Design and manufacture of advanced composite structures using Fibre-Patch-Preforming

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Abstract
The dry process chain enables the use of low-cost materials, highly automated processes and has high potential to reduce significantly the manufacturing costs of composite structures. One of the processes developed by EADS INNOVATION WORKS [1] for automated preform manufacturing is the Fibre-Patch-Preforming. The process enables new laminate design and as a result new product properties. The developed preforming robot system enables the positioning of unidirectional carbon fibres patches on any position and orientation on the tool. The process aims to reduce manufacturing costs as it is a fully automated process as well as composite structures weight through tailoring the fibre thickness and orientation.
The machine concept first demonstrated in 2008 has been further developed to improve its productivity and the flexibility. The process has been adapted to manufacture 3D structures in one single step using cooperating robots geometry adjustable end-effectors.
Software is being developed to enable the design optimisation of composite structures based on FPP cut fibre tapes and to program its manufacturing. The software will assist the optimization of the laminate, describe the as-built structure and allow off-line programming of the FPP machine.
This paper intends to present new developments of process and design related to the FPP technology and describes its potential for improvement of CFRP manufacturing in the aerospace industry.

1. Introduction

Carbon fibre reinforced plastics have great potential to outperform metallic structures in different aerospace airframe applications due to their higher weight specific performances. With the growing demand for energy- and cost-efficiency, composite structures have been gradually introduced into aircrafts design through a step by step approach and is currently representing respectively 50% and 53% of the structural weight for the recent 787 and A350 [2]. The use of carbon composites is aiming to reduce both weight and maintenance costs. This progressive evolution is still restrained by some downsides inherent to the use of composites among which are the manufacturing limitations and costs.

Enabling sufficient manufacturing flexibility and repeatability, the hand lay-up of prepregs and autoclave cure is the most established manufacturing process for aerospace CFRP components. The high manufacturing costs are mainly consequences of the high material prices as well as high labour efforts while the manufacture related design constraints are directly linked to the use of the limiting semi-finished fibre products.

Enhanced by the need for cost-efficient production methods, other manufacturing technologies are progressing. LCM processes are seen as potential efficient solutions to reduce the CFRP manufacturing costs. The textile and infusion manufacturing route can promote low-cost material, automation and the manufacture of integrated structures and could be applicable for a large range of applications. The traditional dry process chain uses standard textile materials available as UD, woven cloth or NCF and is a sequence of successive steps such as cutting, stacking, draping, activating and assembling [3]. These steps are usually only partly automated and therefore still requires significant manual work.

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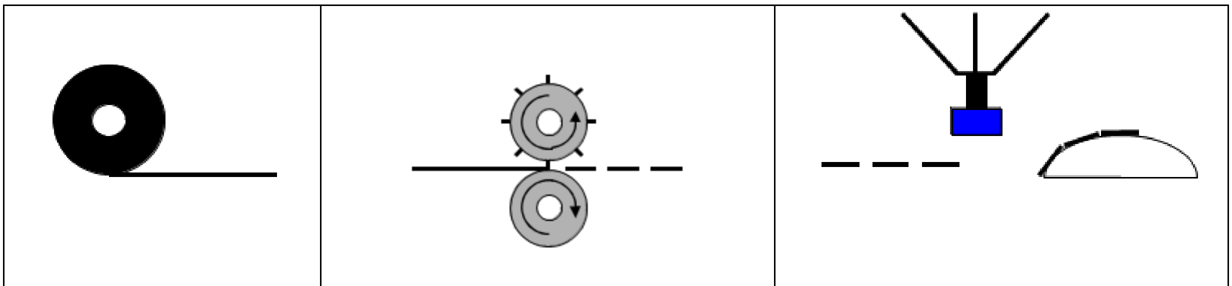
The manufacturing costs are mostly reduced through implementation of highly automated lay-up processes. Some are now used in serial production such as braiding, winding or for instance AFP used in serial production for fuselage and tail skin structures [4]. However the design freedom is generally decreasing as the automation grade increases, preventing the use of such processes for a wide range of applications [5]. Other technologies such as the use of SMC through spraying of short fibres would enable both high automation and geometrical flexibility. However the important discrepancies in the material properties caused by the poor control on fibre orientation leads to high design safety factors and therefore to important weight penalties.

