ON AN INTEGRATED PROCESS AND MACHINERY CONCEPT FOR ECONOMIC INDUSTRIALIZED PRODUCTION OF HIGHER QUALITY WIND TURBINE ROTOR BLADES

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ABSTRACT

Fraunhofer IWES has investigated the production process of typical wind turbine rotor blades and developed a cost model to compare the current manual production process to new industrialized production concepts. The aim is identifying key methods to reduce blade cost: Development of cost-effective rotor blade materials with similar properties, reduction of manual labor and increase of production reproducibility for robust quality, as quality costs pose a significant part of blade costs. Fraunhofer IWES will show methods to achieve cost-effective production and present industrialized fabric handling and finishing processes as they are key factors for blade quality.

Different production strategies developed by using draping simulation and a simplified finite element analysis for the complete lay-up process result in an industrialized fabric placement process to address these quality and manufacturability aspects of large blades.

In many production processes the final shape of the rotor blade is created by manual labor to reproducibly achieve the desired aerodynamics and surface quality. Fraunhofer IWES is developing a fast automated process for measuring, CNC-trimming and -grinding the blade to a shape with better aerodynamic and guaranteed structural performance by increased reproducibility.

Fraunhofer IWES is currently building up a demo center for processes development and validation on the full scale blade level.

Therefore Fraunhofer IWES has defined the specifications for an innovative easy-to-use CNC tool machine designed for industrialized rotor blade manufacturing, including an integrated CAD-CAM-solution.

1 INTRODUCTION

Wind turbines for rotor blades fulfill a very diverse and conflicting set of requirements: Low weight, high strength, precise outer free-form shape, a long design lifetime of 20 years with little or no maintenance and high fatigue loads, all while posing a significant, 20-25% share of total wind turbine costs. These requirements are best met by fiber reinforced plastics, even though their manufacturing processes are still largely under development, especially for parts the size of wind turbine rotor blades.

Currently the rotor blade production is still dominated by manual labor, which leads to high tolerances, requiring high safety factors and a less-than-optimal blade design, and which reaches its limits with current and upcoming blade dimensions. The size of wind turbines is expected to increase up to 10 MW with rotor diameters up to 180 m within the near future, as the total production cost per kilowatt-hour of electricity decreases with increasing wind turbine size.

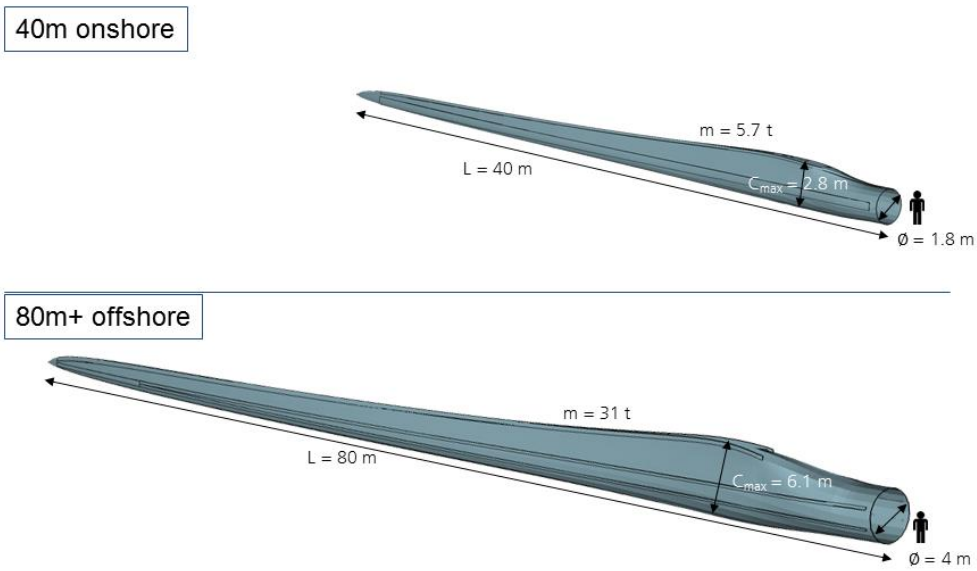

Figure 1: Typical dimensions of current and upcoming wind turbine rotor blades

Industrialized manufacturing will not only ease the production of large wind turbine blades, it also promises significant improvements leading to higher reliability, higher blade value and ultimately lower cost-of-energy for the entire turbine.

The BladeMaker research project aims to lower the total blade costs by 10% through industrializing blade manufacturing processes in a consortium of material suppliers, rotor blade and process experts and automation technology suppliers.

2 STATE OF THE ART: MANUFACTURING PROCESSES AND COST DISTRIBUTION OF WIND TURBINE BLADES

Most wind turbine rotor blades currently available on the market are built in a largely manual multi-step process. First, parts with massive laminates such as spar caps or root segments are manufactured by placing dry non-crimped fabrics into auxiliary molds and infusing them with resin in a vacuum infusion, then dry non-crimped fabrics are laid up in the main mold for the sandwich panels, followed by the sandwich cores, the premanufactured parts and another layer of non- crimped fabrics. The blade half shells are then infused with resin, shear webs glued into one half and the main mold is closed for gluing the blade shells together. After opening the main mold and demolding the rotor blade, some post mold finishing is conducted, the blade is painted and various additional parts such as lightning protection and blade root connection are added.

