RESULTS OF A CASE STUDY ON THE APPLICATION OF AUTOMATED FIBER PLACEMENT FOR A HELICOPTER AIRFRAME STRUCTURE

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Abstract

Due to economic and ecologic reasons a number of different technologies for the automated layup of composite parts for H/C airframe structures are currently evaluated. Automated Fiber Placement (AFP) is one of the promising technologies as it shows appropriate characteristics to lay-up fiber material over three-dimensional curved tooling-surfaces and in particular over sandwich areas for helicopter shell elements, due to its capability of laying-up individual narrow prepreg tows. As today’s field of AFP application is focused on monolithic parts a study was carried out to evaluate and optimize all relevant parameter along the process chain for a H/C bottom shell in sandwich design. The key potential of the technology was found in a considerably higher layup rate compared to manual layup and more consistent part quality as well as largely reduced scrap rates.

1. INTRODUCTION

With the introduction of the Boeing 787 and the Airbus A350 XWB automated manufacturing technologies were established for the manufacturing of large monolithic carbon fiber reinforced plastics (CFRP) parts.

In the competitive environment of the current H/C markets an increasing demand for automated production technologies can be observed. The basic approaches focus on a cost and weight reduction as well as on an improved reproducibility to overcome the drawbacks of the established manual part production.

Helicopter structures face several economic and technical requirements derived from profitability, mission and certification demands. The technical requirements include high strength and stiffness, low weight, high level of integration (to reduce assembly time and reduce weight caused by overlaps and assembly parts like rivets), the ability to endure under various load cases and crash resistance.

2. HELICOPTER SANDWICH PARTS

2.1. Applications for sandwich parts

For complex shaped parts of helicopter airframe structures state of the art are high performance composite materials to meet the ambitious requirements. CFRP-sandwich parts ensure a very low structural weight and allow an increased level of integration to reduce assembly time and avoid additional weight induced by assembly parts like rivets and overlapping material in joint areas.

At Airbus Helicopters, structural CFRP sandwich parts have been used for many years and have proven to meet these requirements very well. Structural design concepts based on sandwiches are used for a number of airframe components like side- and bottom shells sandwich.

CFRP H/C bottom shell

Taking into account the typical annual production rates for H/Cs the current manufacturing solution is to combine honeycomb sandwich cores with the manually laid-up of pre-impregnated carbon fiber sheets to realize complex shaped geometries.

Smaller unit numbers and the complexity of helicopter parts, as well as the additional challenges faced through the use of sandwich parts have prevented the use of automated manufacturing technologies until now.

2.2. Manufacturing process for sandwich parts

After cutting the prepreg layers are draped manually into the mold and compacted frequently after a number of layers, with this step necessitating the time consuming setup of a vacuum. Subsequently, the part is cured in an autoclave. Finally, the part is milled or sawed to match the final outline.

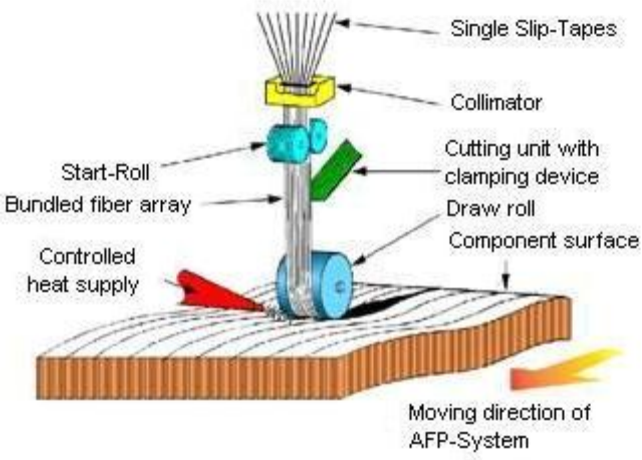
Although high quality parts can produced in hand-layup processes, considerable effort is required in order to achieve consistent high layup quality, i.e. through laser guided ply positioning. A further downside of this process is the comparatively low Buy-to-Fly-Ratio (i.e. the ratio of raw material delivered from the supplier to the weight of the actual flying part) caused mainly by the cutting process, even when using modern nesting procedures.

