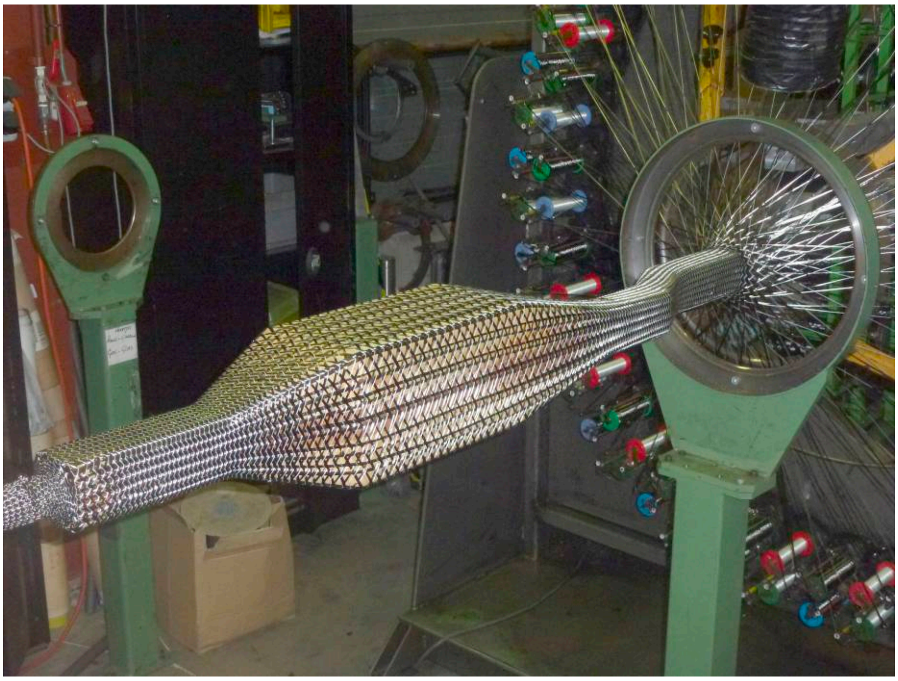
Nationaal Lucht- en Ruimtevaartlaboratorium

National Aerospace Laboratory NLR

Executive summary

Innovating the overbraiding design process to optimise the development of composite aircraft structural components



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Knowledge area(s)
Computational Mechanics and Simulation Technology
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Descriptor(s)
overbraiding
process automation
knowledge based engineering

Problem area
The composite materials market is constantly expanding. Because of their stiffness, strength, light weight, and high corrosion resistance properties, advanced fibre materials are recognised as being suitable for an increasingly wider range of applications. The automotive and the aerospace industries already use composite materials on a large scale.

The Dutch small and medium enterprise (SME) Eurocarbon B.V designs and manufactures composite structural components, such as braided crash cones for cars and landing gear components and wing spars for aircraft. Eurocarbon applies *overbraiding* for the manufacturing of composite material dry pre-forms of fiber-reinforced products. The overbraiding process comprises the iterative braiding of dry fiber layers over a mandrel until sufficient material is applied. Eurocarbon wants to improve its design process and to reduce costs.

This report is based on a presentation held at the Royal Aeronautical Society 3rd Aircraft Structural Design Conference, Delft, The Netherlands, October 9-11, 2012.

The manufacturing of overbraided products typically involves labour-intensive and costly "pre-production" steps. Several trial overbraiding runs and inspections of the trial results are required before the applicable overbraiding machine "program" is established and the desired braid angles and degree of coverage of braid material over the mandrel is obtained, and hence the actual production can start. The trial runs and inspections involve costly man and machine hours and materials. Major cost reductions can be achieved by automating the pre-production steps of the production process, especially if the number of products is small.

Description of work
In the context of the OBODAS research project, partly funded by AgentschapNL, NLR and Eurocarbon successfully collaborated in investigating and developing an innovative solution in which knowledge of the overbraiding process is translated into an innovative proof-of-concept tool. The tool applies a simulation of the overbraiding manufacturing process and optimises the process against specified design parameters. When the required overbraiding result is achieved, the applied simulated machine program is translated into an applicable program for the target braiding machine. Knowledge based engineering technology has been applied to turn this tool into a practical and user-friendly proof-of-concept industrial tool that provides the automation of the overbraiding pre-production steps in an attractive and efficient way.

Results and conclusions
The paper contained in this report describes the overbraiding pre-production support tool. In the context of the OBODAS project, the tool was successfully evaluated in close collaboration with the industrial partner Eurocarbon, who enthusiastically embraced the tool. The tool has proven to reduce the need for trial-and-error as yet practised in the overbraiding of complex-shaped structural components. As such, it supports the industry in achieving the desired time, cost and weight reduction.

Applicability
The solution described in this paper helps industries to efficiently develop high-quality light-weight complex-shaped hollow composite components for use in state-of-the-art and next-generation products. Applications are expected in the automotive and aerospace industries as well as in other applications such as healthcare (e.g., prostheses) and sports equipment (e.g., carbon-fibre bikes).

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Summary

Aircraft manufacturers such as Airbus aim to shorten the development cycle and reduce costs while building increasingly better aircraft. As a result their supply chain is challenged to supply aircraft components in reduced time and at lower costs. To be more competitive while ensuring high-quality products, the Dutch aircraft industries as suppliers to Airbus respond to these challenges by continuously enhancing and optimising the engineering and production processes. The Dutch small and medium enterprise (SME) Eurocarbon B.V faces the same challenges as supplier to the Dutch aircraft industry. Eurocarbon designs and manufactures composite structural components, such as parts of landing gears, struts, and shafts. It applies circular braiding, or overbraiding, for the manufacturing of composite material dry pre-forms of fiber-reinforced products. The overbraiding process comprises the iterative braiding of dry fiber layers over a mandrel until sufficient material is applied.

