conducted. Within the final full-scale tool heat patch distribution, separate and independent heat patches were incorporated for

- the monolithic areas,
- the sandwich sections,
- metallic inserts,
- transition sections in between monolithic and sandwich areas.

4. Economic and ecologic evaluation

Besides technological aspects an economic and ecological evaluation should be carried out, in order to quantify benefits of a self-heated CFRP tool towards an existing state of the art metal tool for curing helicopter rotor blades. Besides the evaluation of the tool manufacturing, the use-phase should be considered in these investigations as well. Therefore an energy measurement during the use-phase, an Economic Viability Assessment (EVA) and a Life Cycle Assessment (LCA) was carried out for both tooling technologies.

In the beginning the ecological and economical characterization of the benchmark tool was conducted. Accompanying the construction and designing of the self-heated 1m demonstrator CFRP tool, an EVA was carried out as well as the measurement of the energy consumption during the use-phase. Partially based on these results, the final full size CFRP tool design was deduced.

To achieve the mentioned goals the full size CFRP tool was investigated in the second project period in detail. An Economic Viability Assessment (EVA), and energy measurement as well as a Life Cycle Assessment (LCA) for the full size CFRP tool have been carried out. Although some input data for these calculations could be transferred from the results of the scaled tool demonstrator, still a lot of input data were missing and had to be collected.

The main results of the mentioned investigations are summarized and presented in the following for the three regarded tools – aluminum, 1m CFRP demonstrator, full-size CFRP - in LEEToRB.

4.1. Analysis of the use-phase

The use-phase includes for both tooling technologies the manufacturing of one rotor blade. Depending on the tooling concepts, different manufacturing technologies were analyzed. While the process with the aluminum tool is a prepreg process, the CFRP tool is designed for a preform-injection process. That means, that the curing cycles in the use-phase differ significantly in time and temperature levels, so the two tooling have to be compared as an own and complete different technology.

The analysis of the use-phase concentrates on the energy consumption of the tools. The expected energy saving with a self-heated CFRP tool is one of the main motivations and goals in this project. Therefore the power consumption of all regarded tools are measured during their use-phases. The results are presented in Figure 26 and in Figure 27 the corresponding cycle times are visible. The procedure of the power measurement as well as the definition of the curing cycles are described in deliverable 5.1 or rather 5.3 in detail.

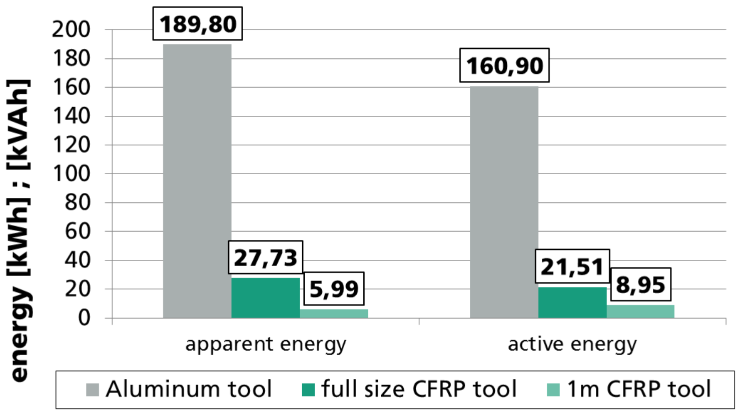

Figure 26: Measured apparent and active energy consumption of all tools for one use-phase cycle in comparison.

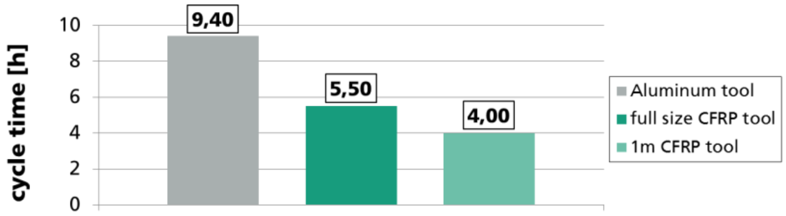

Figure 27: Total curing cycle duration of all tools for one use-phase cycle in comparison.

With the measurement of the energy consumption during the use-phase for one rotor blade it is proved, that a saving of 85% to 87% is expectable with a CFRP tool. Additionally a reduction of the curing cycle duration of 41% is measured.

In summary the energy savings are ascribable on the one hand to the reduction in the cycle times and on the other hand to the increase of the power and energy efficiency of the tool. A distribution in percent is, regarding the mentioned variables, not possible with the measured data. To make such a statement, the CFRP tool has to be measured under the same conditions like the aluminum tool, what means, the prepreg curing cycle has to be applied to the CFRP tool. This investigation was not possible within the project time.

