MANUFACTURE OF A ROTOR BLADE PITCH HORN USING NOVEL BINDER YARN FABRICS

F. Weiland[1], C. Weimer[1], C. V. Katsiropoulos[2], S. G. Pantelakis[2], M. Asareh[3], D. D. R. Cartié[3], A. R. Mills[3], A. A. Skordos[3], L. Dufort[4], P. De Luca[4], A. K. Pickett[5]
[1]Eurocopter Deutschland GmbH; Laboratories, Materials and Processes LMP,
Industriestrasse 4-6, 86607 Donauwörth, Germany; christian.weimer@eurocopter.com
[2]Laboratory of Technology and Strength of Materials,
Department of Mechanical Engineering and Aeronautics, University of Patras,
Rion, 26500, Greece; xkatsiro@mech.upatras.gr
[3]Composites Centre, Cranfield University, MK43 0AL, UK;
a.a.skordos@cranfield.ac.uk
[4]ESI Group, 99 Rue des Solets, 94513 Rungis Cedex, France;
Patrick.de.Luca@esi-group.com
[5]ESI GmbH, Mergenthalerallee 15-21, 65760 Eschborn, Germany;
tony.pickett@arcor.de

SUMMARY

This paper describes the development of a preform manufacturing process for a rotor blade pitch horn using a novel material generation of pre-bindered carbon fiber yarns. The layer design of the part was optimized and an automatable manufacturing chain was developed and validated. Simulation of the draping and infusion process supported and optimized the process. Cost modelling was conducted.

Keywords: preforming, rotor blade, Binder Yarn, binder activation, processing, simulation, cost modelling

INTRODUCTION

Carbon fiber composites are widely used in aircraft applications today due to their superior weight related mechanical properties. High manufacturing costs of CFRP compared to aluminium parts mainly depend on the market prices of carbon fibers and the low degree of automation in the manufacturing process.

Today, manufacture of advanced composites uses either layers of pre-impregnated plies (Prepregs) to form a laminate, or resin infusion of dry textiles (Liquid Composite Molding – LCM). Prepreg composites have superior mechanical properties due to the use of toughened resin, but suffer from high material costs, complex manufacturing and limited shelf life. LCM technologies can overcome many limitations and the manufacturing of dry fiber preforms offers high potential for automation, which can lead to significantly reduced part costs [1].

The overall project aim of the European project PreCarBi is the development of new materials and technologies for carbon composites to combine cost effectiveness with high part quality via the use of binder yarn fabrics [2]. The present paper focuses on the applicability of Binder Yarn technologies in the context of a rotor blade pitch horn manufacturing.

THE ROTOR BLADE PITCH HORN

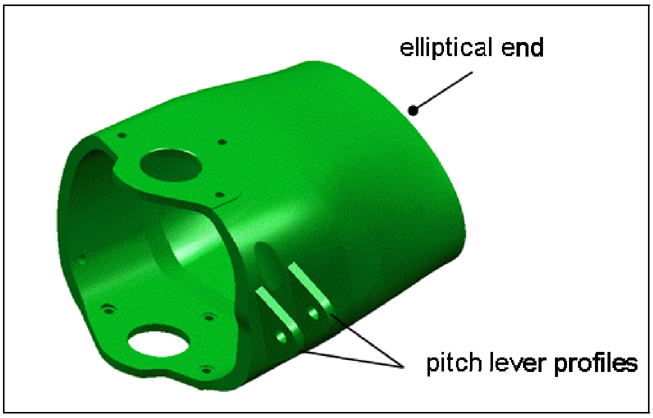

Fig. 1: Pitch Horn (Eurocopter Deutschland GmbH)

The pitch horn (Fig. 1) represents the root section of the main rotor. In order to carry both torsional loads into the blade itself and to provide sufficient ring stiffness, it consists of carbon fabric with ±45° fiber direction and unidirectional fiber bands arranged in circumferential direction. Profiles are attached to the part, which induce the torsion loads from the pitch levers. In this area the wall thickness has a maximum of 15mm. Within this project redesign needed to be undertaken in the area of highest part complexity. The pitch horn has overall dimensions of around 400mm length and an inner diameter between 80 and 150mm. The parts end facing the rotor mast has a quasi-rectangular shape whereas the opposite end is of elliptical shape.