The overbraiding process involves labour-intensive and costly “pre-production” steps. Several trial overbraiding runs and inspections of the trial results are required before the applicable overbraiding machine “program” is established and the desired braid angles and degree of coverage of braid material over the mandrel is obtained, and hence the actual production can start. The trial runs and inspections involve costly man and machine hours and materials. Major cost reductions can be achieved by automating the pre-production steps of the production process, especially if the number of products is small.

In the context of the OBODAS research project, NLR and Eurocarbon have successfully collaborated in investigating and developing an innovative solution in which knowledge of the overbraiding process is translated into an innovative proof-of-concept tool. The tool applies a simulation of the overbraiding manufacturing process and optimises the process against specified design parameters. When the required overbraiding result is achieved, the applied simulated machine program is translated into an applicable program for the target braiding machine. Knowledge based engineering technology has been applied to turn this tool into a practical and user-friendly proof-of-concept industrial tool that provides the automation of the overbraiding pre-production steps in an attractive and efficient way.

The paper contained in this report describes the overbraiding pre-production support tool. The tool was successfully evaluated in close collaboration with the industrial partner Eurocarbon, who enthusiastically embraced the tool. The tool has proven to reduce the need for trial-and-error as yet practised in the overbraiding of complex-shaped structural components. As such, it supports the aerospace industry in achieving the desired cost and weight reduction.

Contents

3rd Aircraft Structural Design Conference, Delft, the Netherlands, 9-11 October 2012

Innovating the overbraiding design process to optimise the development of composite aircraft structural components

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Abstract

Aircraft manufacturers and their supply-chain are interested in composites and the efficient and automated production of composite components as this can lead to more complex-shaped and light-weight aircraft components in reduced time and at lower costs. In this paper we describe a successful example of the translation of knowledge of the *overbraiding* process into an innovative, efficient, practical and user-friendly industrial overbraiding support tool. Overbraiding, or circular braiding, is a process for the manufacturing of dry fiber preforms used for the production of carbon fiber-reinforced polymers. The overbraiding support tool described in this paper helps aerospace industries to develop high-quality light-weight complex-shaped hollow composite components for use in next-generation civil aircraft more efficiently. The tool applies simulation of the overbraiding process, optimises the process for specific design requirements, and supports the creation of applicable overbraiding machine instructions. Although being sophisticated internally, the tool's appearance and mode of operation is tailored to easy and efficient application by the overbraiding expert on the factory floor. The tool reduces the need for trial and error as currently practised in the overbraiding of complex-shaped components. As a result, the tool helps the aerospace industries to achieve time, cost and weight reduction in the production of composite components, and hence contributes to the aircraft manufacturers' aim to shorten the development cycle and reduce costs while building increasingly better aircraft.

Keywords: reduce time to market, manufacturing with novel materials, manufacturing CRFP, composite aircraft structural components, overbraiding, process automation, knowledge based engineering

1. Introduction and overview

Aircraft manufacturers aim to shorten the development cycle and reduce costs while building increasingly better aircraft. As a result their supply chain is challenged to develop and supply aircraft components in reduced time and at lower costs as well. In the same time, the use of composite materials is gradually increasing. Aircraft manufacturers and their supply chains are interested in the use of composite components in both secondary and primary, ever more complex aircraft structures, mainly because of their potential for weight reduction. Manufacturing composite structures however is a labour-intensive and costly production process. Therefore, aircraft component suppliers are also very interested in increasing efficiency and decreasing costs of the production processes of high-quality composite components. One such process is the overbraiding of dry fiber preforms used for the production of light-weight complex-shaped hollow composite structural components.

To be more competitive while ensuring high-quality products, the aircraft industries as suppliers to aircraft manufacturers such as Airbus respond to the challenges of reducing time and costs by continuously enhancing and optimising the engineering and production processes. For example, in particular in the area of composite structural components, the Dutch Small to Medium-sized enterprise Eurocarbon B.V as supplier to amongst others the Dutch aircraft industry faces the same challenges. Eurocarbon manufactures composite structural components, such as parts of landing gears, propeller blades, struts, and shafts. It applies the overbraiding production process for the manufacturing of dry preforms for these fiber-reinforced products. Overbraiding comprises the iterative braiding of dry fiber layers over a mandrel until sufficient material is deposited. Resin transfer moulding is subsequently applied to impregnate the dry fiber preforms in order to produce the composite components.

The manufacturing of overbraided preforms typically involves a labour-intensive and costly machine set-up procedure involving trial and error overbraiding runs to determine the applicable overbraiding machine instructions – a computer numerical control (CNC) program – in order to produce braids with particular characteristics. Major cost reductions can be achieved by automating this preproduction step, especially if the number of equal components to be produced is small.

Automation of the overbraiding machine set-up was the topic of a research project carried out collaboratively by the National Aerospace Laboratory NLR, Eurocarbon, and the Production Technology group of the Faculty of Engineering Technology of the University of Twente. The prime objective of the project was to improve the overbraiding process used in the manufacturing of complex shaped composite hollow structural components, in order to improve the resulting products and to reduce time and costs of manufacturing the products. The participation of Eurocarbon was prerequisite to ensure industrial applicability in the medium and long term. Eurocarbon owns several overbraiding machines and has many years' experience in the manual transformation of 3D design information into overbraiding process parameters.

In the project, knowledge of the overbraiding process was translated into the proof of concept of an innovative and efficient overbraiding preproduction support tool that can easily be applied in setting up the overbraiding machine. Given the geometry of a mandrel, the tool applies a simulation of the overbraiding manufacturing process and optimises the process for a specified braiding result. When the required result is achieved, the simulated overbraiding procedure is translated into instructions for the target overbraiding machine so that the actual braid can be produced. The research project focussed on the simulation as well as the development of facilities for the preparation of the simulation inputs and the inspection and deployment of the simulation results, to enable practical and efficient application of the simulated overbraiding process and its results in an industrial environment. Details concerning the simulation and the application were settled in close collaboration with the industrial partner Eurocarbon.