A statement on the scalability of the results from the scaled tool demonstrator to the full size CFRP tool is not possible, because also different curing cycles; or rather resins are used. Thus, the curing cycles differ in time and temperature level, what makes this investigation or rather comparison impossible.

4.2. Economic Viability Assessment (EVA)

The economic evaluation is split into the manufacturing of the tool itself and into the consideration of the use-phase. For both tooling technologies, the same boundary conditions are taken. The production costs derive from the machine hours and the machine hour rates. The depreciation is linear over a period of 10 years with a workload of 70% based on the underlying asset. The imputed interest rate of 6% is used for the minimum scenario and of 12% for the maximum scenario of the machine hour rates. Furthermore the maintenance costs, the tooling costs, the equipment costs, the occupancy costs and the energy costs per machine hour. All these costs depend on the respective machines that are required for the tool manufacturing. The used materials differ for both tools significant as in transport, storage or preparation. Because of that and in order to keep the results directly comparative, without any distortion caused by different overhead costs or profits, they are neglected.

A minimum and a maximum scenario are investigated, because interest, rents, hour rates, and material prices can differ in Germany. Only the material price for CFRP is quite stable and not changed within the scenarios. A more detailed description of the boundary conditions and the development of the scenarios are already presented in deliverable 5.1, 5.2 and 5.3. The results of the EVA for the benchmark and the CFRP full size tool are presented, separated into the three categories “material cost”, “labor costs” and “production costs” in Figure 28.

It is visible that manufacturing of the aluminum tool is about EUR 38 thousand and EUR 17 thousand (according to the scenarios) more expensive. This corresponds to an increase of either 17% in the case of the minimum scenario or 14.5% in the case of the maximum scenario. It is remarkable that the material costs of the benchmark tool are about 4% or rather 45% higher. Although the price per kg is much more expansive for CFRP, the material amount is less than for the aluminum tool.

The decisive difference between the total manufacturing costs of the different tools is caused by the labor costs and the production costs. The total costs of the CFRP tool are mainly driven by the labor costs, whereas the production costs make up the smallest part. In contrast to that the production costs are dominating the total costs of the benchmark tool. The sum of the labor costs and the production costs without any surcharges is in case of manufacturing the CFRP tool 12.2% or 18.7% lower and represents 54.3% or 64.1% of the total manufacturing costs of the CFRP-tool. This share consists about 85% percent of labor costs, which is proportional to the working hours. In case of the benchmark tool, the labor costs only make up about 9% of the defined sum. In this case, the sum of the labor costs and the production costs is driven by the production costs which depend on the machine hours.

As already mentioned, the results, especially for the labor costs driven CFRP tool, strongly depend on the set wage hours. Because no further overhead costs or profits are considered they are quite low in this calculation, which promotes the CFRP tool.

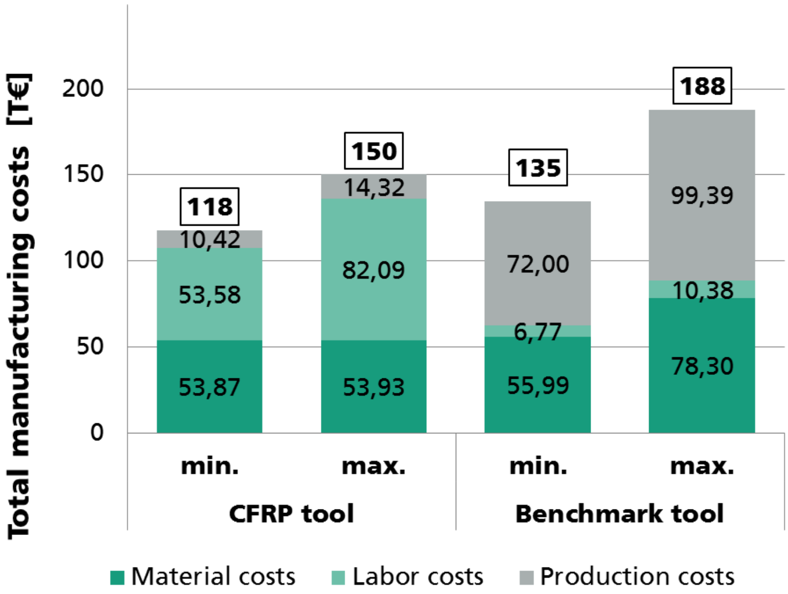

Figure 28: Total manufacturing costs of the CFRP tool and the benchmark tool in comparison, each separated into the minimum and maximum scenario.