There is therefore some need for a cost-efficient CFRP manufacturing process that would enable both high automation grade and design flexibility while ensuring precise control in order to be potentially widely applied to CFRP structures. The Fibre-Patch-Preforming [6] process attempts to provide a solution to this problem. The process philosophy and the recent developments are here presented and addressed.

2. Automated manufacturing using Fibre-Patch-Preforming technology

The FPP process is a complete preform process chain that has been developed at EADS INNOVATION WORKS in cooperation with MANZ [7]. It is a combination of a material supply unit and a lay-up robot; in the supply unit, a band of bindered carbon spread tow is guided through a feeding system and cut to regular long fibre reinforcements called patches. The patches are then placed at a specific position on the feeding system in order to be picked-up by the lay-up robot.



Spread tow | Cutting of short fibre carbon patches | Automated lay-up of patches

Figure 1: Illustration of FPP process steps

The lay-up robot enables the positioning of the short fibres carbon patches at any pre-defined position and orientation. An end-effector, mounted on the lay-up robot (Delta DR1200), grasps the patch using vacuum, places it on the mold and drapes it on the mold and fixes it using thermal activated binder. The sequentially stacked patches will finally create the preform.

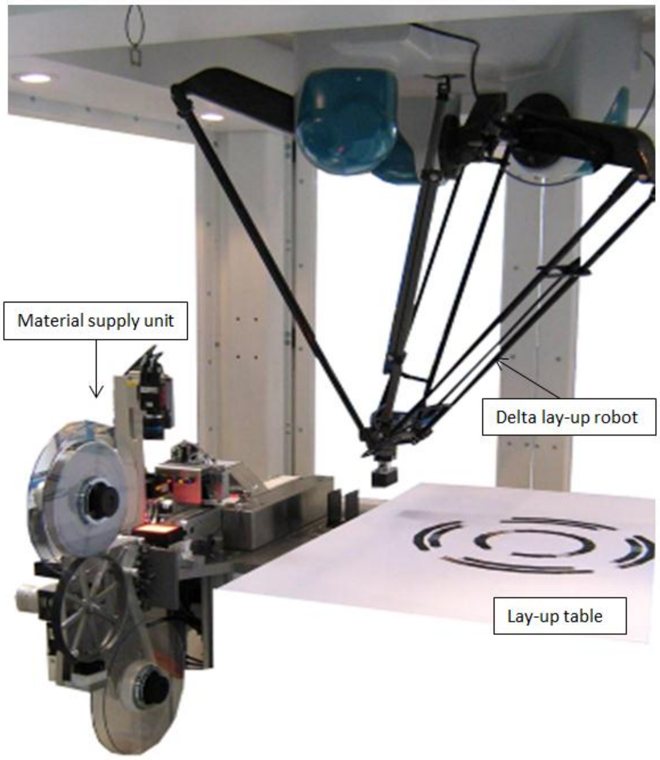


Figure 2: Picture of a FPP machine

The material supply unit is continuously delivering the patches, with adequate speed so that after one patch has been laid, the following one is ready to be picked-up. The Delta robot enables an extremely quick movement of the end-effector so that the patches can be placed with a frequency of 1Hz. High machine speed is required to enable sufficient productivity.