3. AUTOMATED FIBER PLACEMENT

3.1. ATL vs. AFP

In order to reduce the manual effort for the layup of composite laminates two roughly comparable technologies for automated layup are investigated: ATL (Automated Tape Laying) machines place single bands of fibers with typical widths of 75mm, 150mm or 300mm onto a mold, making complex geometries impossible and even slightly spherically curved surfaces challenging to manufacture as proper bonding of the material is difficult to assure.

Currently, Automated Fiber Placement (AFP) is considered as the most promising technology for the manufacturing of complex helicopter parts based on the experiences made with fix wing parts. AFP shows appropriate characteristics to lay-up fiber material over three-dimensional curved tooling-surfaces and in particular over sandwich areas for helicopter shell elements.



Automated Fiber Placement (AFP) process

3.2. AFP process

A typical AFP machine consists of a movable head attached to a gantry or robot. The unidirectional fiber prepreg slit-tapes with typical widths of 1/8”, 1/4" or 1/2” are fed into the APF machine on reels and placed on the mold with a high reproducibility. During layup, they are activated by a heating unit in order to adhere to the substrate, placed and compacted to the substrate and cut in programmed places (part boundaries, cut-outs, sectioning due to part’s curvature/complexity). The narrow bands of fiber allow for proper application of the material even on complex, spherically curved surfaces such as sandwich areas.

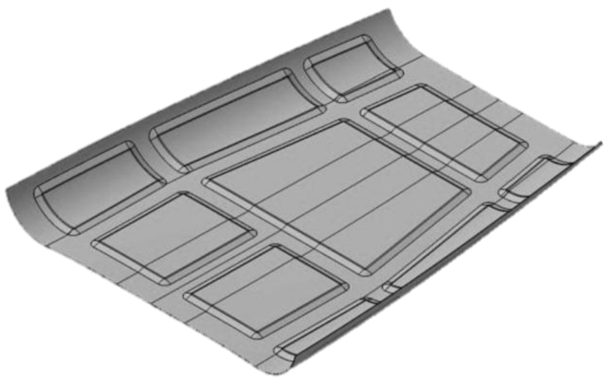
The curing process is equal to that of manually laid up CFRP prepreg parts, only differing to meet the requirements of the materials.

Due to the ability to cut all slit tapes individually the scrap rate can be reduced AFP is a material-efficient and thus economically friendly layup process.

4. CASE STUDY ON AN H/C AIRFRAME PART

4.1. Challenge

The case study was performed to understand and exploit the full potential of the AFP technology for H/C airframe sandwich parts.



H/C bottom shell used for the study

The challenge was to adopt the technology to complex shaped helicopter airframe sandwich structures promising significant improvement potential due to higher lay-up rates, better lay-up accuracy and a more closed and faster data loop. Therefore the complete process chain had to be investigated as there are plenty of aspects in each step that have to be considered as well as interactions between the steps.

4.2. Methodology

There are numerous factors influencing the process and subsequently the quality of an AFP-produced part. In particular, the tack and width tolerances of the prepreg slit tapes, material of the mold, compaction pressure, layup speed, layup temperature, geometrical contour of the mold and layup (fiber) orientation, curing cycles have significant impact on lay-up results.