For evaluating the economic viability of the CFRP tool, not only the manufacturing costs have an impact on the decision making process. Also the accruing costs during the use-phase of the tools need to be compared. The fixed costs are determined by the difference between the total manufacturing costs and the recycle credit. The variable costs are the result of the energy consumption per cycle and the electricity price. Further costs in the use-phase, like machine costs, labor costs and material costs are not considered, because they relate to part "rotor blade" and not to the tooling technology. Figure 29 shows the averaged total cost for manufacturing rotor blades during the use-phase, depending on the use-phase cycle numbers. The shadowed areas reflect the range from the minimum and the maximum scenarios. The broken line correlates to the fixed costs, which are the manufacturing costs for one tool. The continuous line represents the total costs, which includes additionally the costs for the use-phase, depending on the number of use-phase cycles. Because of the lower energy consumption during the use-phase of the CFRP tool, the total costs increase much slower.

An accepted life cycle of 1000 cycles is not state of the art and is not possible to realize with a CFRP tool at this point. Therefore this calculation is carried out with the assumption of the half life cycle for the CFRP tool. After 500 curing cycles a second tooling is needed. The fact that an epoxy master (form for the tool layup) could be used for three times is considered here and makes the second tooling a bit cheaper. The diagram shows that in this case, the production of rotor blades is more expansive with the CFRP tool. In summary, an economic benefit strongly depends on the possible cycle numbers.

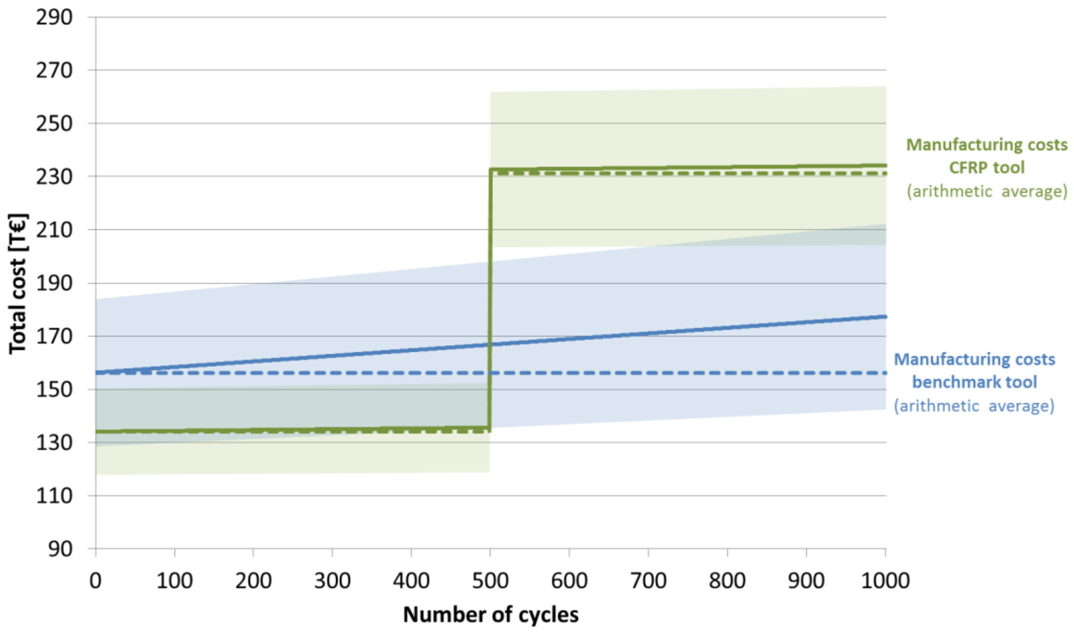

Figure 29: Break-even point analysis – total costs during the use-phase for 1000 cycles for the aluminum tool and 500 cycles for the CFRP tool.

For a better economic benefit of a CFRP tool, the manufacturing costs have to decrease. As the labor costs are dominating the total cost; the biggest saving potential can be achieved obviously by the reduction of working hours. With the effect of a learning curve of the process and some kind of automation, it is possible to save working hours. Additionally solutions for an increase of the life cycle are necessary. Furthermore it should be mentioned, that a CFRP tool could be used as a stand-alone tool, without the additional need of a press. This circumstance is not considered in the investigations, because in LEEToRB the developed tool is not a stand-alone tool. A stand-alone tool could reduce the use-phase costs, because of the renounce of a press. On the opposite, it could increase the costs for the manufacturing of the tool, caused by the need of higher stiffness and hence a more stable design. Anyway, this circumstance should be regarded in future more detailed.