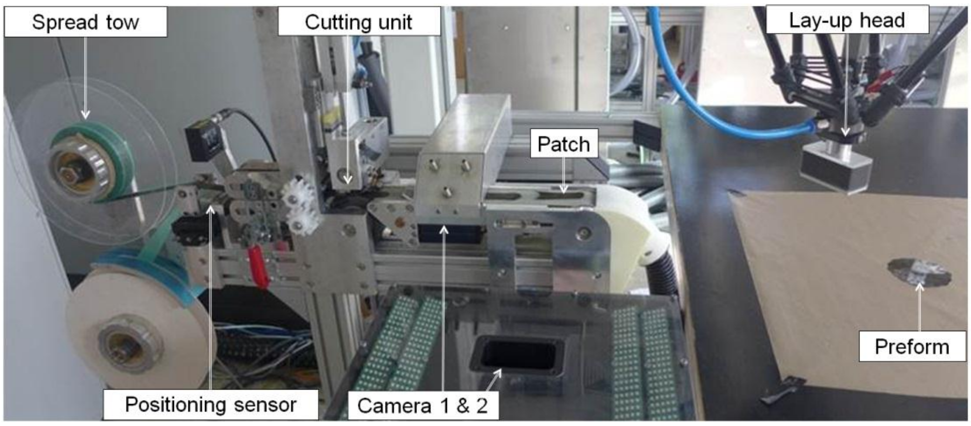


Figure 3: Visualisation of the detailed FPP process chain

During the process some cameras ensure high quality and repeatability of the process. The geometry of the cuttings is controlled in the material supply unit using a camera that compares it to the theoretical expected shape. Only the reinforcements whose quality is within the specified required tolerances will be further processed. Once a patch has been picked up, its actual position on the end-effector is measured. The measured value is then used to correct the movements of the end-effector in order to improve the accuracy of the patch position and orientation. This monitoring allows a repeatable preform production with high tolerances, as the discrepancies are then only due to the robot tolerances and to potential deformations during draping of the patches with the end-effector.

The Fibre-Patch-Preforming process is therefore a fully automated process that enables the direct manufacturing of new type of preforms where the fibre orientation and thickness can be locally tailored. The ongoing developments of the process are aiming to improve the process capabilities and enable its use for CFRP production.

3. Improvement of the process capabilities

Based on the first prototype of the FPP process some new features are being integrated in order to improve the machine capabilities and widen its potential applications.

The preform is manufactured through the stacking of patches whose geometry is defined by the cutting unit. The standard patches used are rectangular carbon reinforcements with 20mm of width and 60mm of length. In order to provide more flexibility and more productivity to the machine, an advanced material supply unit, working with different tow width and a parametric cutting length will enable the preparation of diverse patches. It is aimed to create patches whose width is variable between 20 and 50mm and length between 40 and 200mm. This material supply unit enables to adapt the material size to the structure requirements and to increase the machine productivity.

The high-speed lay-up robot only permits the vertical stamping of the end-effector at the defined position on the tool. Therefore it enables the manufacturing of 2D structures or structures with simple curvatures. A new machine configuration is being developed, aiming at manufacturing most 3D complex geometries. For that purpose, the use of a tool positioning robot has been added to the existing FPP machine. This robot, typically a 6-axis robot, will position the preforming tool with the right position and orientation, and in cooperation with the lay-up robot allow the positioning of patches on 3D geometries. Thanks to this robot combination, the high frequency of the process is maintained as the lay-up robot is still used at full speed while the positioning robot orient the right position of the tool normal to the end-effector surface.

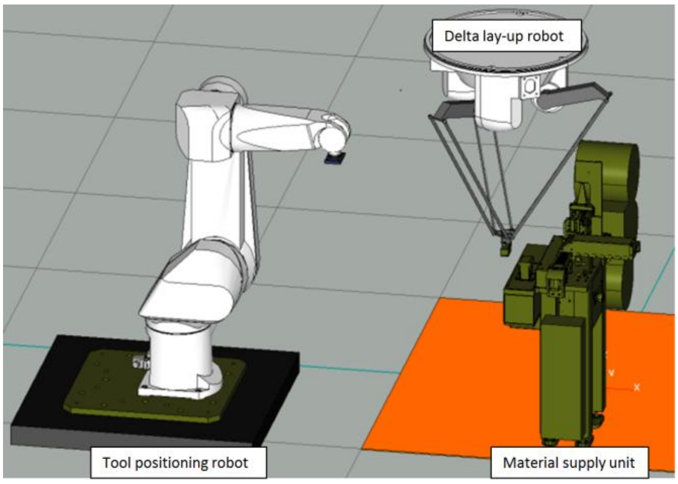


Figure 4: Illustration of robot cooperation

The direct manufacturing of 3D structures requires a flexible end-effector that additionally to its other functions will allow draping of the patch reinforcements on the tool surface. For that purpose its design has been modified in order to enable enhanced flexibility and perform high deformation for the draping of complex structures featuring double curvatures, radius and edges.