Prepreg Design and Manufacture

The prepreg design as realized in today's production consists of ±45° woven fabric alternating with circumferentially arranged UD-Bands. The "U"-shaped profiles are embedded in the layers during the lay-up process using an epoxy filler material. The manufacturing process includes a high degree of manual work. Two pitch horn halves are built up in separate negative molds, in which every layer is manually placed, trimmed to final dimensions and compacted under vacuum.

Design Adaptation to Preforming Requirements

In order to enable the application of automated preforming process elements the layer sequence required adaptation. The redesign allowed automated plying and handling by packaging fabrics of the same type. Also a new concept for the manufacture of the U-profiles was developed. A simplification of both processes was achieved and significant cycle time reduction is expected.

EVALUATION OF THE PROCESS WINDOW FOR BINDER YARN FABRICS

In LCM, resin is infused into dry textile preforms within a mould. The two predominant techniques for producing preforms are sewing (or stitching) and use of polymer binders. Low melting thermoplastics and uncatalysed thermosets are the main binder categories [3], although blends are also an option. Binders are either sprayed or sprinkled onto the preform or are imbedded between fabrics as a veil [3].

A novel approach being studied within the PreCarBi project is the addition of an epoxy based binder at the carbon tow manufacturing stage. Binder coated carbon fibre (BCCF) tows are not tacky at room temperature and therefore can be used in conventional textile machinery. Upon application of heat and pressure, the BCCF tows become tacky and when cooled down under the same compaction pressure they become rigid. This process is called activation.

Activation process parameters (temperature and pressure) were investigated for a number of heating techniques, which included ultrasonic, microwave, laser, conventional ovens and heated vacuum tables [4]. A double lap shear (DLS) test (unidirectional tow pullout) was used to measure the binder adhesion strength after activation in order to investigate various activation systems and parameters.

Heated vacuum table and ventilated electric oven were selected as the activation techniques for studying variation of activation temperature and pressure respectively. Adhesion strength data obtained for specimens activated within a ventilated electric oven under activation pressure of 0.01 bar for 30 min. are shown in Fig. 2(a). The data suggests that for activation temperatures of 110°C to 180°C the strength of the binder adhesion remains around 1.00 MPa. At temperatures below 110°C lower adhesion levels are achieved as the binder is insufficiently activated. At 190°C and beyond, the binder starts to oxidise and hence looses its adhering properties.

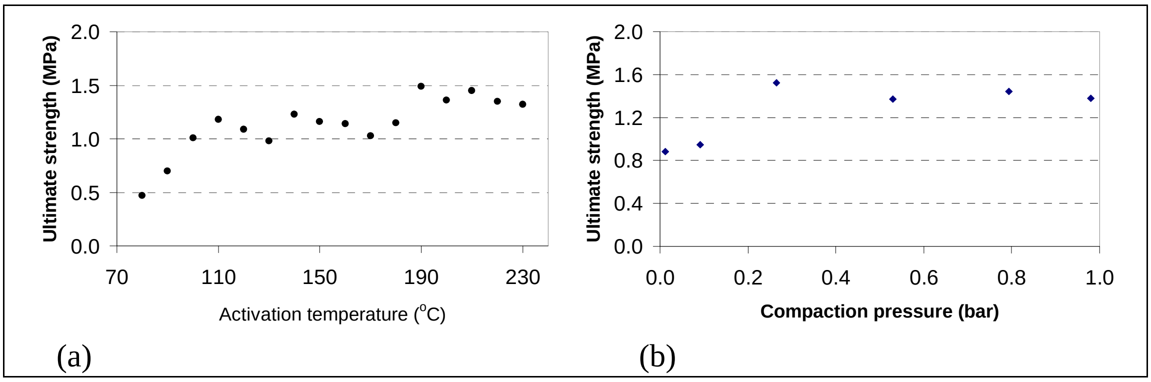

Fig. 2 (a) Evaluation of activation temperature, specimen made in electric oven
(b) Evaluation of activation pressure, specimen made using heated vacuum table

Fig. 2(b) shows adhesion strength data for specimens activated at 140°C for 30 min. using a heated vacuum table. The results show that a minimum compaction pressure of 0.25bar is required for preform adhesion strength of 1.40MPa, although increasing the compaction pressure does not improve the binder adhesion properties.