4.3. Life Cycle Assessment (LCA)

The ecological investigation of the benchmark and the full size CFRP tool is realized through a Life Cycle Assessment (LCA). The results for both tools are already presented in detail in deliverable 5.3. Here the main results of the CFRP tool and the comparison to the benchmark tool are given.

The regarded impact categories are the Primary Energy Demand (PED), the Global Warming Potential (GWP) and the Ozone Depletion Potential (ODP), which are based on the methods by the Centre of Environmental Science at Leiden University (CML) from 2013.

In order to generate comparative results, the general boundary conditions like the functional unit, which is one tool in kilogram, or the system boundaries of the LCA, are the same for both tools. For reliable results and through the uncertainty of some input parameters, a minimum and maximum scenario was conducted for all important parameters. The life cycle (curing cycles during the use-phase) of the tools is integrated into the minimum (500 cycles) and maximum (1000 cycles) scenarios. For more detailed information about the modelling and the boundary conditions of the minimum and maximum scenario, compare deliverable 5.3.

The resulting PED, GWP and ODP for both scenarios of the CFRP tool are presented in Figure 30, Figure 31 and Figure 32.

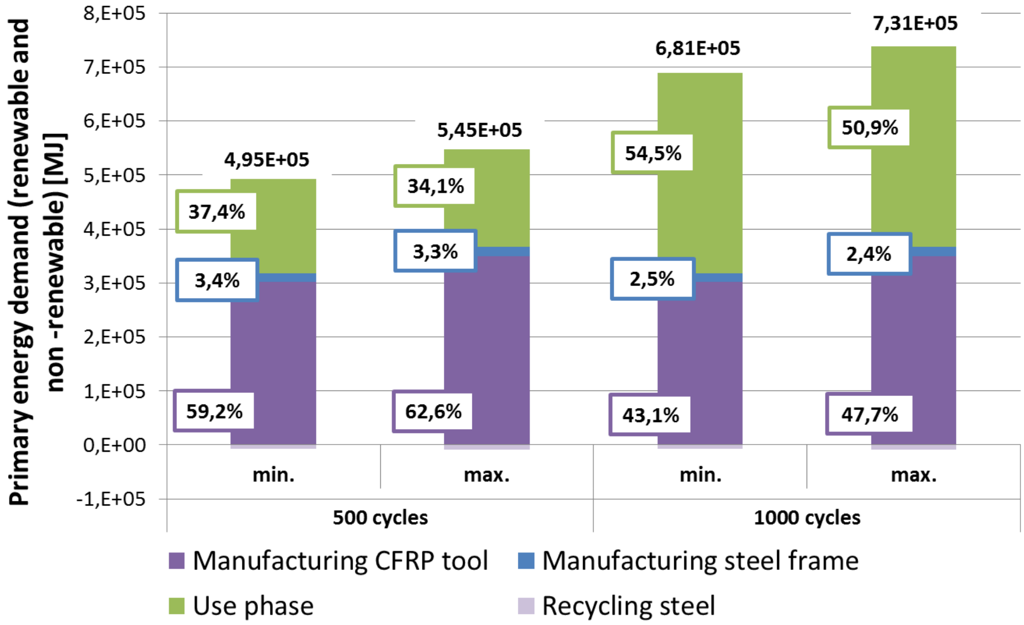

Figure 30: PED for minimum and maximum scenario of each life cycle phase – CFRP tool.

The primary energy demand for all scenarios is driven by the manufacturing of the tool and the use-phase, depending on the number of cycles. The influence of the "tool manufacturing" is about 43% to 65% of the total PED, if the recycling of steel is included. The use-phase also has a very strong impact with 34 to 50.9%. Although steel is a high energy demanding material, it has a small impact here, because the needed amount of steel is relatively small. In summary the difference between the minimum and maximum scenario for a fixed cycle rate is about 9.2 % on average.

The strong impact of "tool manufacturing" to the PED, is caused by the production of carbon fibers, which is a very energy intensive process and makes up 80% of the part "manufacturing CFRP tool". Detailed information about this investigation are already given in deliverable 5.3.