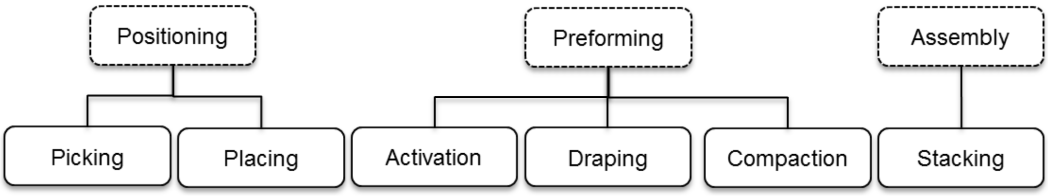


Figure 5: End-effector functionalities

The new machine concepts is being implemented in a united cell. In parallel dedicated software are developed in cooperation with CENIT [8] to create adapted design and simulation solutions.

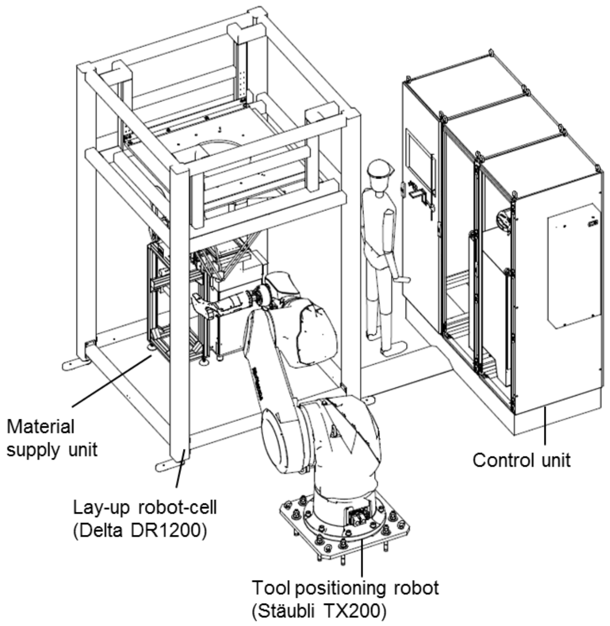


Figure 6: Illustration of the FPP cell

4. FPP laminate design

The FPP technology has many degrees of freedom that will influence the mechanical properties of the CFRP. The design shall therefore consider the optimisation possibilities linked to the use of patch based material in order to exploit the full potential of their benefit. The laminate design will therefore be defined using a set of parameters and rules, established on theoretical and experimental evaluations that will assist the laminate optimisation

4.1 Laminate patch parameters

In order to define the laminate, the designer will have to specify the parameters that will govern the definition of the patch architecture, some of these are here addressed. The designer can select the patch parameters adapted to its application among which are the material thickness, width, length and cutting shape.

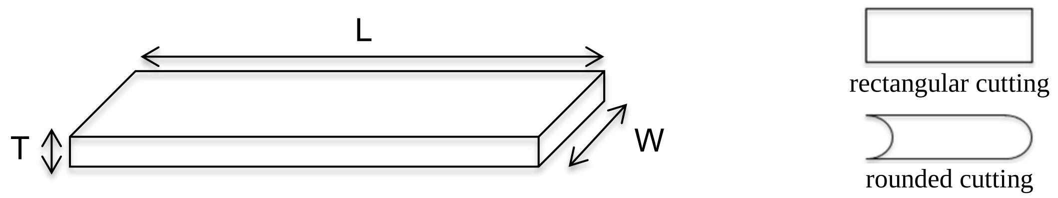


Figure 7: Patch material parameters

The preferred patches layout will be specified using parameters controlling the longitudinal and lateral distance between neighbouring patches. The designer can choose a strategy promoting the occurrence of gaps or overlaps.