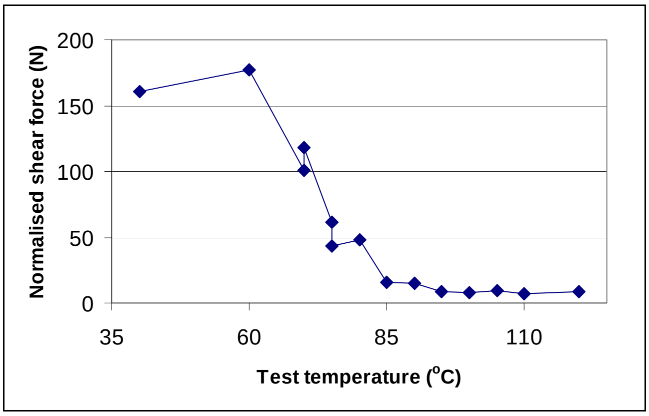

Fig. 3: Picture frame test results for heated vacuum table specimen

A series of picture frame tests was carried out to investigate shear resistance of BCCF preforms at various temperatures within an environmental chamber. Fig. 3 illustrates mean values of normalised shear force between 0 to 40mm crosshead displacement (equivalent to shear angles ~ 0^{o} to 25^{o}C). It shows that re-forming the preform should take place at temperatures higher than 95^{o}C in order to minimise the forming load and the preform damage.

PreCarBi-Fabrics Used For The Pitch Horn

For the layers with a fiber direction of ±45° NCF was chosen (274GSM, Tricot-Loop stitch) consisting of 50% preimpregnated carbon fiber tows alternating with untreated 12k-tows. In order to keep the binder fraction low also the unidirectional layers of the part were prepared using a woven UD-band with 50% Binder Yarn fraction (268GSM). Within the PreCarBi project a whole material family of woven fabrics, Non Crimp Fabrics (NCF) and unidirectional bands has been developed. Every fabric type is based on the same 12k carbon fiber tow.

PREFORM MANUFACTURING PROCESS CHAIN

The focus of the development of the preforming process chain was to increase the degree of automation, to decrease the cycle time and to reduce the number of process steps and material costs applying the novel bindered materials. The preforming process basically consists of in-plane manufacturing of four Intermediate Preforms (IP's), to pairs of which are draped and activated on a male mould to form a Sub-Preform representing one half of the Pitch Horn Final Preform. Subsequently the assembly of the Sub-Preforms in the infusion tool is carried out and the infusion process is conducted (Fig. 4).

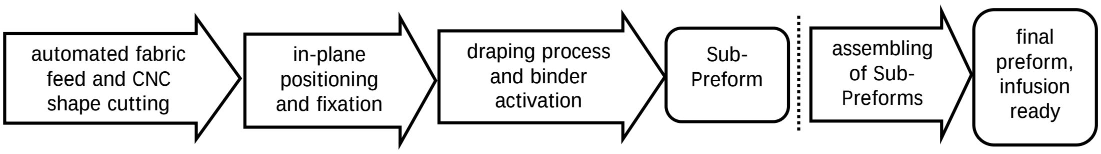

Fig. 4: Preforming Process Chain

Automated In-line Stitching and Cutting Operation

Stitching operations can produce a local fixation of multiple layers with defined seam patterns allowing maximal, still controllable, drapability [5]. Non Crimp Fabrics (NCF) are laid-up strainlessly by an automated and synchronously driven lay-up module to feed the 2-axis stitching portal, which applies a double locked stitch. Based on CAD-data the sewing operation is carried out automatically both stabilizing the edges of the fabric patterns and fixing fabric layers to each other. A conveyor-belt system transports the material to the CNC-Cutter, where the final shape of the patterns is produced (Fig. 5). Results of this continuous, fully automated and reproducible part of the process chain are shaped, multi-layer fabric patterns of high material quality and handling stability, called Tailored Reinforcements (TR's).