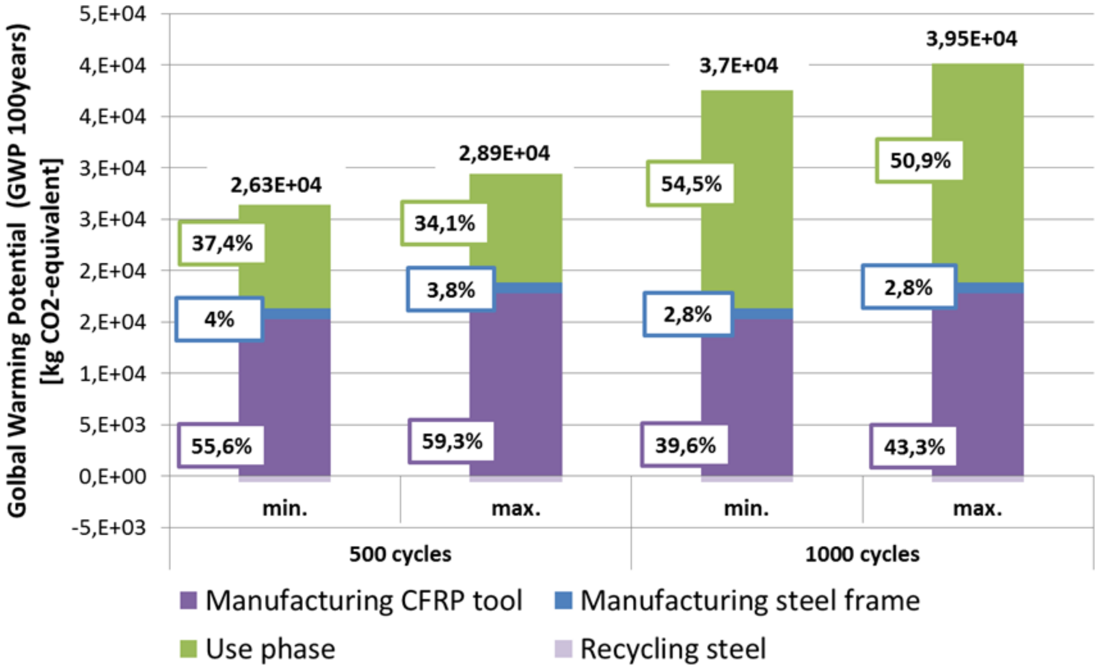

Figure 31: GWP for minimum and maximum scenario of each life cycle phase – CFRP tool.

Figure 31 shows the result for the GWP, which behaves quite similar to the PED. The difference between the minimum and maximum scenario for a fixed cycle rate is about 9.2% on average. In contrary to the PED and the GWP, the ODP shows a complete different behavior, visible in Figure 32.

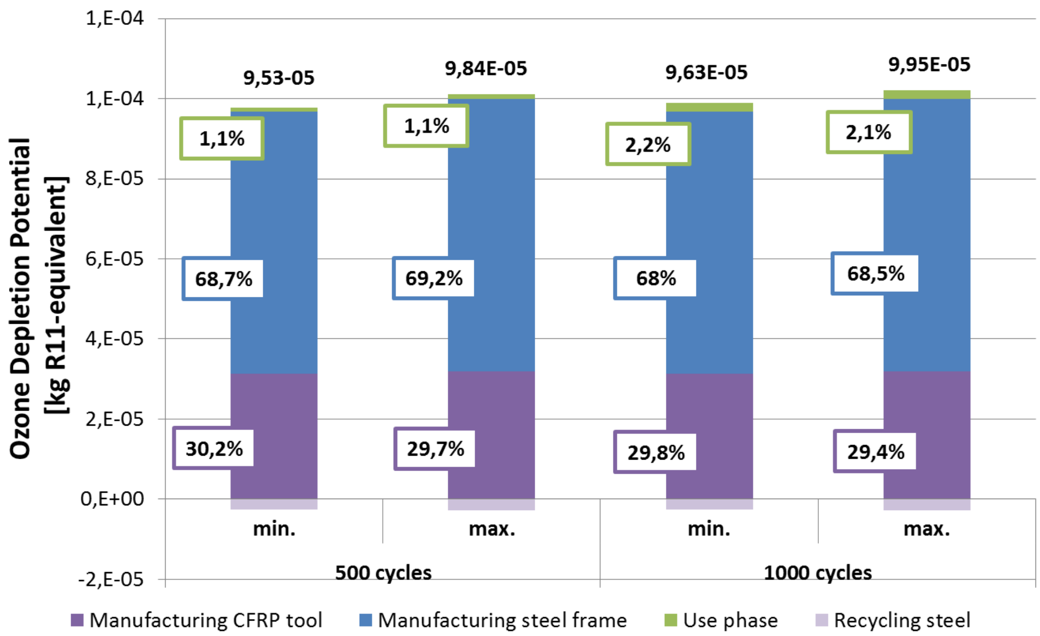

Figure 32: ODP for minimum and maximum scenario of each life cycle phase – CFRP tool.