Knowledge based engineering (KBE) technology has been applied to provide the simulation capability in the form of a practical and user-friendly industrial tool that supports the automation of setting up an overbraiding machine in an efficient and accessible way. KBE aims to capitalise engineering process and product knowledge by capturing engineering knowledge, translating the knowledge into tools that support or even automate the engineering process, and applying the tools efficiently in the engineering process (ref. [1], [2]). KBE has already proven its value in industrial settings, e.g., ref. [3].

The prime interest of Eurocarbon in the project was to experience the possibilities and advantages of application of both simulation and KBE technology for the automatic derivation of overbraiding machine parameters in order to produce a preform of a product that meets specified design requirements.

The proof-of-concept tool was successfully evaluated in close collaboration with Eurocarbon, who enthusiastically embraced the solution. The tool has proven to reduce the need for trial and error as yet practised in the overbraiding process. As such, it supports Eurocarbon in achieving the desired cost and weight reduction.

In this paper we describe the tool and its application, thereby focusing on the KBE aspects. In section 2, we describe the overbraiding process and present the technical challenge that lead to the results described in this paper. In section 3, we present the solution explored in the research project to face the technical challenge. In section 4, we describe the application of the solution in terms of validation and evaluation of the proof-of-concept tool developed in the project. We summarise, conclude, and provide directions for possible future work in section 5.

2. Context: the Overbraiding Process and its Challenges

Circular braiding, or overbraiding, is a process for the manufacturing of dry fiber preforms used for the production of composite components. The process is used in the production of biaxial and triaxial braids. It comprises one or more overbraiding runs of dry fiber layers over a mandrel until sufficient material is applied. Overbraiding is suited for automated series production of preforms using circular horn-gear braiding machines, which are commonly used in the textile industry (e.g., ref. [4]). Figure 1 shows an example of such an overbraiding machine at Eurocarbon.

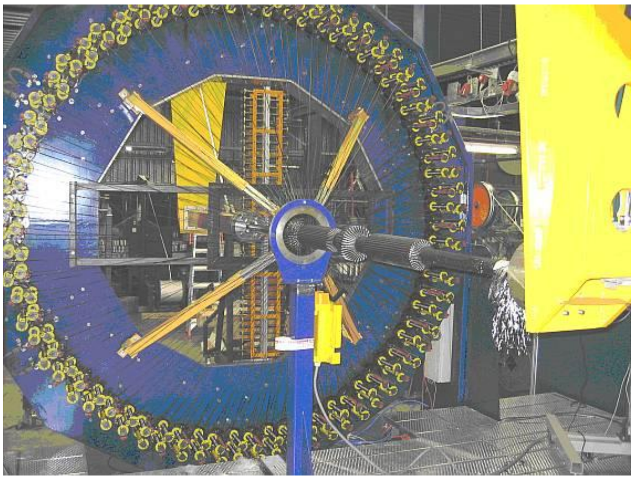


Figure 1. One of Eurocarbon's overbraiding machines

An overbraiding machine runs carriers around a mandrel, which is located in the center of the carrier track ring. Half of the carriers are running clockwise where the other carriers run counter clockwise. The path of a clockwise carrier is crossing the path of a counter-clockwise carrier every time it meets one. From every carrier a tensioned dry tow is connected to the mandrel. The result is a smooth bi-axial braid pattern around the mandrel, made from continuous fibers by moving the mandrel through the machine. Triaxial braids are obtained by incorporating longitudinal fibers to the braid. The braiding of a triaxial braid is shown in Figure 2.

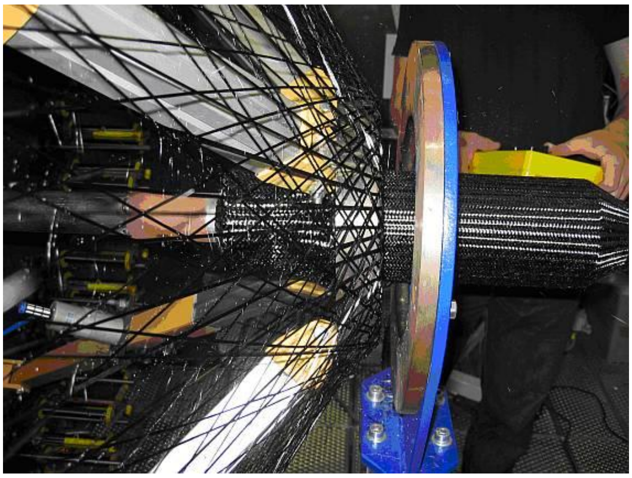


Figure 2. Braiding a triaxial braid

Both biaxial and triaxial braid types can be applied in the production of complex shaped double curved hollow components. An example of a biaxial braid is shown in Figure 3.

Figure 3. The preform of a complex-shaped hollow component as an example of a biaxial braid

After overbraiding the dry fibers are impregnated with resin by resin transfer moulding (RTM) or vacuum infusion. After curing and removal of the mandrel, a semi-finished carbon-fiber-reinforced polymer (CFRP) product is manufactured. An example overbraided and RTM-impregnated component is shown in Figure 4.