Fraunhofer IWES has investigated these process steps on an exemplary 40m rotor blade design to create a cost model of each and every step. The calculations for this cost model have been conducted for two separate scenarios, one assuming a small scale production with a single mold set, reaching 220 blades per year, the other one coming closer to a serial production with 1800 blades per year on multiple mold sets.

As Figure 2 shows, the cost distribution over the process steps is similar in both scenarios. Apart from manufacturing spar caps and applying core materials, post mold processing and preforming of shells, webs and root flange inserts form the largest contributors to blade costs. Additionally, the quality of the root flange insert is a key factor in the reliability of the rotor blade, and the final aerodynamic shape created during the post mold processing determines the energy yield of the turbine.

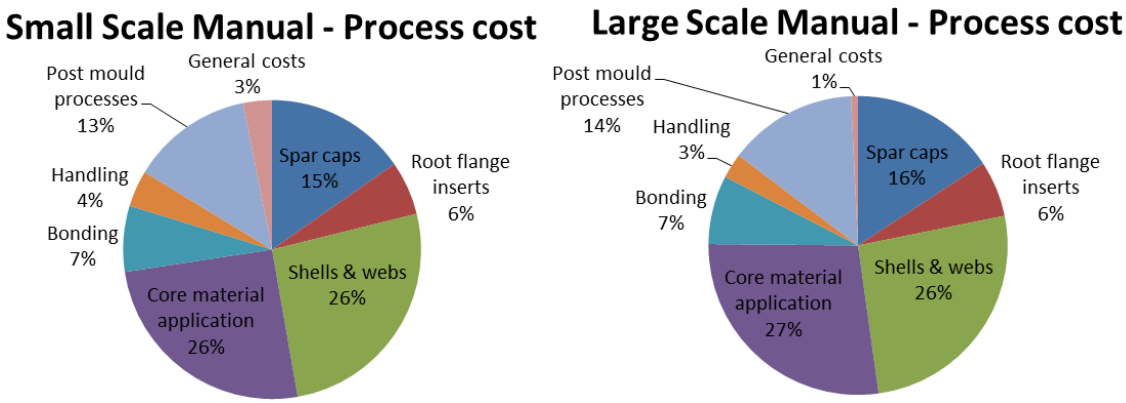

Figure 2: Cost distribution for a 40m-Blade calculated for different production scenarios

3 PREFORMING PROCESS FOR BLADE ROOT SECTION

3.1 Materials and Processes

Composite materials for high performance applications like rotor blades are made from roving or textiles like woven or non-crimp fibers. Non-crimp fibers, NCF, are currently widely used for the manufacturing of blades. The NCF integrates different layers of roving direction in one fabric. This leads to significant higher area weights and therefor to higher throughputs by manual application.

The root section of a blade has to transfer the complete loads from the blade into the blade bearing by additional bolts assembled or integrated at the root end. The bending and torsion loads and the additional high pressure on the bolt area require high composite thicknesses. The composite design for this section is made of up to 140 layers of textiles. Typical dimensions on a 40m-blade are approximately 1.50m length and 2m diameter.

For the production of the root section different manufacturing scenarios have been set up in the blade industry. The simple way of manufacturing is stacking the layers directly in the main mold. For the hardening of the blade the complete textile lay-up of shell and root will be done in one shot. This leads to a longer usage time of the mold for the different process and for a single blade.

For the reduction of molding times the root is manufactured by Preforming in a parallel process. Basic process is the cutting, handling, lay-up of the textile cut-offs. This process is widely automated for the cutting process, some manufacturers are supplied with cut-offs directly from the NCF-manufacturer. The handling and lay-up is done manually. By increasing the production numbers or by increased dimension of blades this manual stacking process will be limited in time and in the handling of the cut-offs with the required quality. The NCFs show a great variety in their mechanical properties. Additionally these kinds of textiles are very sensitive against mechanical loads. For the basic requirements of industrialized blade production both the key factors – molding times and constant quality – will be achieved by an automated solution for root section manufacturing.