The manufacturing of the steel frame has with 68.5% the biggest impact on the total ODP, although the needed amount of steel is quite small. Here the allocation of the raw material steel, is dominating with 99.96% to 99.97%. This strong impact has already been visible in the results of the benchmark tool, where the heat-/ and cooling plate, made out of steel. In contrary the use-phase is with only 1 to 2 % negligible.

In comparison of the two regarded tools, a big ecological saving potential with a self-heated tool out of CFRP, for the three regarded categories, is visible. There is a total saving of 64.4% (500 cycles) or rather 71.5% (1000 cycles) in the PED and 66% (500 cycles) to 72.9% (1000 cycles) in the GWP. The biggest saving though is in the ODP with 92.8%, exemplarily shown in Figure 33.

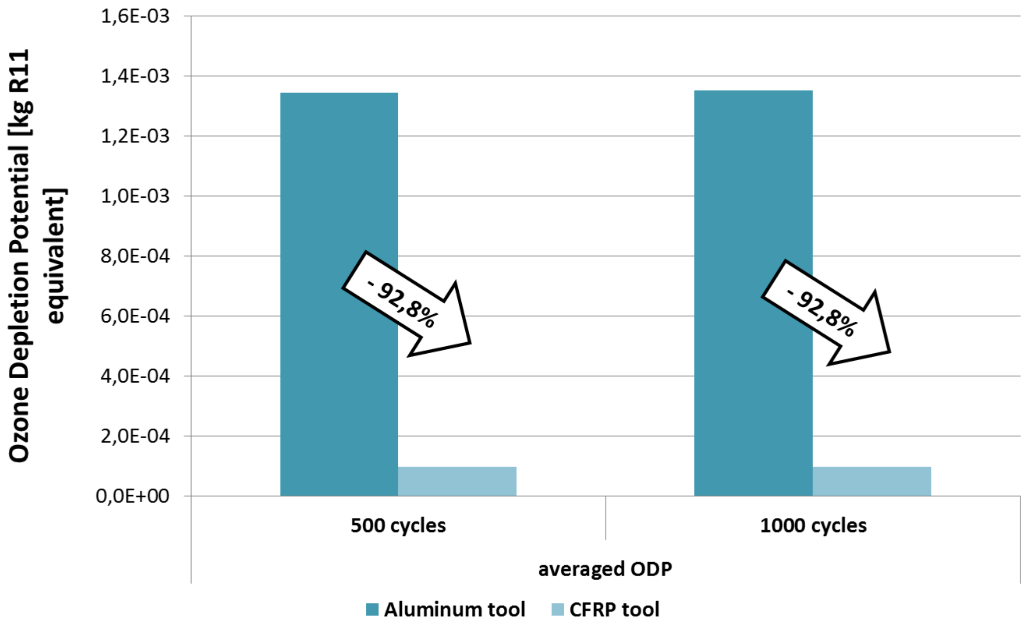

Figure 33: Comparison of the tools - total averaged ODP for the 500 and 1000 curing cycles.

Indeed an accepted life cycle of 1000 cycles is not state of the art and is not possible to realize with a CFRP tool at this point. For that reason, a break-even point analysis was carried out, whereas the CFRP tool has to be renewed after 500 cycles. As the lowest saving potential is expected in the PED, only this analysis is presented here in Figure 34. Nevertheless, this investigation was carried out for all impact categories.

The averaged total PED for manufacturing rotor blades during the use-phase depending on the use-phase cycle numbers is visible as a continuous line. The shadowed areas represent the min/max range and the broken line represents the PED for manufacturing the tools. Due to the lower energy consumption during the use-phase of the CFRP tool, the total PED increases much slower for the CFRP tool.

The second CFRP tooling has a lower PED demand as the first one, because the master can be used up to three times. Anyway the saving in PED with a self-heated tooling out of CFRP is still big enough, that with even a second tooling, the CFRP tool achieves better results.