Overbraiding machines in general can be programmed in terms of CNC instructions. These instructions apply to the speed of the mandrel relative to the traversal position of the mandrel in the machine (i.e., traversal speed) and the rotation speed of the carriers around the mandrel (i.e., braiding speed). Some machines also allow for the mandrel to be positioned in varying angles during its run through the overbraiding machine. The number of carriers is subject to the chosen machine and cannot be changed during the overbraiding process. The same limitation counts for the chosen tow and the braid type. Thickness variations of independent layers and coverage ratios are subject to changing section circumferences. Fiber orientations and coverage ratios of the braided material on the various sections of the mandrel largely depend on the geometry of the mandrel - in particular, on the angle between the tow and the surface the tow is applied to -, the used traversal and braiding speeds at the various sections, the chosen tow, the braid type, and several other factors. Engineering of proper RTM tooling considering fiber volume fractions related to material allowables becomes problematical when the complexity of the geometry increases.

Figure 4. Fragment of an example overbraided and RTM-impregnated hollow cylinder

As a result, the manufacturing of an overbraided product generally involves a labour-intensive and costly preproduction step of determining an overbraiding machine set up. Each time a new mandrel geometry is used (or a new braiding material is chosen, another configuration of the overbraiding machine is used, etc.), an applicable overbraiding machine CNC program needs to be developed to be able to produce the required braid. Although years of experience in producing braided preforms certainly helps, developing a suitable CNC program still involves a high degree of trial and error. Several trial overbraiding runs and inspections of the trial results are in general required before a good CNC program can be established and the actual production of the component that meets the specified demands can start. The trial runs and inspections involve costly man and machine hours and materials. Major cost reductions can be achieved by automating the machine set up.

The main technical challenge of the research project comprises automation of the set-up of an applicable CNC program for the overbraiding machine. Ideally, the program can be derived from the required geometry, characteristics of the foreseen overbraided and by RTM technology impregnated end product (i.e., design parameters), and precise specifications of the braiding tooling and material. This ideal solution involves a large multi-disciplinary effort, including not only overbraiding simulation and KBE, but also optimisation and other disciplines such as finite element modeling (FEM). The research project focused on a practical solution that is an initial step towards the ideal solution. The step comprises the semi-automated generation of an applicable overbraiding machine program from a mandrel geometry, required characteristics of the resulting braid, and information about, among other things, the braiding material and the overbraiding machine. A solution to support the first step has been developed and validated in the research project in terms of an efficient and customer tailored proof of concept tool. This tool is presented in the next section.

3. Solution

The answer to the technical challenge described at the end of the previous section comprises a solution in terms of a proof of concept overbraiding preproduction support tool that supports the generation of an applicable overbraiding machine program for a given overbraiding case. The tool is based on a combination of knowledge about the overbraiding process, simulation of the overbraiding, and KBE technology. As indicated in the introduction, the tool basically simulates the overbraiding of a specified mandrel and optimises the process for specified braiding results. When the required result is obtained, the applied simulated overbraiding procedure (i.e., the CNC program used for the simulated overbraiding machine) is translated into a CNC program for the target overbraiding machine. In the research project the tool has proven to reduce the need for trial and error as yet practised in the overbraiding of complex-shaped structural components.

The simulation of the overbraiding process as applied by the tool is yet based on kinematic modelling only, and is described in more detail in refs. [5] and [6]. Related work on overbraiding modeling and simulation is described in refs. [7], [8], and [9]. In the remainder of this paper, we focus on the KBE aspects.

The KBE aspects are reflected by the tool being the result of translating detailed knowledge of the overbraiding process and its products into an efficient, practical, user-friendly, and customer-tailored proof-of-concept industrial tool. The tool is targeted for easy operation on the 'factory floor', to derive from a minimum set of inputs the overbraiding machine program for braiding a specified mandrel.

The tool comprises several packages, including an overbraiding simulation program, databases for braiding material data and overbraiding machine specifications, and software for postprocessing, visualisation, and creation of video animations. The tool can be operated through an easily approachable user 'dashboard'. The context of the tool, in terms of its inputs, outputs and dashboard, is depicted in Figure 5. The use of the tool is explained in the remainder of this section.

The input of the tool includes the geometry of the mandrel, a specification of the braiding material and its data, a specification of the overbraiding machine, a "braid plan" controlling the movement of the mandrel through the overbraiding machine, a description of the desired braiding result (i.e., the design parameters), and some parameters to control the simulation process. The output of the tool comprises a model of the overbraided product available for inspection by the engineer, the applicable CNC program readily available for uploading to the overbraiding machine, and optionally a video animation of the simulated overbraiding process.

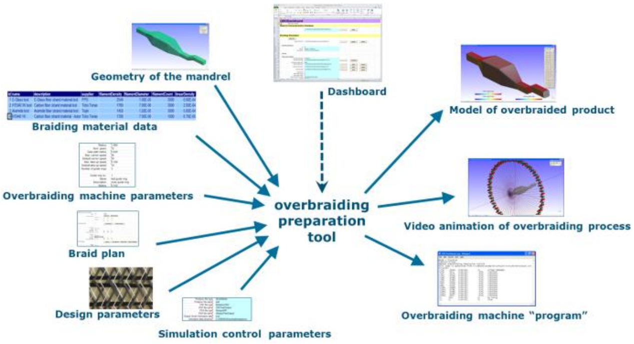


Figure 5. Context of the overbraiding simulation tool that helps to determine an overbraiding machine program to produce a product that meets specified design requirements

The tool is centered around the dashboard, which provides the engineer with a user-friendly graphical user interface for easy operation of the tool, such as specifying the inputs and inspecting and using the outputs. To support smooth introduction of the tool in the customer's environment, thereby keeping the learning curve as small as possible, the dashboard is implemented as a Microsoft Excel workbook. Excel is chosen since engineers generally have experience with it. A fragment of the dashboard is shown in Figure 6.