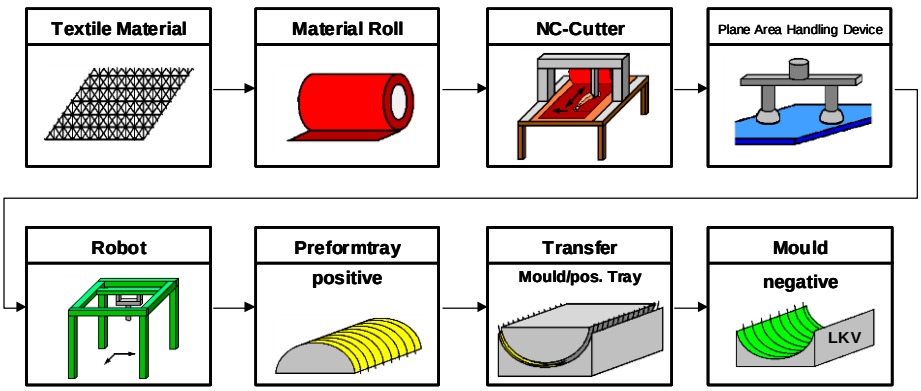

Figure 3: Exemplary Process Chain with pre-cut part-manufacturing by NC-Cutter [1]

3.2 Tools for simulation of textile handling process and lay-up for quality-related process planning

As composite materials gain their properties during the manufacturing process, the impacts of preforming process on the properties should be taken into account very early in the design stage. Tools for simulating the handling process and the layup process will decrease the uncertainties in the design process of a rotor blade and will eliminate additional design effort for production planning. Additional the integration of tool- and process design into the blade development process will be conducted.

Two basic tools have been identified which can be used in the different stages of product and process development, as shown in Figure 4.

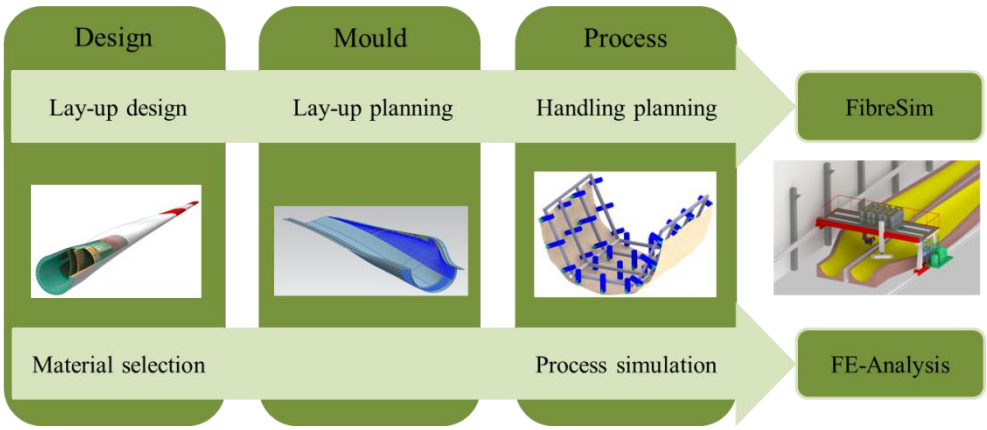

Figure 4: Continuous use of simulation tools for design and production planning

The handling of textiles can be realized by different handling operations. The project BladeMaker is researching the manufacturing of thick composite structures by automated pick & place-process. In the last years there a lot of different alternatives for pick & place of textiles have been developed. For simplifying the handling solution and reducing the intended invest a planning tool based on an adapted FE-Model will be used for the planning of handling devices. In a first application a limited numbers of special suction grippers will be used for the pick & place of fabric cut-offs. This will lead to different deflection of the cut-offs made by varying fabrics or textiles. The handling process has to be executed with minimized mechanical impact on the textiles. The textiles show a low bending rigidity with orthotropic structure which can be measured with a special tool (Cantilever test).

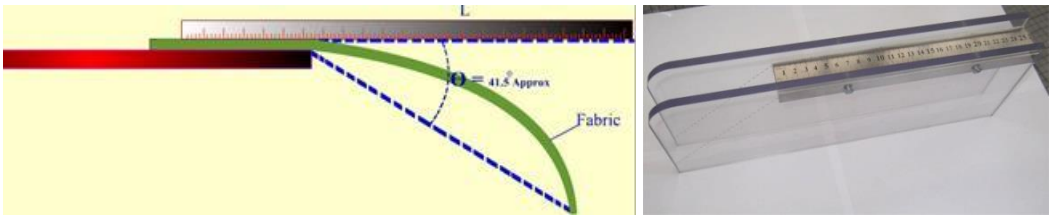

Figure 5: Principle of the cantilever test for measuring bending stiffness of textiles [2]

Because of the different fabrics and textiles used for blade manufacturing the automation equipment has to be able to adapt to the varying properties during the running process. The bending stiffness depends on the textile structure, e.g. the layer design of the NCF, the fibres and roving diameters.

Based on work at the University of Bremen and applied University of Bremen [2,3,4] the FE-analysis is used for the simulation of the handling. The cut-offs for root sections of a blade have got large dimensions and different geometries depending on their position in the blade.