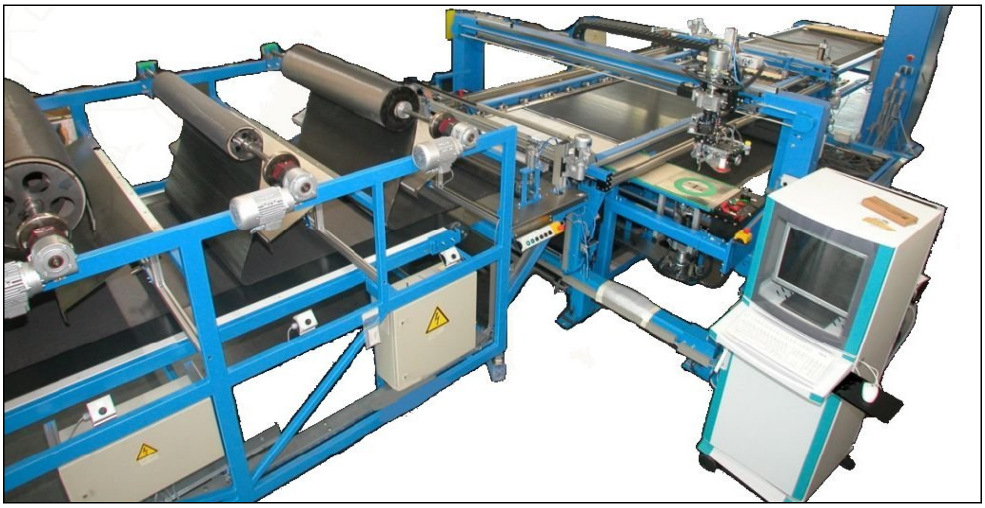

Fig. 5: In-line lay-up and 2-D-stitching modules (Eurocopter Deutschland GmbH)

Draping and Binder Activation

One Sub-Preform (= Pitch Horn half) is manufactured from two Intermediate Preforms (IP's) by conducting a draping and binder activation process. Forming the planar IP’s to a complex shaped geometry induces the risk of generating fiber misalignment and high shear angles within the preform. An approach minimizing this effect was found using simulation as described latter in this paper. After the draping step vacuum is applied and binder activation is conducted following the evaluated process window [4]. Successful trials have been performed automating this step with a heated deep-drawing machine. The resulting Sub-Preforms show a high degree of stiffness and shape stability making them easy to handle during assembly and infusion.

Assembly of Sub-Preforms and Infusion

Investigations on two different infusion strategies have been undertaken. Both strategies are based on a vacuum infusion in a female tool. A selection between an infusion along the part length (perpendicular to UD-fiber direction) or in circumferential direction was required. Focal points for the infusion strategy were porosity requirements, cycle time and reproducibility of the process. In-plane infusion test with a lay-up sequence and dimensions of the final part have been undertaken. The infusion along the part length delivered best porosity results in agreement with the simulation results.

PROCESS SIMULATION AND OPTIMISATION

Draping

The draping of the pitch horn component was simulated using the kinematic draping code PAM-QUIKFORM. This type of model is based on the assumption of inextensible fibre tows and considers deformation in the form of shear for woven and non-crimp fabrics [6]. The code allows definition of a drape starting point and a draping direction, which together with the geometry description suffice to obtain a unique solution to the problem. Recent developments have led to the incorporation of some additional processing strategies, such as draping along the bias direction. Fig. 6 illustrates the results of process simulation for the draping of ±45 layers on one half of the pitch horn tool for the cases of a conventional process design using the apex of the geometry as a drape start and of a bias draping curve aligned to the axis of the component. It can be observed that maximum shear reaches values over 30° in both process designs. In conventional draping the area around the apex is unsheared with high shear occurring at the top side of the quasi-rectangular section part and the sides of the elliptical section part of the component. In curve draping the top of the component is largely unsheared, with high shear occurring on the sides of the quasi-rectangular section part.