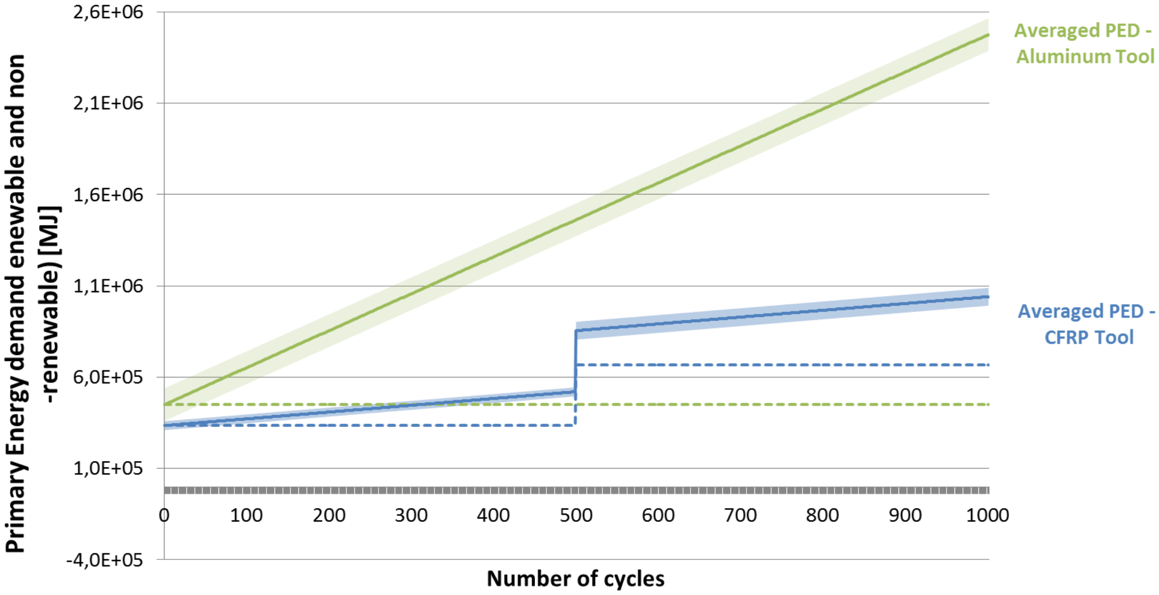

Figure 34: PED - Break-even point analysis of the PED for the whole life cycle of both tools.

5. Summary

Commonly used resin transfer molding (RTM) tools made from steel show a poor performance in terms of environmental and economic aspects within the context of rotor blade manufacturing. This is mainly due to the high weight and therefore bad manageability, the intensive energy consumption for heating during the process, a high ratio of scrap when cut from solid material and high-energy expenditure for the production of raw material in the first place. Furthermore, the weight of the molds results in undesired deflections that must be eliminated by additional material usage for stiffening the tools. On the contrary, the use of composites in tool manufacturing is known to be a solution for the above stated problems but is not yet capable of satisfying the strict requirements for RTM processing within aerospace. The project LEEToRB comprises the development of “**L**ightweight, **E**nergy-**E**fficient **T**ooling for the Manufacturing **o**f **R**otor **B**lades” within the Framework of the Green Rotorcraft (GRC) programme of the EU research project Clean Sky. Carbon fiber reinforced polymer (CFRP) molds are utilized in combination with a novel heating system introduced by the consortium partner Qpoint Composites GmbH to provide the cabability of manufacuring of CFRP parts with complex geometries including highly varying cross-sections in an energy-efficient way. To do so, four major topics are adressed within the project: The manufacturing of the CFRP RTM prototype tools is carried out by Qpoint Composites GmbH. Development of process technology as well as curing simulation is accomplished by the Technische Universität München. Finally a life cycle assessment is made by the Fraunhofer Institute. The target application of the work conducted is provided by Airbus Helicopters.

5.1. Process technology and manufacturing

The work related to the process technology starts with the definition of the process parameters and a research about occurring problems with CFRP molds in liquid composite molding (LCM) processes. Based on that the development and investigation of mold surfaces and coating material is planned. Two experimental set-ups are defined. The first setup is called “long-term test” and investigates the performance of different coating materials depending on the number of injections. Therefore a small RTM tool with a generic mold geometry is designed and manufactured with three different surfaces: Plain untreated surface, high performance tooling gelcoat and a metallic paint. The tests show an equal decrease of vacuum integrity independent from the tool surface. The visual inspection of the tool surface shows a strong wear out in terms of surface breakouts of the untreated surface and almost no wear out of the treated surfaces. A second setup investigates the strength of edges in composite molds. Therefore a test rig has been designed, mounted in a compression test machine that loads the edges until failure. The results show that the way of positioning the fibers in the edge and the ductility of the matrix system influence the edge strength significantly.

In the second phase of the project a simplified rotor blade demonstrator tool is designed and built to verify the new tool design without shearing edges and to validate the simulation results. Therefore, a simplified rotor blade has been designed that includes the typical elements of a rotor blade: a monolithic connection area, a transition area and a sandwich area. Based on the part geometry a mold is designed that includes a new centering and a new sealing concept. To manufacture a part by RTM within geometrical tolerances the deformation of the tool due to the infiltration pressure is calculated by a FEA analysis. The results are used to design an egg crate stiffening structure. The tool is manufactured at consortiums partner QPoint Composites GmbH. The manufacturing process starts with the design of the tool heating. Based on input of the simulation five heating areas that can be controlled separately are applied. After manufacturing of the simplified rotor blade tool eight simplified rotor blades are manufactured. Seven of them are used to optimize the infiltration process by adapting the infiltration parameters temperature and pressure. One demonstrator is used to validate the curing simulation results. The quality of the rotor blades is measured by optical analyzation of the fiber volume content and the porosity and by measurement of the part thickness at different positions.