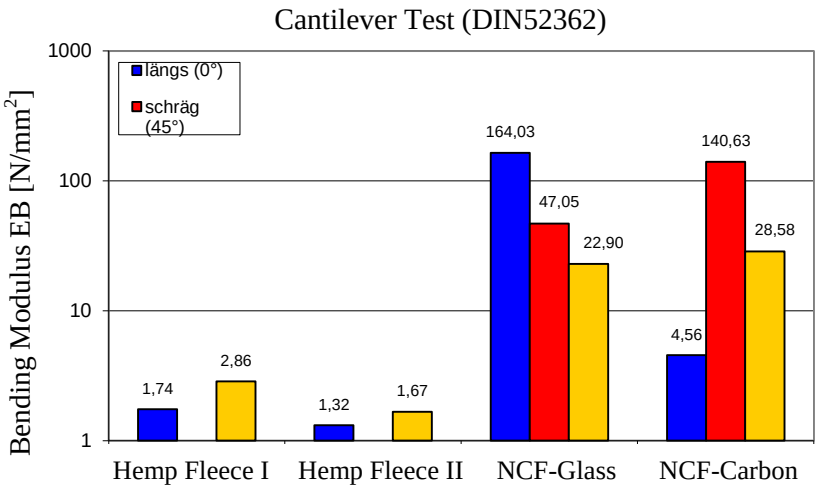

Figure 6: Typical data of bending stiffness of technical textiles used in different application

With these measured propoerties of the textiles plus the weight, the thickness and the geometry it is possible to set up a geometrical-nonlinear FE-Model for large deflections. Based on this model the adaptive handling solution will developed. For this purpose the existing FE-Model based on nonlinear, orthtropic shell-Elements by ANSYS will be enhanced by an optimisation algorithm as shown in Figure 7.

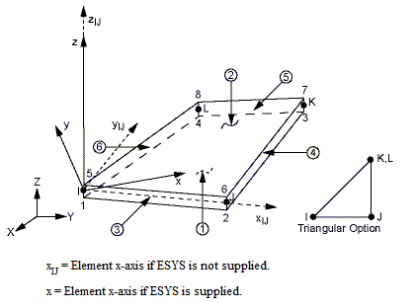

Figure 7: 8-node Ansys-Element used for the simulation of the handling process [5]

The simulation results have been evaluated by practical trials. For this purpose a mechanical clamping gripper, built at the University of Bremen, was used [2]. The cut-offs of different materials, carbon-, glass- and hemp fibres, were tested and their deflection was measured at several points. Exemplary Figure 8 shows the result for an NCF made of glass. The length of he specimen was 1000mm, the width 500mm. The first model, red line, was adapted to different boundary conditions, resulting in the new model, blue line,which shows good results for the intended aim integral design of handling devices.

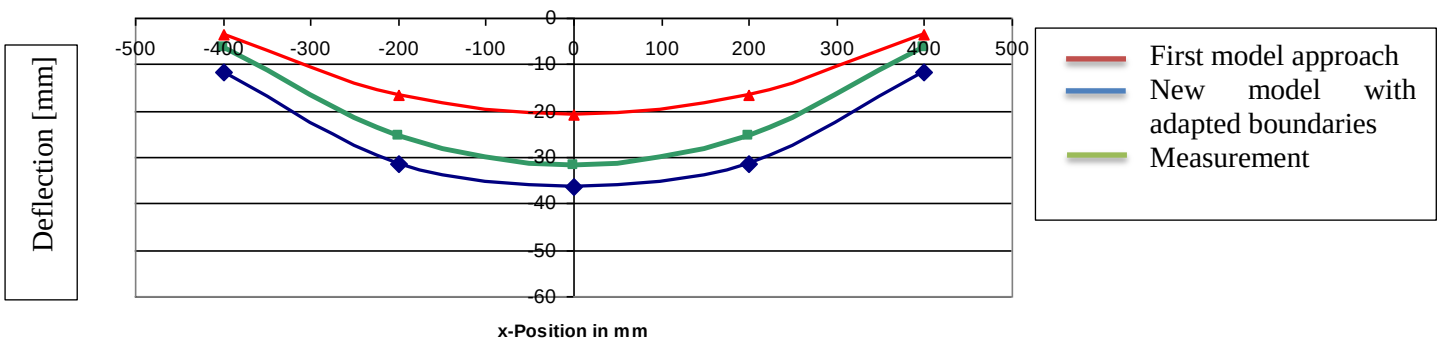

Figure 8: Comparison of real and simulated textile deflection for glass fibre NCF [2]

This FE-approach is the first of two different tools used in the digital design process for the development of automation equipment, because of different requirements for the handling and the lay-up process. In the second step the fabric layup design and the draping of textiles will be assisted by a digital tool.

This lay-up simulation also provides the CAD data for controlling the automation system and automated fabric cutters. It creates solid CAD models with anisotropic material properties for structural calculations, fabric layup plans for cutting and manufacturing and analyses of the draping process. This workflow has been demonstrated at Fraunhofer IWES as shown in the figures below.

This information can be used for the different approaches of the tool design, material selection and automated or manual process planning. Summarized the digital process chain will reduce complexity and time both for the development of tools and handling equipment and for the production planning.