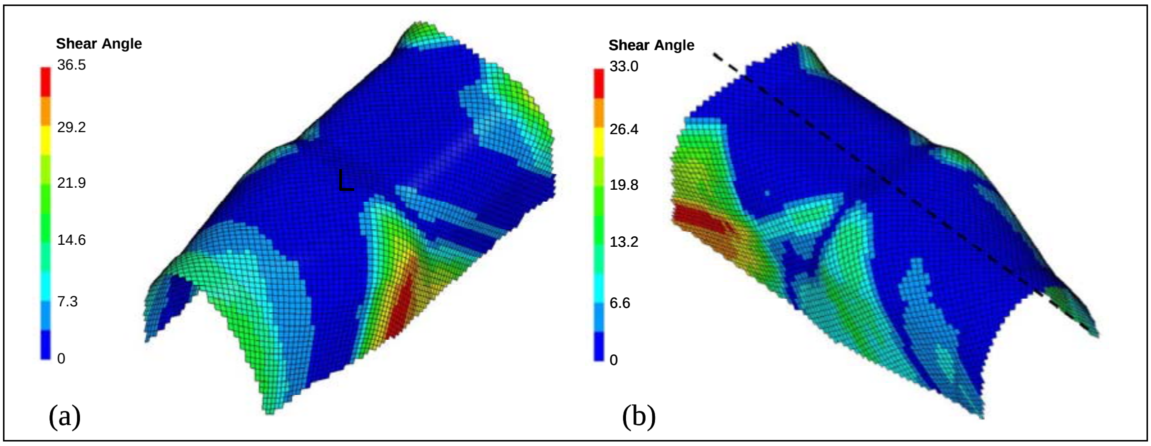

Fig. 6: Shear angle distribution in the pitch horn using (a) conventional draping starting from the apex and (b) a bias curve

A genetic algorithm originally described in [7] was utilised to optimise the draping process. The objective of the optimisation was to minimise the maximum shear occurring over the surface of the draping component, whilst the parameters of the design were the position of the drape start in conventional draping and the position and orientation of the bias curve in curve draping. Fig. 7 illustrates the results of optimisation. It can be observed that the optimisation induced reduces maximum shear by more than 10°. In conventional draping the optimisation code moves the drape start away from the apex of the geometry into the quasi-rectangular section part of the component. This results in shifting of the high shear zone to the top of the elliptical section part. In bias draping the genetic algorithm obtains a solution which is radically different for the original process design. The bias curve is aligned in the normal to the axis direction and lies across the boundary between the elliptical and the quasi-rectangular section of the pitch horn. Compared to the initial process design (Fig. 6b) the high shear region shifts to the top of the geometry.

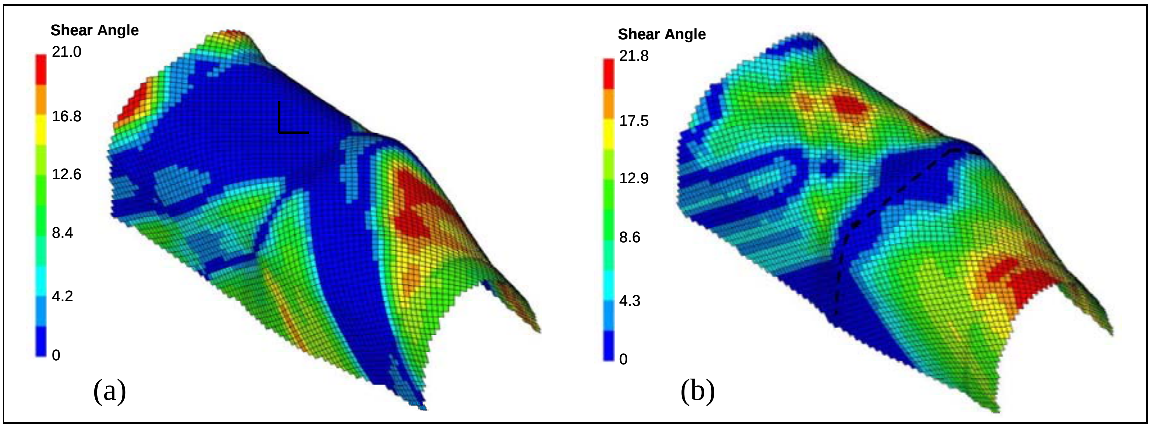

Fig. 7: Shear angle distribution in the optimised pitch horn draping using (a) conventional draping starting and (b) a bias curve

Infusion

This section describes preliminary works conducted in the field of the numerical simulation of the filling of the rotor blade pitch horn. A finite element software is used [8]. The part was divided into zones, to each of which a given thickness and a given permeability are assigned. Surface elements have been used to get preliminary information on the resin flow front evolution. As mentioned before, two infusion strategies were investigated. The filling time carpet plot shows that the injection strategy using injection lines along the part length (Fig. 8, right) represents a potentially higher risk than the injection from one end of the part (Fig. 8, left) due to the fact that the flow front does not remain straight. Finally, a simulation using tetrahedrons elements was run to get a first idea of the effects of the higher permeability of the UD compared to the NCF. Fig. 9 shows a snapshot of the filling with a zoom in the zone of larger thickness.