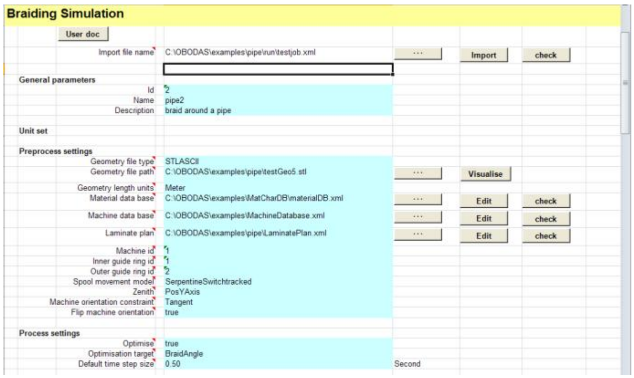


Figure 6. Fragment of the dashboard, serving as user interface for the overbraiding preproduction support tool

The dashboard supports the user in determining the applicable overbraiding machine program in the following five steps:

1. Specification of inputs
2. Running the overbraiding simulation
3. Inspection of simulation results
4. Creation of a video animation of the overbraiding process (optionally)
5. Generation of the overbraiding machine program.

These steps, including the tool packages involved, are elaborated in the remainder of this section.

1. Specification of the inputs

The inputs (cf. Figure 5) serve mainly to perform the simulation of the overbraiding, and comprise:

- a specification of the geometry of the mandrel;
- braiding material data for strands and yarns;
- overbraiding machine parameters;
- a braid plan corresponding to the geometry;
- design parameters;
- simulation control parameters.

The geometry of the mandrel is a 3D model (cf. Figure 7). It is usually created using one of the commercial computer-aided design (CAD) software packages commonly available in the aerospace industry and its supply chain. In practice, manufacturers such as Eurocarbon receive geometries from their customers.

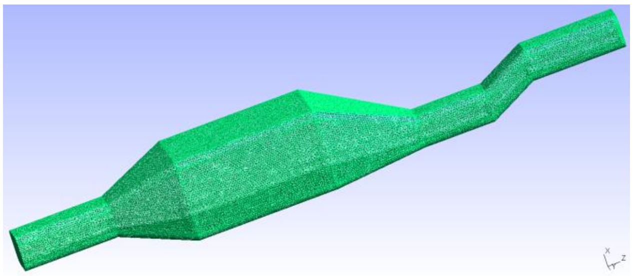


Figure 7. Example geometry of the mandrel shown in Figure 3, and used in the project for validation purposes (cf. section 4)

The braiding material is specified in terms of its material data. The data for strands include filament density, filament diameter, filament count, and linear density. Those for yarns include strand reference, strand count, and initial width. The materials and the material data required for the overbraiding simulation are defined and maintained in a material database, which contains a collection of frequently used materials. The database enables the definition of additional materials and the specification and inspection of values for the material data in a user friendly way, by means of a dedicated Excel sheet. The actual values for some data of commonly used braiding materials were determined with standard measuring devices. For example, one yarn was positioned manually on a cylindrical mandrel before measuring the initial width with a calliper gauge. The obtained accuracy is within a range of 0.1 mm, which is considered sufficient. Other data was taken from the standard yarn material data sheets.

The overbraiding machine is specified in terms of a set of parameters. These parameters include the radius of the carrier track ring, the number of carriers, the maximum and default carrier speed, the number of guide rings, and the radius and height per guide ring. The parameters for a collection of overbraiding machines are defined and maintained in the overbraiding machine database. This database supports the definition of additional overbraiding machines and the specification of machine parameters in a user friendly way, also in terms of a dedicated Excel sheet.

The braid plan mainly serves to control the movement of the mandrel through the overbraiding machine. The braid plan corresponds to the input geometry. The plan enables specification of the center curve of the mandrel (defining the 'path' of the mandrel with respect to the overbraiding machine during the overbraiding), the braid angle, the mandrel sections (i.e., intersection of a plane and the mandrel) and the segments (i.e., surface of the mandrel between two sections), and the runs over segments. The plan caters for specification of multiple overbraiding runs over segments. Construction of a braid plan is also facilitated through a dedicated Excel workbook.

The design parameters may include parameters such as fiber orientation, ply thickness, and cover ratio; cf. Figure 8. In the scope of the research project, optimisation is yet only supported with respect to the braid angle (i.e., fiber orientation).

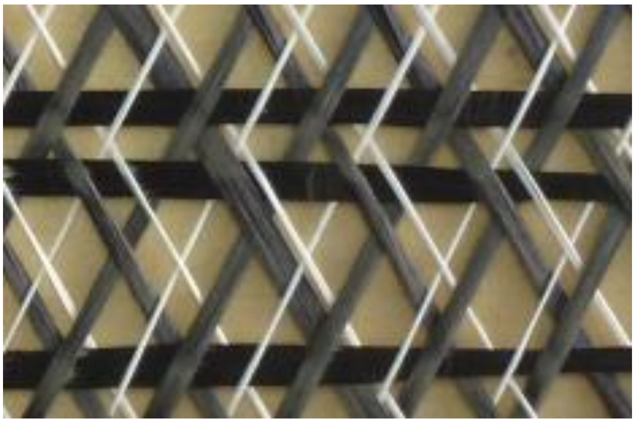


Figure 8. Fragment of an actually braided layer, showing fiber orientations and coverage

The simulation control parameters serve to specify, among other things, whether or not to optimise, and what target to optimise for (which currently is the braid angle only), the time step size to be used in the simulation, and whether or not to generate intermediate results to be used for a video animation of the simulated overbraiding process.

2. Running the overbraiding simulation

The overbraiding simulation runs as a batch process, under control of the aforementioned simulation control parameters. The simulation is performed using the overbraiding simulation program *Braidsim*. This program was originally developed in the context of PhD research carried out at the University of Twente (UT) in collaboration with NLR and Eurocarbon (ref. [4]). It was extended by UT in close collaboration with Eurocarbon and NLR in the scope of the research project (ref. [6]).