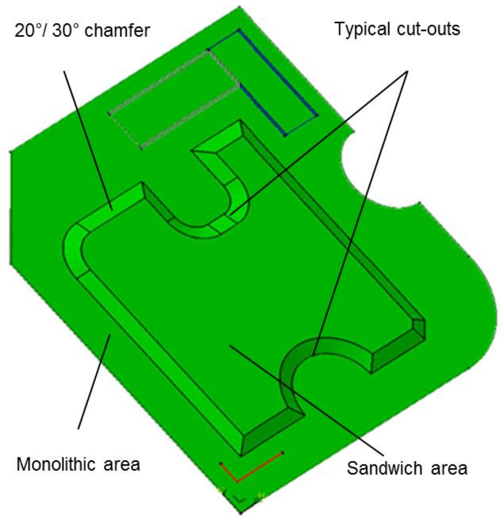
AFP induces defects include gaps, twisted tows, sandwich core crush, fiber undulations, gaps and overlaps, bridging, telegraphing and porosity. While many of these defects occur in manually produced laminates as well, the formation mechanisms of these faults differ greatly, as the lay-up process is inherently different. Some of the faults in AFP parts can be traced to the input parameters (core crush is induced either by excessive compaction force or autoclave curing pressure), while others are an indirect consequence of interacting effects during layup.

Apart from the general feasibility of AFP for helicopter parts, the technology has to provide economic advantages to pay back for effort and investment costs and to increase advantage to competitors. Therefore higher AFP layup rates are required. Complex geometries necessitate extensive motion of the machine, slowing down the actual layup speed considerably.

4.3. Material (Prepreg)

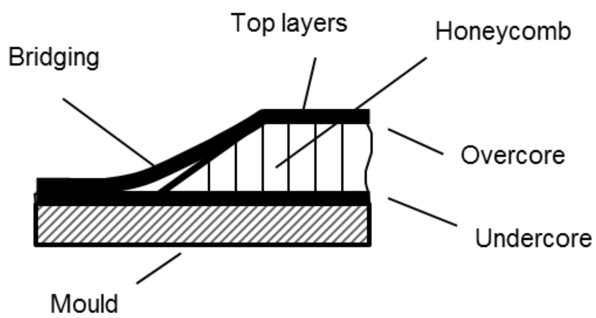
The material is decisive basis for performance and feasibility of the technology for H/C sandwich structures. It has great impact on the range of application of parts as well as on layup quality and process stability.

First step was the definition of requirements and the selection of materials to ensure the best performance in the combination of AFP slit tape material, core material and adhesive films in terms of requirements and lay-up quality. With a first set of AFP manufacturing parameter it was possible to learn the technologies basics and iteratively improve performance using a generic test part.



Generic test part

Sufficient tack of the AFP prepreg material has to be ensured in order to guarantee adhesion of the tows to the substrate. This is especially valid for the chamfers of the sandwich areas if the fiber direction is not rectangular and the risk of fiber bridging occurs. Other critical areas are cut-outs and edges. This is especially challenging when placing fibers in concave geometries in the vicinity of sandwich core ramps, as a bridging effect often occurs then.



Bridging effect

The complexity of the geometry to be laid up is limited by the machine’s geometrical properties, i.e. prohibiting layup radii <400mm due to collisions of the machine head with the mold.

Further research was conducted in order to find the material suited best as a core material. Properties of the core material influence many parts of the process, i.e. easy manufacturability of the core geometry, shelf life, sensitivity to heat and compaction during layup and pressure sensitivity during curing. During layup, heat conduction properties of the core material influence the layup quality in sandwich areas. Furthermore, the core material affects crash resistance and other mechanical characteristics of the cured part.