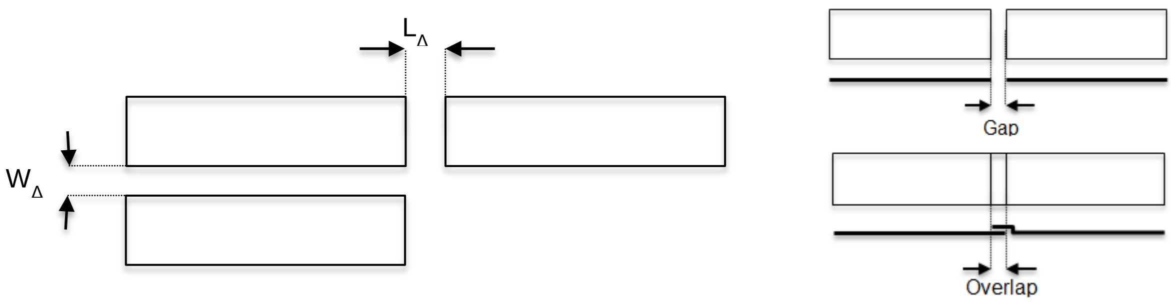


Figure 8: Patch layout parameters within a ply

As the patches cannot follow accurately the defined ply design contour, it will therefore be specified how the defined surface should preferably be covered using an allowance criteria, notably if it is preferred to leave a gap and end the lay-up before the boundary, or it is preferred to exceed the boundary.

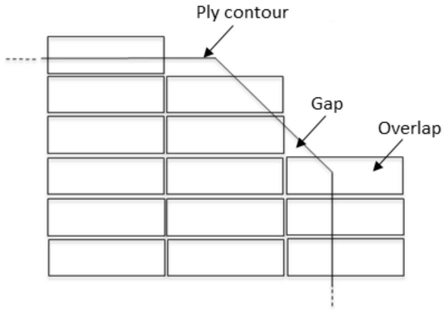


Figure 9: Illustration of the partial coverage of the ply area with the patches

4.2 Considerations for FPP laminate optimisation

A FPP layer is manufactured with patch as a baseline material and will feature some fibre break lines where there is only resin. In order to manufacture a structure with high mechanical properties, it is necessary to design plies that consist of several sub-plies. The break lines of the stacked sub-plies must be placed at different locations to ensure that enough fibres are present in all cross-sections of the ply so that the loads can be carried. Therefore the position of the patches must be well distributed in the fibre direction. An optimization needs to be carried out with a dedicated algorithm to ensure that the break lines are evenly distributed according to a defined set of guidelines and create an acceptable FPP laminate.

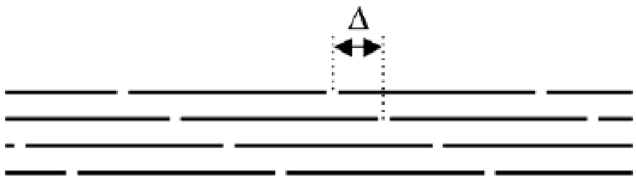


Figure 10: Illustration of the reparation of the break lines of the sub-layers

A shifting of the patches in the transversal direction can as well be done in order to distribute the local imperfections (gaps, overlaps) in the ply by shifting the sub-plies in the transversal directions.

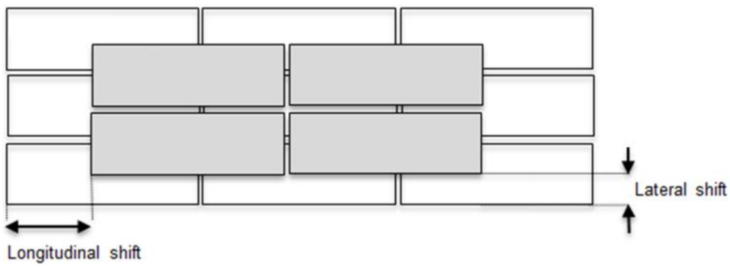


Figure 11: Illustration of the defect repartition with shifting of the sub-layers

Besides these layout parameters the designer will specify the local orientation of the fibres. As the FPP technology enables steering of the reinforcements, the fibres can be directed along some splines on the ply surface. Some guidelines will be generated over the surface according to these splines and a defined strategy. The guidelines will define the local orientation of the patches.