Braidsim simulates the overbraiding process based on kinematic modelling. It predicts fiber orientations by a virtual projection of the tows on the geometry of the mandrel, which may have changing section sizes. The composite designer, however, prefers the inverse route, with the software indicating which process settings should be used to achieve the desired preform thickness and fiber distribution. Put in other words, the simulated process should be optimised for the desired parameters. In the context of the research project, the optimisation was implemented for the braid angle only, not yet for the ply thickness and cover ratio.

Using the inputs specified in step 1, Braidsim generates three results, comprising:

- the resulting braided product of the simulation,
- the intermediate results of the simulation, and
- the simulated CNC program.

The resulting braided product is ready for close inspection by the designer (cf. step 3). The optionally produced intermediate results of the simulation enable the designer to have a look afterwards at the overbraiding process and the virtual product at each time step of the simulation. The intermediate results also enable the creation of a video animation of the overbraiding process by concatenating images of the intermediate results (cf. step 4). The simulated CNC program comprises the simulated instructions that are used for creating the virtual braided product in the simulation. This program needs to be translated to CNC instructions for the actual overbraiding machine used for producing the actual preform (cf. step 5).

3. Inspection of simulation results
The inspection of the simulation results mainly consists of visual inspection of the virtual overbraided product. Using a postprocessing and visualisation tool, such as the open software tool *Gmsh* (ref. [10]), the user can interactively inspect the result, using operations such as rotate, zoom in and out, and filter, thereby visually checking result values all around the mandrel; see Figure 9. The result values include, for the weft, warp, and stem yarns, the areal density of the primary braiding material, the braid angle, the locking indicator, the required fiber direction (as derived from the braid plan), the slip direction, and the slip tendency. The values also include the center line arc length, the component thickness, the run thickness, the biax cover factor, and the optimisation weight factor.

4. Creation of a video animation of the overbraiding process
Creating an animation video displaying the simulated overbraiding process is possible if the overbraiding simulation program was instructed to produce intermediate results for each time step. If that is the case, then the user first interactively selects (using Gmsh) a camera position with respect to the mandrel. Next, a series of pictures of the intermediate results is generated. Each picture displays the center lines of the yarns, both present in the overbraiding machine between the carriers and the mandrel as well as already applied to the mandrel; see Figure 10. Finally, the series of pictures is consolidated in a single video with a user-specified number of pictures per second. The video can be created using the free video capture and processing program *VirtualDub* (ref. [11]). The video displays the simulated process of overbraiding.

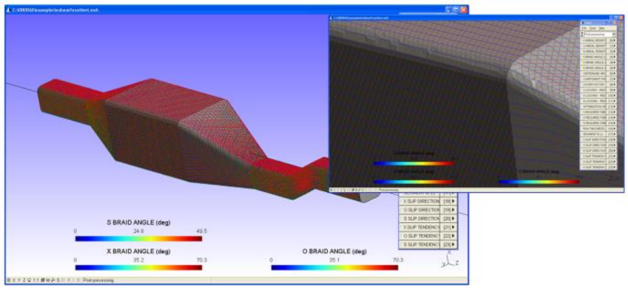


Figure 9. Inspection of the results of an overbraiding simulation

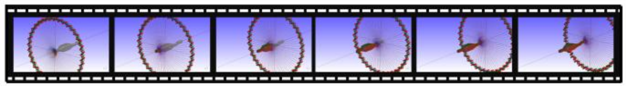


Figure 10. An animation video is created as a series of consecutive results per time step

5. Generation of the overbraiding machine program
Generation of the overbraiding machine program comprises the conversion of the simulated CNC instructions to a CNC program for target overbraiding machine. This conversion is supported by the *translation* capability of the tool. The simulated machine’s CNC program was used in the simulation by the virtual overbraiding machine in producing the virtual product. The simulated CNC program is produced in an intermediate neutral format, independent of any specific actual overbraiding machine. This program specifies for each consecutive time step the braiding speed (‘carrier speed’) and the traversal location and angular position of the mandrel with respect to the overbraiding machine at that time step. The target overbraiding machine program is a list of CNC instructions to control one of Eurocarbon’s overbraiding machines. Eurocarbon has several generations of overbraiding machines, each generation with its own set of instructions.

The translation program enables the user to generate the overbraiding machine program by first importing a Braidsim CNC output file, next controlling and checking the results of the translation from the CNC results of the simulation to the target machine instructions, and finally exporting a file containing the CNC program for the target overbraiding machine. The translation capability is operated using an Excel sheet; see Figure 11. The translation program supports the user in making a trade-off between the required accuracy of the overbraiding program and the available precision of the target overbraiding machine, by enabling the user to inspect the translation results through a diagram that plots per time step the traverse speed of the simulated overbraiding machine as well as that of the target overbraiding machine. The translation program also allows the user to apply correction factors, to deal for example with the use of positive and negative values for position, traverse speed, and braiding speed, which may vary per machine.

The resulting instructions may be uploaded to the overbraiding machine, the mandrel may be mounted on the overbraiding machine, and the overbraiding process may be started for real.