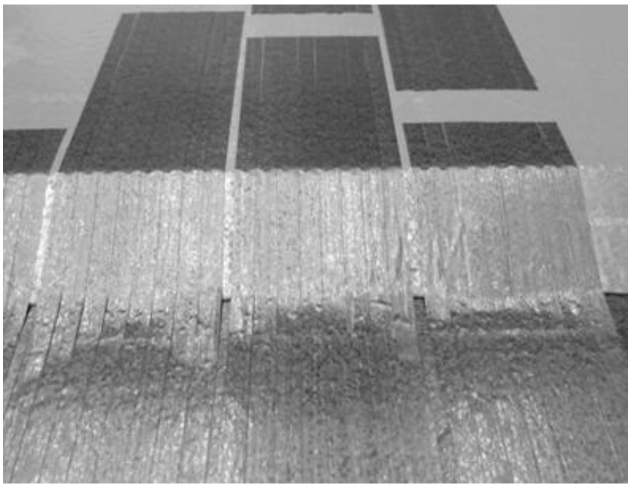
4.4. Design and AFP strategy definition

The results of simulations of the lay-up strategy as well as of the lay-up process itself were used in the following optimization loops to generate suitable test part designs. One important result was the definition of the lay-up strategy in terms of constant angle versus an angle offset programming to ensure a best fiber orientation and the gap and overlap strategy.

In parallel, the limits and tolerances of the AFP process were identified based on effects of defects tests, taking into account technology specific failure effects.

During the course of numerous experiments, guidelines have been developed for AFP-friendly specific design. This includes geometries of core ramps, cut-outs, inter-core-gaps, in and out of plane fiber radii and more.

One of AFP technologies' advantages is cutting on the fly without impact on lay-up rates. As the tests revealed, bridging in ramp areas is decisively increased by acceleration of the AFP machine on the sandwich core field that causes tension of the Slit Tapes with the result of debonding in ramp areas. To mitigate this effect without slowing down the machine, a cutting strategy is a promising solution.



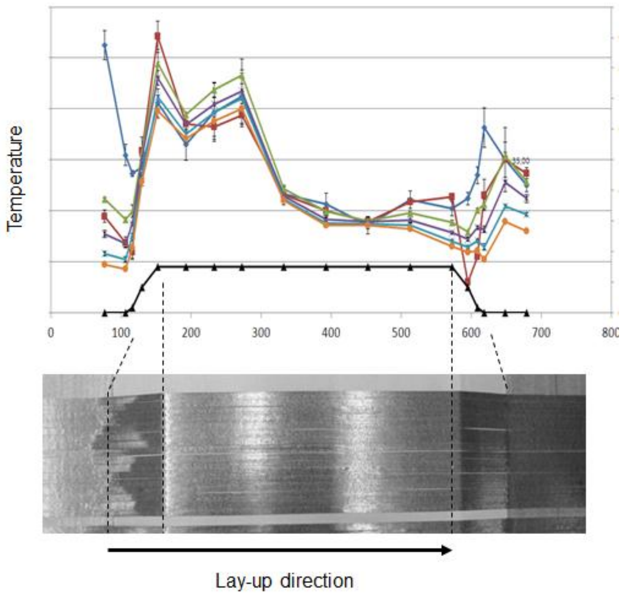
Decreasing bridging effect due to different cutting strategy

The test scenario encompassed varying distances between ramp edges and cutting lines in combination with differing lay-up speeds to show the limits. As this strategy has great potential for fibre orientation perpendicular to core ramps, the AFP machines capabilities impeded the usage for angular fibre orientations, required for H/C basis laminates.

As mentioned before, originally focus was set on research of AFP specific sandwich core design. In particular adapted ramp section geometries have been developed with improved harmonic characteristics to avoid or decrease a potential appearing bridging effect.

4.5. Temperature distribution

During the manufacturing trials, temperature tests were conducted to ensure a homogenous heat distribution to guarantee sufficient tack between the fibers and the substrate without overheating (precuring) any of the materials involved. These tests revealed a very inhomogeneous temperature distribution with peaks close to the slowly passed ramp areas.