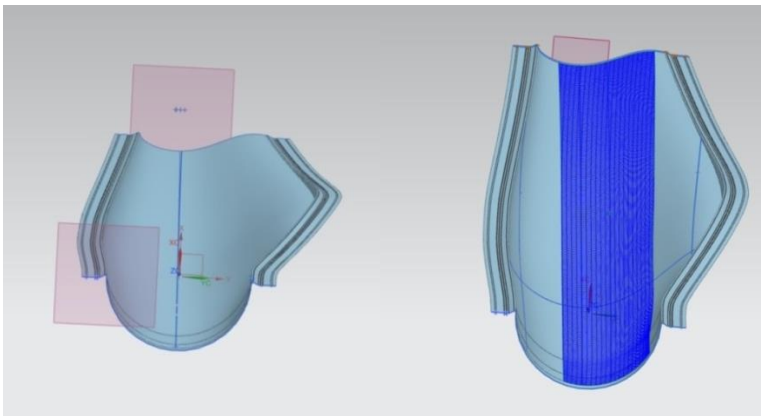

Figure 9: Defining sections and layer widths for fabric layup

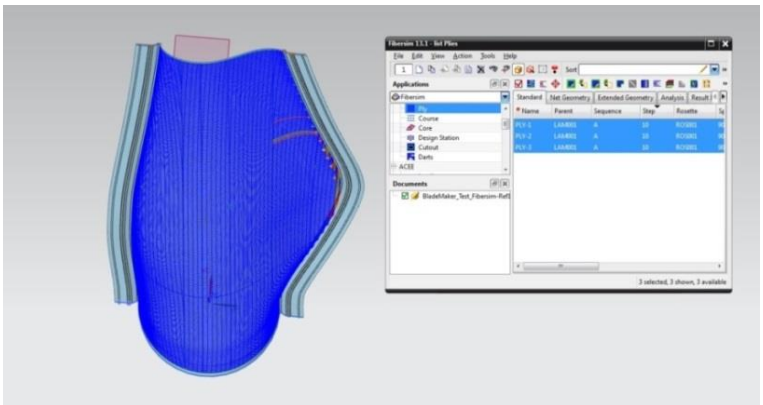

Figure 10: Defining sections and layer widths for fabric layup (cont.)