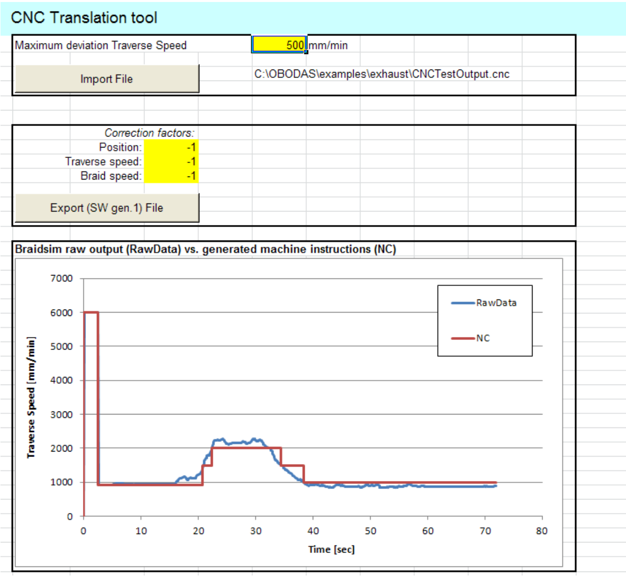


Figure 11. The interactive translation program supports the end user in generating CNC instructions for a specific generation of Eurocarbon overbraiding machines, thereby allowing the user to make a trade-off between the required accuracy of the instructions and the available precision of the target overbraiding machine

4. Application: validation and evaluation

In the context of the research project, a solution to the technical challenge as described in section 2 was implemented by means of a proof of concept tool as presented in section 3. The tool was both validated for its accuracy and evaluated for its applicability. The validation took place by using an existing complex-shaped mandrel and comparing the resulting virtual product of the simulation against the actual braided product using the generated overbraiding machine program. To evaluate the applicability of the tool, Eurocarbon applied the tool in industrial cases and provided valuable feedback. This section describes the validation process and results and the evaluation conclusions.

Validation

Validation of the tool for its accuracy with respect to the overbraiding process took place by using an existing and representative mandrel as reference mandrel: the example component (i.e., the ‘exhaust pipe’ as it was called on the work floor) as shown in Figure 3 and Figure 7. The reference mandrel contains sufficient interesting challenges for overbraiding. A wooden specimen of the mandrel as well as its geometry in a suitable CAD format were available. Furthermore, a 96-carrier overbraiding machine from Eurocarbon was selected for the actual overbraiding. A schematic overview of the validation process is depicted in Figure 12. The geometry of the reference mandrel is fed into the overbraiding preproduction support tool. The generated overbraiding machine program is fed into the overbraiding machine and is used for the actual overbraiding of the reference mandrel. Finally, the simulation result is compared against the actual overbraiding result, in particular with respect to braid angles. The process is elaborated below. For the validation, it was decided to apply the validation process twice: braiding the reference mandrel forward and braiding it reverse, both starting with a clean mandrel and using the same selected overbraiding machine and braiding material.

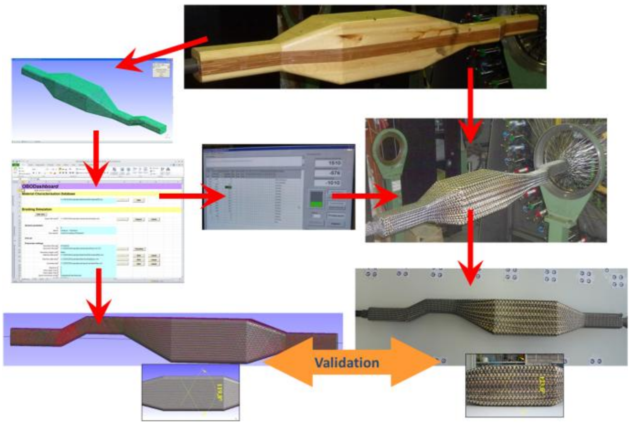


Figure 12. Schematic overview of the validation process applied in the research project.

The validation process started with application of the overbraiding preproduction support tool to generate both the virtual model of the overbraided product (i.e., the braided mandrel resulting from the simulation) and the simulated CNC program. Next, the simulated CNC program was translated into the target overbraiding machine program, using Eurocarbon’s knowledge about the actual precisions of and required correction factors for the selected target overbraiding machine. Subsequently, the overbraiding machine was prepared with the ‘hardware’ mandrel positioned properly in the machine, proper braiding materials on the bobbins mounted on the carriers, and the target overbraiding machine program loaded. Then the CNC program was run; cf. Figure 13.

After the mandrel was dismounted, photographs were taken from all faces of the overbraided reference mandrel to enable determination of the fiber orientations in terms of the angles between the tows. Both the plotted simulation results as well as the photographs of the actual braiding results were loaded into a CAD program, lines were projected on selected focus points in the four different faces in the four segments of the mandrel, and angular dimensions were added; cf. Figure 14. Finally, the deviations in measured braid angles between the simulated and the braided results, both with forward braiding and reverse braiding, were computed and analysed.

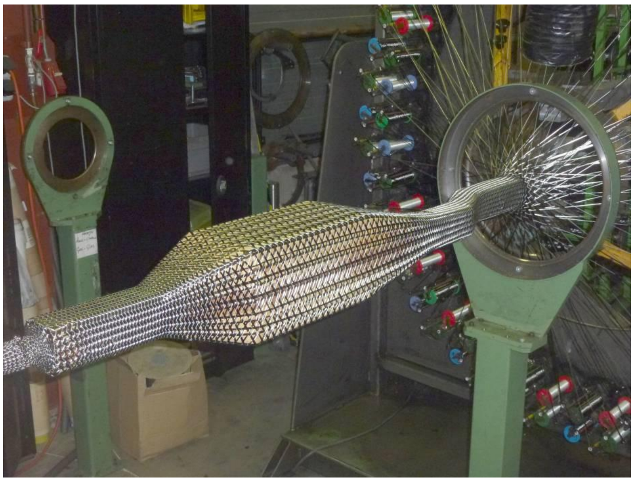
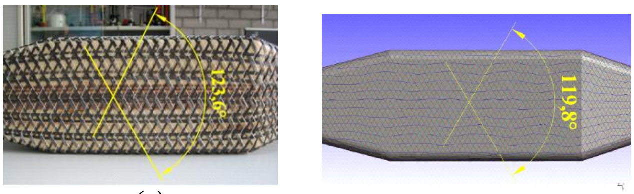