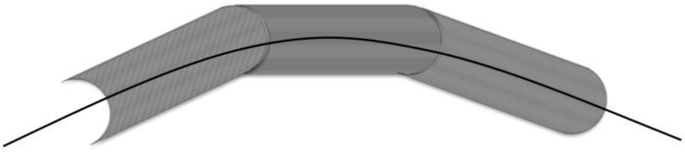


Figure 12: Illustration of fibre steering using a sequence of UD patch reinforcements

All these parameters and inputs will be defined by the designer using the dedicated FPP design module integrated in the Catia V5 CPD design workbench. An algorithm will then optimise the arrangement of the patch based on the given inputs and criteria. After the optimisation, the calculated laminate arrangement will be visualised in the software.

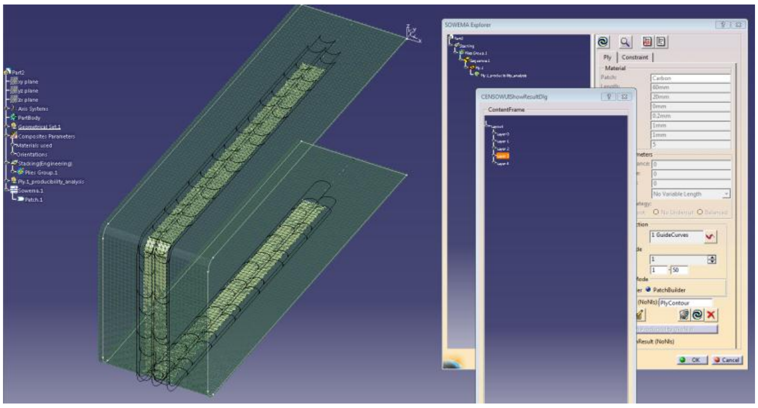


Figure 13: Visualisation of the FPP design module integrated in Catia V5

5. FPP Off-Line Programming

The machine control for the lay-up of the numerous patches can be done using Off-Line Programming thanks to dedicated simulation software.

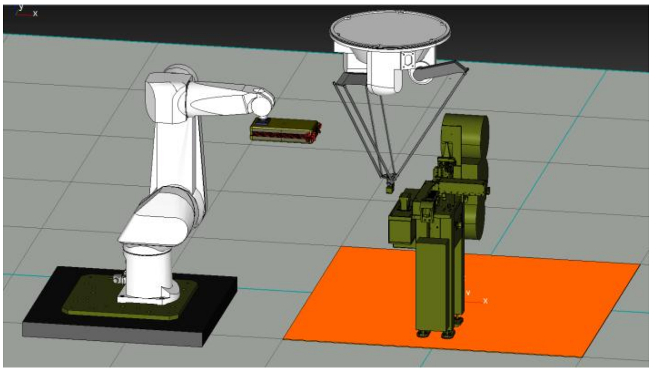


Figure 14: Representation of the simulated unit

The machine configuration is simulated in the software where the preform tool and patch data can be imported and positioned. Based on this information the program defines the lay-up position of each point as well as the motion of the lay-up and tool positioning robots. The manufacturing is then simulated to validate the calculated robot motions and detect eventual collision and will then allow the creation of alternatives, if necessary. Once verified the programs can be exported to the manufacturing cell.

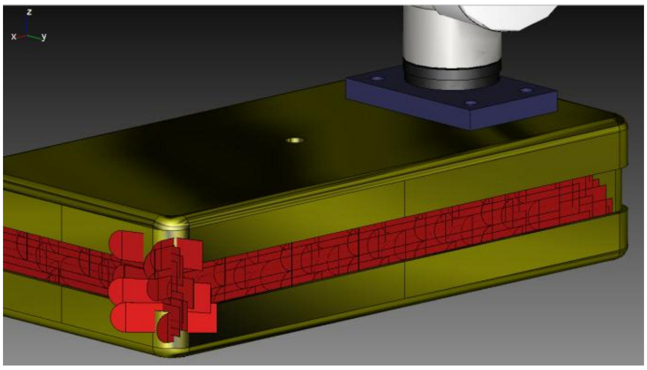


Figure 15: Visualisation of imported patch data on preform tool

During the generation of the machine programs some optimisation will be performed to have high lay-up quality and productivity. The software will indeed take into account the draping of the end-effector on the tool in order to correct the lay-up position and ensure high lay-up tolerance. The coordination of the robot movements and lay-up position will also be adapted to ensure high process speed. The design and manufacturing software thus ensure precise control of the laminate composition as the design is created as manufactured.