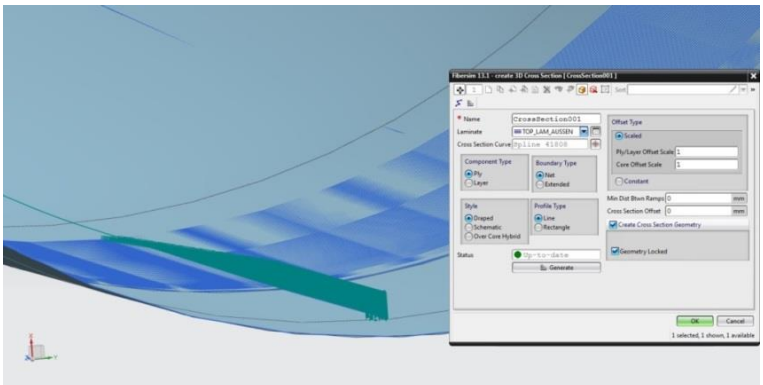

Figure 11: Creating cross-sections and solid bodies from layup

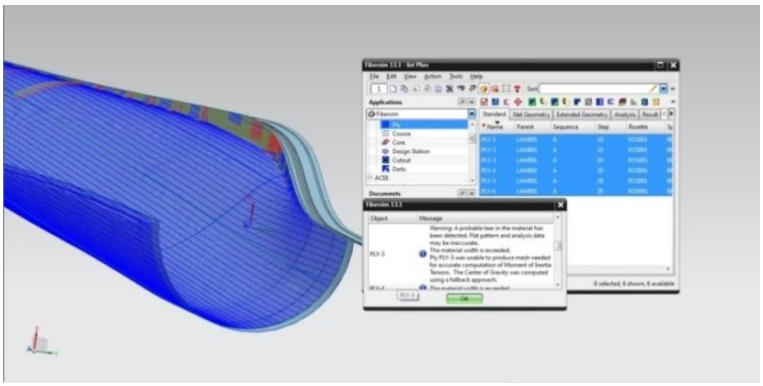

Figure 12: Analyzing distortions required if fabric shall fill the free-form

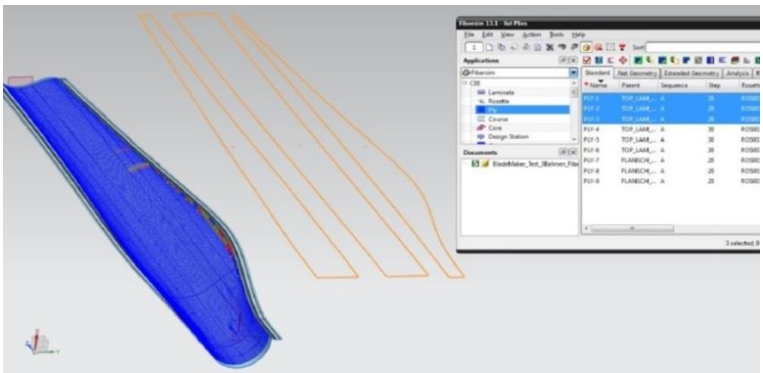

Figure 13: Creating the ply book for cutting the fabric to shape

3.3 Industrialized Textile handling

For a process with industrialized textile handling, a system is required which is able to pick and place the dry non-crimp fabrics reproducibly. After the cutting of material on the cutting table it is required to pick up the material and either place it in the mold directly or on a storage table first and then picking it up again and placing in the mold. The second option reduces the cutting table occupation time. Fraunhofer IWES intends to conduct this process with the help of a gantry robot with an application head mounted on it. The application head will have vacuum grippers for picking up the fabric material. Additionally, integrated image processing and other sensors will enable the robot to place it in the mold with accurate pressure in order to achieve precision.

The aforementioned application head needs to ensure that the non-crimp fabrics are not damaged during the handling process. Damages can occur in the following forms: gaps, deformations, distortions, deflections of the fiber orientation and buckling of fibers. All of these damages can influence the mechanical properties of the resulting composite material. Another aspect which has to be analyzed is the accuracy of the placement process and in this case the definition of the required number of vacuum grippers.

3.4 Development of industrialized Pick&Place for large fabrics

For the development of the handling and application head which will be integrated in a robotic solution Fraunhofer IWES has developed a test booth called Pick & Place, shown in action in Figure 14. This test booth will used for the evaluation of single gripping technologies but also for the evaluation of the handling simulation.

Figure 14: Pick & Place test booth in operation

Based on the required gripping technology, for example low pressure gripping units, the loads for a safe gripping and the deflection for the different types of fabric can be evaluated by the FE-method explained above. Based on this data the intended handling solution will be designed and tested in an exemplary application environment.

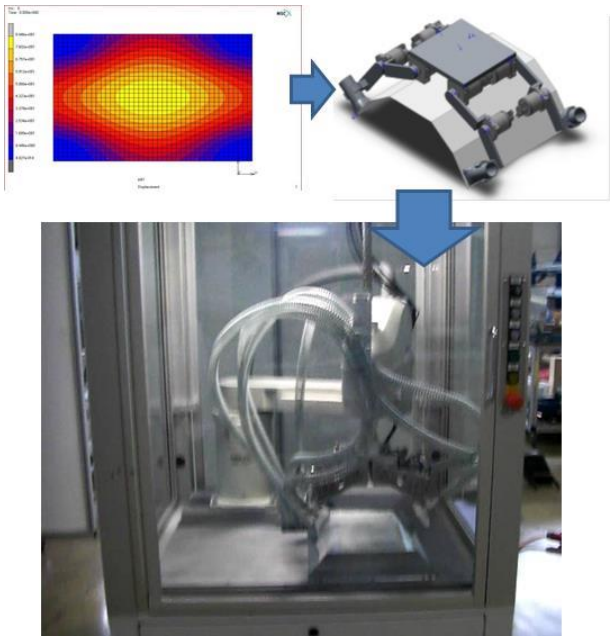

Figure 15: From the FE-Model to gripper application, for an exemplary application [3]

4 POST-MOLD PROCESSING

4.1 State of the Art: Finishing Processes - Activation vs. Surface Processing

Post-mold processing can be separated into two distinctly different steps:

1. Surface Processing for creating the final blade shape
2. Activation of the surface prior to coating

In current manual manufacturing, the distinction between the two is mostly a matter of experience and using rib jigs to check the work during the first step, when laborers are actively trying to change the shape of the blade, rather than just barely touching the surface in the second step. The distinction becomes larger when the processes are automated. For the activation process, there are automated solutions on the market and partly already being used in production, i.e. [6], [7] and [8]. The challenges for automating the surface processing step are higher, as detailed in the following section.

4.2 Requirements for automated surface processing

For successful automated surface processing, the automation solution needs to integrate seamlessly into existing process chains. The process needs to be adaptable to different blade types, quick to setup, easy to clean and maintain and quick to run when compared to manual post mold processing, which takes approximately three hours per blade. The rotor blade shall be processed without requiring complex fixtures, meaning the exact location of the part will not be known in advance. Therefore, sensitive tools are required to adjust to these uncertainties. As an automated surface processing process aims to shape the blade, the system requires a connection to a CAD system to receive a target geometry which should be reached as closely as possible, depending on the existing geometry of the part. The result of this process will be a part that is consistently very close to the CAD part, not depending on human intuitiveness for reproducible quality.

Once an automated surface processing solution fulfills these requirements, the root flange surface can also be integrated, along with a milling head to create holes for the blade root connection, if applicable, resulting in an integrated post-mold machining system capable of running every post-mold process.