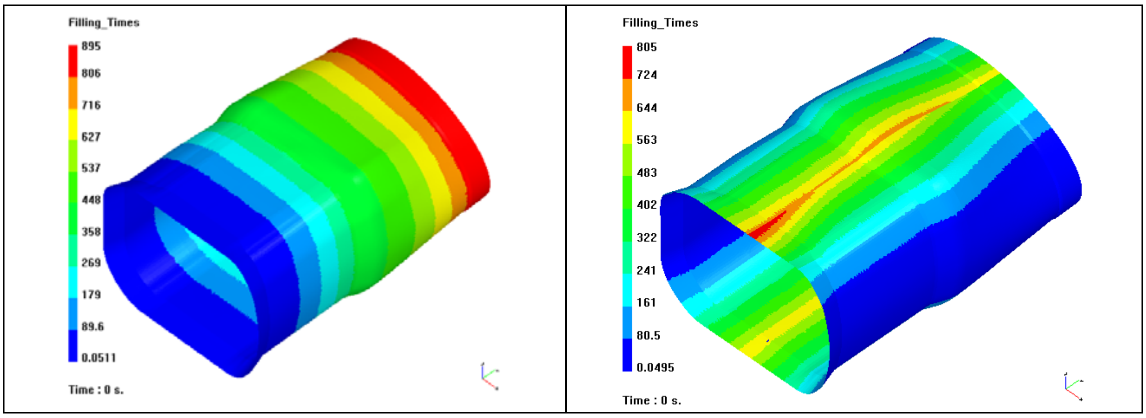

Fig. 8: Two different infusion strategies and associated filling times contour

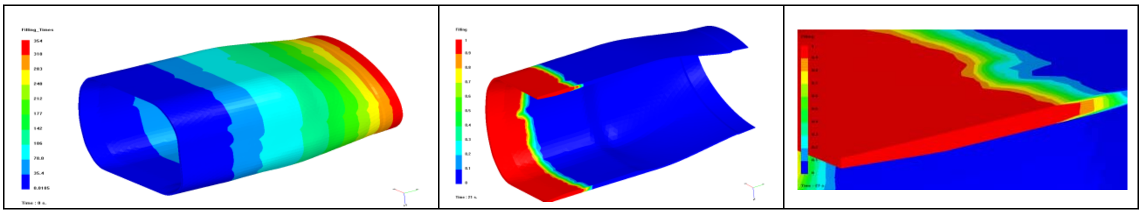

Fig. 9: 3D simulation with filling times contour and intermediate filling with details

Future work in the field of infusion simulation will account for the effects of draping and of the resulting preform shearing onto the permeability variations over the perform surface. Studies will be conducted to scrutinize the effects of the preform compression in the radii, which are thickness variations as well as the through-the-thickness permeability gradient.

COST ANALYSIS

Cost Model

With the aim of manufacturing a composite rotor blade pitch horn of a specified quality at minimum cost using an LCM process along with the Binder Yarn based production technology, a cost analysis is performed. The analysis is based on the principles of Activity Based Costing methodology and is fully parametric, as far as the process parameters are concerned.

Unlike comparative techniques, process oriented cost models are adaptable to new processes, enable identification and quantification of part cost drivers, and may be used in order to decide improvements in manufacturing processes [9]. In the present approach, for the cost analysis the Activity Based Costing (ABC) methodology is used; it is a costing method that derives the product's cost as a sum of the costs of all activities involved to make a product. These activities may refer to a single process or to a production line. An overview of the ABC method is shown in Fig. 10.