Figure 13. The braided reference mandrel near the end of the execution of the overbraiding machine CNC program



(a) *(b)*

Figure 14. Braid angles computed at the corresponding location in the braid (a) and the simulated result (b), both at forward braiding

An important conclusion with respect to the analysis of deviations in braid angles are that the simulated results are generally close to the actual braid results with respect to the braid angle, and that the deviations are generally acceptable. One observation is that reverse braiding seems to yield the largest deviations, and hence that forward braiding prediction is better than reverse braiding prediction. The deviation for forward braiding differs from -5.6° to 4.9°. For reverse braiding the angle deviations are between -10.4° and 13.6°. A cause was found in the fact that the rings for reverse braiding affect the braid results. With reverse braiding, the large fiber contact angle at the guide rings leads to large friction forces and increased stem yarn dominance. Another observation is that the actual braids show more scatter than the simulation results. One particular segment of the mandrel contains the most scatter for both forward and reverse braiding. This seems to be related to the curvature in the center line of the mandrel.

Small differences during the braiding process could have a large effect on the results. Examples are the surface structure (smoothness), quality of spooling, twist in the tow, applied ring and its quality (carriers), and application of ring vibration device. The simulation can be performed close to the theoretical correct values. The skill of the overbraider is always necessary in order to end up with a correct braid. Additional differences may also be caused by the translation, the start-up errors in transient regions, and the neglect of convergence zone inter-yarn friction. A general conclusion is that the overbraiding process model used in the simulation as well as the translation process may be further improved in order to obtain closer results.

Evaluation by Eurocarbon

To evaluate the applicability of the tool, Eurocarbon as foreseen customer of the solution applied the tool in several industrial cases.

Eurocarbon is active in the field of overbraiding since 1994. Initially, overbraiding was performed using an overbraiding machine with 96 carriers, on which the braiding speed and traversal speed were controlled using potentiometers. Around 1997, the overbraider was equipped with computer control. From then on, the traversal axis was programmable per millimeter, and the overbraider was able to braid with a fixed speed. This situation formed the basis for further serial production.

Over the years, Eurocarbon has done a lot of development work for customers in product engineering. After years of pioneering, Eurocarbon developed a ‘feeling’ for the various speeds of the two shafts to obtain the correct braid angle on the product. After some trial and error, the overbraiding instructions comprising positions and speeds is determined on paper. The next step consists of writing the CNC program. Subsequently, the CNC program is run completely, and the result is analysed. A second iteration is required to adjust positions and speed, to obtain the desired braid angle. In the meantime, valuable time is lost with ‘pioneering’, which varies with the skill of the operator. Another aspect to consider is the use of special and costly materials such as carbon fiber, which makes the trial and error also costly. Only after the iterations, the customer has the opportunity to inspect the end result.

The results of the research project as described in this paper make it possible to specify a simplified geometry of the model, to select and configure a braiding machine, and to specify the desired braid angles at the various positions. The approach of generating the CNC program for the overbraiding machine based on required results and without costly materials and machine hours has caused a shift from ‘pioneering’ towards computer simulation, which reduces the need for trial and error. An additional feature with large added value is the possibility to create an image of each simulation step. The series of these images allow the creation of a movie of the animated overbraiding process. Eurocarbon can present this movie to the customer and hence show the production of preforms beforehand. For Eurocarbon, the tool is a step further towards professionalization and an efficient production process.

5. Summary, Conclusions and Recommendations

In this paper we described a successful example of the translation of knowledge of the overbraiding process into an innovative industrial solution for use in the development of high-quality light-weight complex-shaped hollow composite aircraft structural components. The solution comprises an efficient, practical and user-friendly - yet proof-of-concept - tool that helps aerospace industries to develop the composite components for use in next-generation civil aircraft at lower cost and in shorter time. The tool applies simulation of the overbraiding process that is used as part of the manufacturing of hollow composite components, and optimises the process for specific design requirements. The main output of the tool comprises an overbraiding machine CNC program that allows efficient and reproducible manufacturing of dry preforms of composite components that meet the design. The tool's appearance and mode of operation is tailored to easy and efficient application by the overbraiding engineers on the "factory floor".

An important conclusion with respect to the overbraiding simulation program is that the optimisation for the braid angle was successfully implemented, resulting in a virtual error in the order of 1 degree. Validation using the exhaust pipe showed an overall braid angle error trend in the order of several degrees and a maximum in the order of 5° to 13.6° in the most difficult regions involving up- and down-braiding. The error difference between model and experiment can largely be attributed to the overbraiding simulation program's straight-yarn assumption, neglected overbraiding process start-up effects, and imperfections in the translation process.

Evaluation of the applicability of the solution in practice by Eurocarbon as a supplier of the Dutch aerospace industry has pointed out that the tool indeed reduces the need for trial and error as yet practised in the overbraiding process that is part of the development of composite components. As a result, the solution supports the aerospace industries to achieve time, cost and weight reduction in the production of structural components, and hence contributes to the aircraft manufacturers' aim to shorten the development cycle and reduce costs while building increasingly better aircraft. The research project has successfully brought simulation technology to the factory floor of the aerospace industry. Other industries beyond aerospace have shown interest in the results of the project as well. Spin offs are expected in the automotive branch.

Possible future work may include refinement and improvement of the overbraiding simulation model as applied in the overbraiding simulation program, support for more complex mandrels, improvement of the translation of simulated CNC instructions into actual overbraiding machine CNC instructions, support for incorporation of structural analysis aspects in the design parameters and hence inclusion of FEM in the optimisation loop, increased interoperability with other engineering packages, and improvement and further development of the dashboard to cater for broader application of the solution described in this paper.

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