4.3 CAD-CAM-Integration as a tool for industrialized surface processing

A key to a successful automated surface processing solution is the integration of an adaptable CAD-CAM chain in the process. Particularly the CAM processor will have to be enhanced to enable novel adaptions of the machine program to the unspecific location and shape of the part in the workspace, including material information from the CAD data to properly predict the abrasion rate over the blade surface.

5 MACHINE TOOL CONCEPT FOR INDUSTRIALIZED ROTOR BLADE MANUFACTURING

5.1 Industrialization approach and requirements for rotor blade machine tools

Even in an industrialized rotor blade manufacturing, many processes will still be done manually and the transition to a possible future fully automated production will be gradual. In the first steps, only a few selected key process steps – possibly the preforming and post-mold finishing described above – will be automated, with process steps before, in between and after still being done manually.

This leads to some very specific requirements for rotor blade machine tools, namely them being adaptable when automating more process steps, running in close proximity to manual work conducted at the same time and not obstructing the manual process and part handling steps which will take place in between automated parts of the manufacturing process. Besides these requirements, the dimensions of large rotor blades require appropriately large machines for most of the process steps – a reasonable working envelope for main mold processes on an 80m blade would be approximately 100m long, 15m wide and 4m high – and the large amounts of raw material need to be transported by the machine. Softer requirements include ease of programming, CAD-integration and low restrictions on the hall or work space, and obviously some processes like the rotor blade root insert pre-forming won't require such big machines, as they only work on small parts of the rotor blade.

Figure 16: Existing solutions for large machine tools (Pictures from left to right: Güdel GmbH, MTorres, 2 Komponenten Maschinenbau GmbH)

5.2 State of the art: Industrial Robots versus Machine Tools

There are basically two different approaches to large machine tools – either a standard industrial robot, enhanced by a linear axis if required, or a purpose-built gantry as in [9] can be used to work on large workspaces. Finally, a combination of the two can be done to fulfill special requirements, of which [8] is an example. Table 1 summarizes assets and drawbacks of each solution with specific focus on rotor blade manufacturing while Figure 16 shows some existing solutions.

5.3 Integrated IWES BladeMaker-Approach for Demonstration

Fraunhofer IWES has evaluated Table 1 along with the specific needs of rotor blade manufacturing in a demonstration center and decided to follow a novel lightweight gantry approach shown in Figure 17, eliminating the drawbacks of conventional gantry machines regarding the speed and the foundation requirements. Following this approach, a second gantry was added on the same footprint to enable flexible use and decrease setup times.

	Standard industrial robot	Purpose-built gantry	Combination
Load bearing capacity	-	+	-
Stiffness	-	+	-
Speed	+	0	-
Accuracy	-	+	-
Flexibility	+	-	+
Extendability	-	+	+
Foundation requirements	+	-	-
Outreach	-	+	+
Ease of programming	0	+	-

Table 1: Assets and drawbacks of the three basic solutions for large tool machines

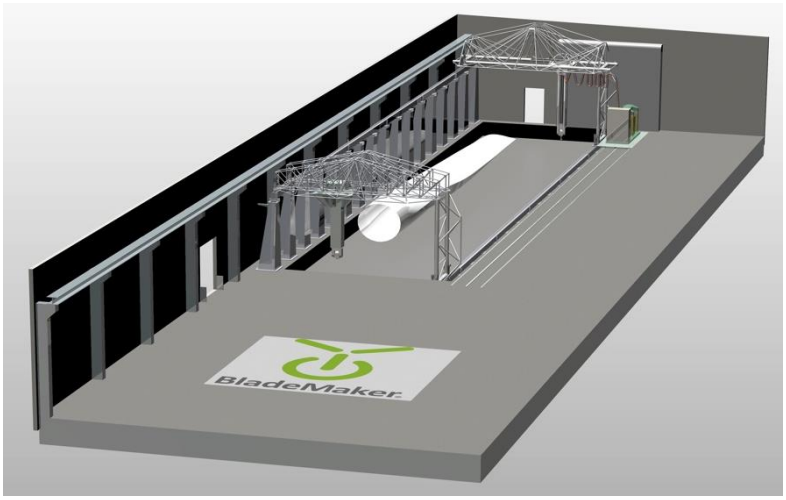

Figure 17: BladeMaker Demo Center for the industrialized production of rotor blades

Within the research project BladeMaker, the machine will be used to build a 20m section of a 40m rotor blade for demonstration and development purposes, so some requirements from serial production background have been lightened, however, the machine concept has been developed with an industrialized serial production of 80m rotor blades in mind. Particularly the size of the machine – the demonstration machine will have a six axis working space of 25m x 4.5m x 2.3m – can easily be upscaled to fit two main mold sets of an 80m rotor blade, as well as the load capacity, which is 400kg at the TCP and 3500kg close to the TCP in the demonstration machine. Features not removed from the demonstration machine include the Siemens 840D sl CNC controller for easy and convenient programming and CAD-integration, the sunken x-axis to keep the working space accessible from the

side as well as the high operating speed up to 2.5m/s and with the low weight of the machine itself very small loads transferring into the hall floor or foundation.