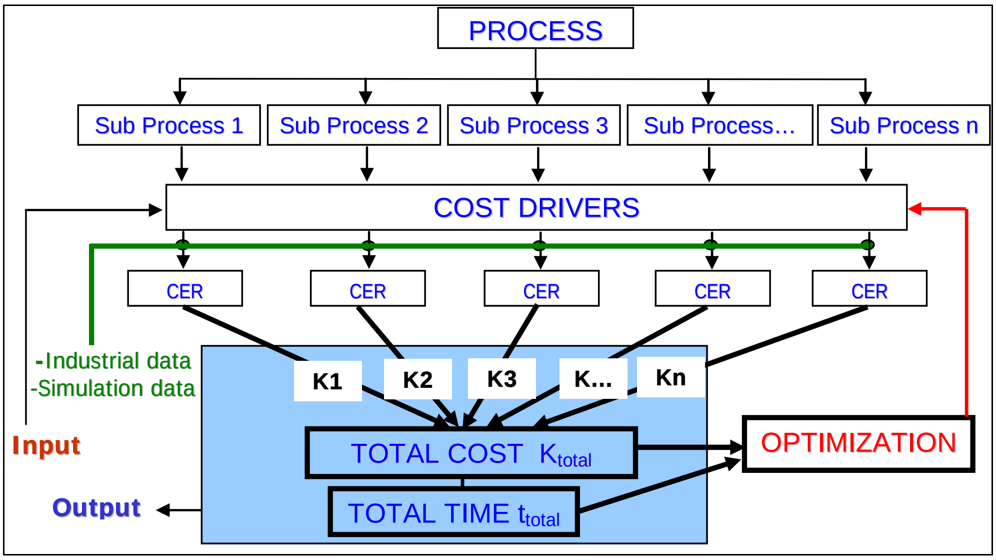

Fig. 10: ABC concept loop [10]

In general the ABC method consists of the following four steps:

a) Identification of the activities or transactions that cause costs during the product development (sub-processes and main processes).
b) Identification of the cost drivers to each sub-process.
c) Assignment of costs to each sub-process via the creation of the Cost Estimation Relationships (CERs).
d) Summation of the costs of sub-processes that occur to 'make' a product.

Cost Analysis And Results

Using industrial cost and process data provided by the manufacturer, the LCM process was divided into sub-processes. Afterwards, the basic 'Cost drivers' were determined for each sub-process; e.g. for the cost drivers related to the part are given in Table 1.

Table 1: Part related cost drivers

part perimeter
thickness
external surface
weight of final part
number of preform plies
number of holes
composite mass density
complexity

After the process' 'cost drivers' have been identified, mathematical functions that express their relation to the consumption of the resources, the Cost Estimation Relationships (CERs), could be formulated. These functions were extracted from the analysis of statistical, experimental or empirical data.

A CER example is the total cost of the sewing/cutting process. It is given by the function:

$$K_{pr-cut} = t_{pr-cut} \cdot \kappa_w = (0.15 \cdot PAP \cdot cmp) \cdot \kappa_w \quad (1)$$

where $K_{pr\text{-}cut}$, $t_{pr\text{-}cut}$, κ_w, PAP, cmp stand for the total cost and time of the sewing/cutting process, the cost of the worker per hour, the perimeter of the part and the complexity of the part, respectively. Equation (1) was derived by means of regression analysis of the process data supplied by the industry. The total cost of the component is calculated as the sum of costs referring to the various sub-processes. It is worth noticing that, although the main target of the present work is to estimate the recurring costs, the depreciation cost of the machines used, K_{cap}, is taken into account at the final step of the estimation relating the production rate (volume) with the initial investment for the equipment as well as the maintenance costs. Furthermore, it has to be mentioned that no learning curve effects are taken into account since the examined process is under development and thus in a very early stage for accounting of a learning curve.
Using the CER's, each parameter’s contribution to the total part cost was evaluated. Additionally, the major cost-and time-consuming sub-steps of the production process were investigated in order to identify and improve the critical sub-processes and their respective process parameters. Those results show, that, when comparing to the ‘conventional’ manufacturing process, the new manufacturing concept leads to a cost saving of more than 30% compared to the conventional method, thus pronouncing an essential advantage from the cost viewpoint.

CONCLUSION

The application of novel Binder Yarn technologies in the context of the preform manufacturing for a rotor blade pitch horn has been successfully demonstrated. Processing of the Bindered Carbon Fabrics was conducted using automated production elements. Stitching technology was combined with bindered materials to make use of each technologies respective advantage for the manufacture of a preform. The simulation of draping and infusion served to both optimize part quality and to reduce process development time. Major cost drivers could be identified in order to focus the improvement efforts and cost savings were quantified.

Current work is concentrating on further automating especially handling steps in the production process. Infusion of the Final Preform using a resin system designed for the combination with the Binder Yarn fabrics is planned and mechanical properties for comparison to the Prepreg part are to be evaluated. In order to further improve the use of simulation, comparisons between quantified experimental and simulation results will be made.

ACKNOWLEDGEMENTS

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