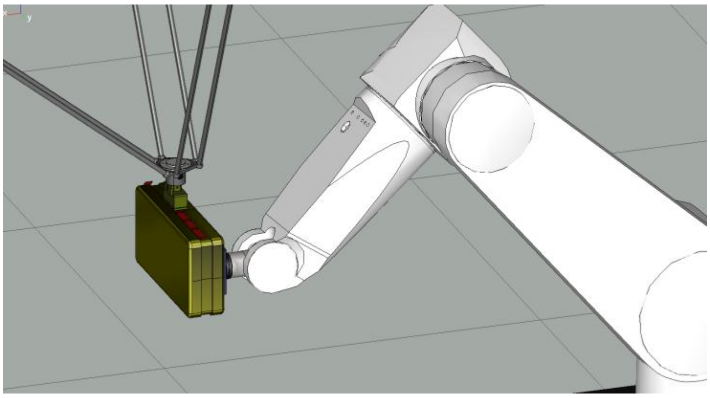


Figure 16: Illustration of lay-up simulation

5. Manufacturing of aerospace CFRP structures using FPP process

The Fiber-Patch-Preforming process has been developed to provide a cost-efficient CFRP manufacturing process with high automation grade and design flexibility while ensuring precise control and repeatability. The recent developments are directing toward that goal as the process can now, assisted with adapted software, perform the automated direct manufacturing of 3D tailored preforms.

The process aims to reduce the manufacturing recurring costs through automation and resource efficiency:
The machine performs the material cutting, positioning, draping, activating and stacking of the patch reinforcements. The manufacturing is therefore fully automated and reduced to a single step. The use of spread tow has the potential to further reduce the costs as the process creates nearly no waste. Besides the material can be manufactured from heavy tows having lower weight specific price which are then spread to the required areal weight.

FPP laminates enable the design of potential efficient designs using high performance material and tailored design:
The machine uses thin ply material which exhibits great performance due to its architecture as it has no crimp and is highly homogeneous and [9-10] showed potential to improve numerous properties among which the strain allowables and impact properties. The process is flexible so that the fiber thickness and orientation can be easily varied. Therefore the laminate can have reinforcements following the main identified load path in order to best use the fibers properties and feature thickening in critical load introduction areas.

However in order to reach sufficient strength, a layer made of patch material must consist of several sub-layers oriented in the same direction so that at each position some fibers carry the loads. There is therefore a knock-down in the performance due to the fibers cuts. The performed investigations showed that more than 90% of the stiffness and 75% of the strength compared to equivalent continuous fiber reinforced laminates could be reached, mainly depending on the patch material thickness.

The process has few manufacturing limitations. The small patches can indeed easily be formed and the drapability issues of standard textile are not encountered. The developed software solution and inline process monitoring ensure high control of the final preform composition as the laminate is designed as manufactured, with high repeatability and tolerance over the local fibre orientation and thickness.

The process capabilities make it potentially interesting for a wide range of application. The current machine configuration aims for an application to small size structures; the robot configuration and material supply unit could be adapted to other size requirements. The machine is particularly suited for the manufacture of small and complex structures such as ribs which are usually poorly automatable. It is also adapted for the manufacture of window frame elements which can benefit from the free orientation of the fibers laid along the radial and circumferential directions. The process can also be advised for combination with other processes. It is indeed efficient for manufacturing local thickening and steered reinforcements than can be placed on larger textiles or interleaved in order to reinforce weak areas and improve the performance for specific loading cases.

The potential of the FPP process is so far still limited by its low productivity. The fibre output is directly linked to the machine frequency and the reinforcement weight, currently around 0.4kg/h. The ongoing upscaling of the patch size will enable to increase the productivity up to 100 times allowing ca. 30kg/h of fiber output. However the use of bigger reinforcements limits the flexibility of the FPP process. The reinforcement size must therefore be selected to best fulfill the structure and productivity requirements, and the optimized solution would be to vary the patch size during the process in order to optimize the material use.

The introduction of the FPP process for the production of CFRP components will require further understanding of the patch based laminates. Both material testing and simulation needs to be performed in order to build an adequate strategy for the analysis and qualification of such materials.

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