In a final step the full scale rotor blade tool is designed at Qpoint composite. The design included the mold surface itself as well as the attachment structure to connect the molds to a rotor blade press.

5.2. Simulation

The simulation work of the project included the following parts:

First, a material characterization was conducted to gather experimental input, which was subsequently used for a least-square model fit of material models originating from literature. The characterization methods consisted of dynamical scanning calorimetry (DSC) to determine exothermic behavior of the curing resin as well as heat capacity. Rheometer testing was conducted to gain knowledge on the evolution of heat capacity with temperature and degree of cure. Heat conductivity of the curing resin was measured by means of the Nanoflash™ method. With the addition of density measurements, the determination of the thermochemical behavior of the curing resin CYCOM 823-1 RTM was completed. Because fiber properties originated from literature, a validation of the material characterization was necessary. A 30 mm coupon was cured with a vacuum bag on a self-heated CFRP plate provided by Qpoint. A total of 18 Thermocouples were placed in three different planes in the setup and the temperature development. Comparison of experiment and simulation showed good agreement of the exothermic peak. Additionally the experiments stressed the need of a more refined cure cycle to prevent high exothermic temperature peaks in thick laminates. A qualitative 1D sensitivity study was used to set up an optimized cure cycle, which required 10 additional minutes and reduced the exothermic peak by approximately 75% compared to standard cure cycle given by the manufacturer.

Second, a simulation strategy was set up to model self-heated CFRP tools within a cure simulation environment. A cure simulation model of the 1 m demonstrator part within the self-heated CFRP tooling was set up and cure simulations were conducted to investigate the temperature and cure development within the tool. In-depth examination of the results showed not only the potential risks regarding temperature overshoots, but also gave educated guesses on the origin of process technology issues such as apparent surface resin films. A comparison to a part produced with the improved cure cycle developed, where the causes for the process technology issues were expected to be impeded, showed significantly improved part quality, supporting the claims derived from the cure simulation. Finally, validation between simulation and experiment was conducted on the 1 m demonstrator part.

Third, a study was conducted to investigate the influence of metallic inserts in the thermal and cure behavior. The study emphasized the need of distinct heat patches and accurate heat patch placement, if high thermal masses such as metallic inserts are included in the part. With assistance of this study every apparent influencing feature on the thermal and cure behavior of the rotor blade was investigated, and simulation research of the rotor blade was concluded.

5.3. Life-cycle assessment (LCA)

The overall goal of work package 5 was an economic and ecologic evaluation of a self-heated CFRP tool towards the benchmark aluminum tool. This should be carried out for the manufacturing of the tools itself, as well as in consideration of the use-phase. With the measurement of the energy consumption during the use-phase the execution of an EVA and an LCA for both tooling concepts, these goals could be fulfilled in order to make a statement of the ecological and economic benefits.

The measurement of the energy consumption during the use-phase of both tools proves that there is an energy saving of 84% to 87% expectable. Additionally the whole heating strategy promises some potential for optimization. With the CFRP tool a totally different process technology and materials have to be used for the production of rotor blades, which leads to saving of time per cycle of about 41%.

The comparison of the tools through the results out of the EVA shows that, under the set conditions, the manufacturing of a CFRP tool can be about 20% cheaper than an aluminum tool. As already said, here the results strongly depend on the set conditions. No overhead costs or additional profits have been taken into account. This benefits the result for CFRP tool, because the results are driven by labor costs or rather by the supposed wage hours.

In spite of the lower energy demand of the CFRP tool during the use-phase and thereby resulting lower energy costs, the benefit of a CFRP tool for manufacturing rotor blades is debatable. The life cycle of the CFRP technology is too short at this point to compete against the aluminum tool. A cost reduction for the tool manufacturing, as well as the increase of the life cycle is needed. A saving in the input of manual work for manufacturing the CFRP tool (working hours) can be expected through a learning curve and some degree of automation. Additionally new solutions for an increase of the life cycle are required.

Through the LCA a huge saving potential in all regarded impact categories for the CFRP tool towards the aluminum tool could be proved (about 60% to 70% for the PED and the GWP and with about 93% for the ODP). In addition with the very small energy demand during the use-phase, the manufacturing of rotor blades for helicopters is ecologically worthwhile with a self-heated tool, out of CFRP.