5.4 Industrialized Rotor Blade serial production

With a machine following the specifications in the previous section, an industrialized rotor blade manufacturing process as shown in Figure 18 is possible, with the question marks identifying those processes whose automation is evaluated within the research project BladeMaker.

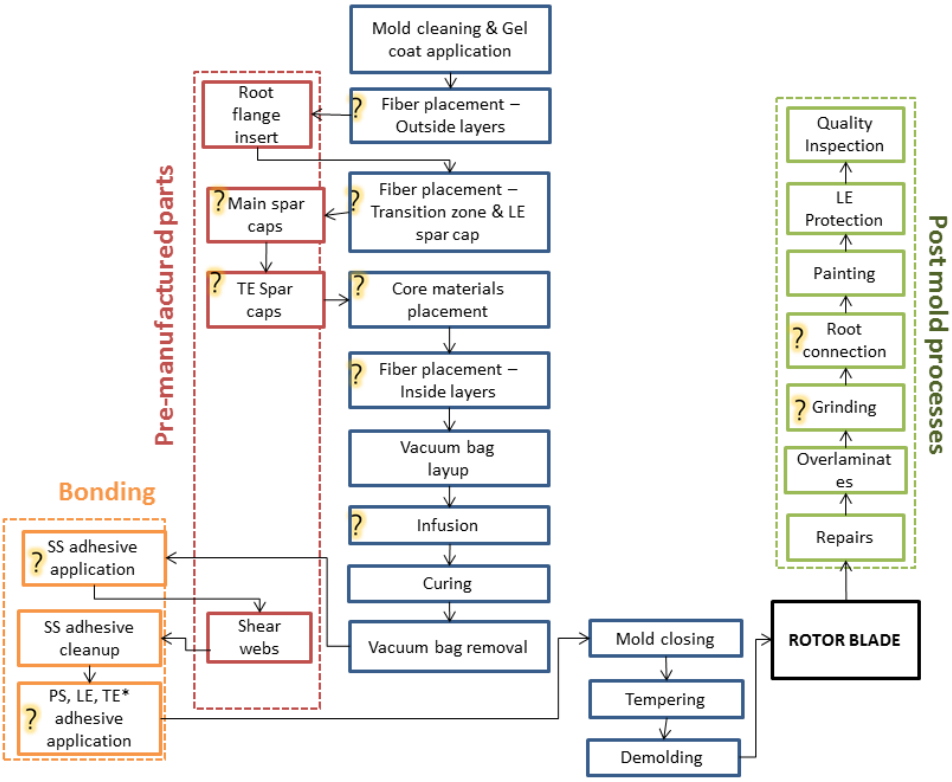

Figure 18: Process flow of an industrialized rotor blade manufacturing process

5.5 Cost Distribution by industrialized Blademaker-processes

Combining the automated pre-forming and post-mold finishing processes discussed in this paper with the other processes whose automation is evaluated within the research project BladeMaker and for which the above-mentioned machine tool is designed, a total cost decrease of 8% to 14% is expected as shown in Figure 19. This does not include adaptions of the blade design possible due to industrialization, through which additional savings are expected, i.e. through tailored spar caps or lower safety factors, nor has the higher blade value due to smaller tolerances on the final blade quality been taken into account.

6 CONCLUSION

Analyzing the cost distribution of typical manual rotor blade production shows significant cost shares in the preforming and post-mold manufacturing steps of 6% and 14% respectively, while being largely responsible for the reliability and energy yield of the rotor blade.

The feasibility of industrializing the entire process and automating these steps has been shown, along with steps taken on the path towards demonstrating these processes on a full size blade part, including material handling and draping simulations and experiments showing the general feasibility.

For the demonstrations on a full scale blade, a novel CNC machine tool is being built up at Fraunhofer IWES, for which the requirements have been shown. Using that machine tool and

combining the automation approaches in this paper with other approaches worked upon within the research project BladeMaker, total cost savings of 8-14% can be expected, with more savings to follow when the benefits of industrialization filter back into the rotor blade design.

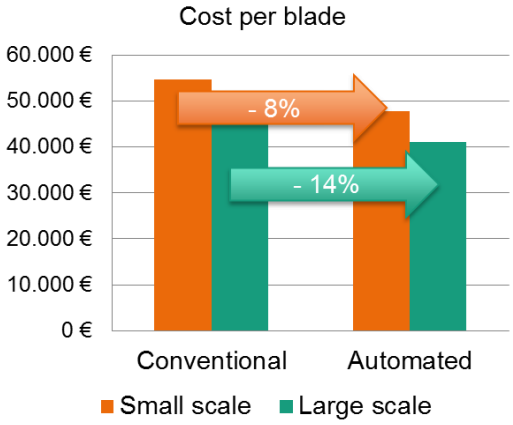

Figure 19: Cost savings due to industrialized BladeMaker processes

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