Temperature distribution of the different courses of typical sandwich layup

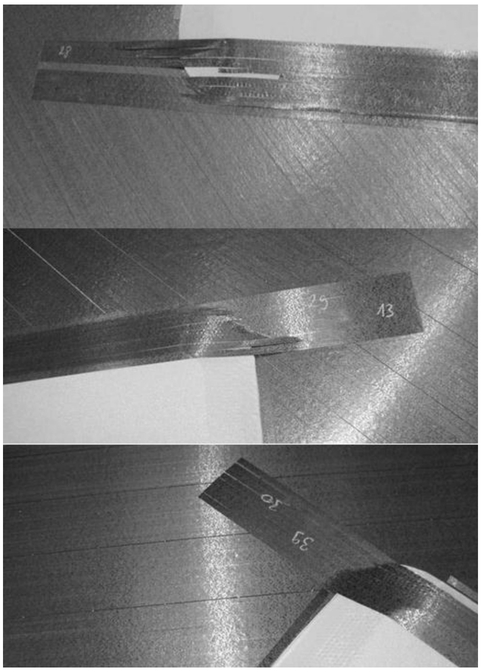
The highest, flat peak was found at the first (up-) ramp, while a lower, more acute peak is encountered at the down-ramp. The measurements show the lowest temperatures just prior to the first peak, i.e. at the beginning of the first ramp. This behavior is caused by the ramp and head tilting for collision avoidance partially shielding the substrate from the lamp and is responsible for the strongest bridging effects encountered when the ramp is ascended. Optimization of the parameters in the ramp-up area showed the desired effect of minimizing bridging under specific fiber orientations. In conjunction with that also the insulation effect of the honeycomb core material has been validated in the temperature tests. The average temperature is significantly higher compared to monolithic areas with same layup speed depending on tooling material. This effect is minimizing with increasing layer in a linear matter.

A sufficient level of tack is especially important for curved sandwich parts as otherwise the fiber layers disband before the next AFP courses are applied.

Curved sandwich areas with insufficient and sufficient tack

4.6. AFP parameters

Test series showed that appropriate parameters were depending on the temperature, the linked lay-up speed and of course, the substrate. Roller pressure and balancing of the AFP head angles showed wider tolerances for adequate results. Using lightweight but less tacky adhesive films demanded for severely slowing down the machine in front of ramps and corners with the heater pointing at the ramp-up area as shown formerly in the temperature test scenario. This then properly activated material in the ramp-areas showed two main effects during lay-up. Inaccurate feeding under correct temp settings leads to an excessive bridging effect.



Improvement of layup quality on sandwich edges

Different tow lengths per course in small radii lead to loops with sizes depending on the overfeed rate. These loops are also defects, disturbing the fibres with ondulation effects. Inaccurate feeding revealed a higher contamination of the laminate with abrasive slit tape wear ("fuzz balls").

As per ply or section several sandwich fields have to faced, an optimal (ramp-) centered approach with full tow count at each core ramp or core edge is not feasible in most cases. Courses have to be subdivided into suitable sub-courses to ensure proper contact of the AFP roller in the sandwich ramps and corners and subsequently the bonding of the material. This procedure is contra productive to the overall layup rate, therefore minimizing these effects has to be performed in design process already. This is just one example for an essential provision of a design guide document in the preliminary and detail design stage of AFP part development.

5. AFP H/C BOTTOM SHELL

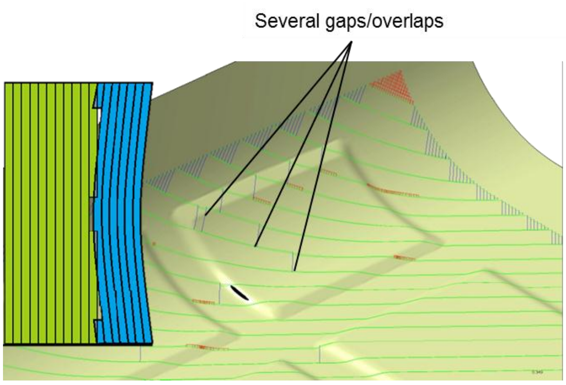
Based upon the results described above, demonstrator parts were designed to prove the feasibility of AFP-laid-up shell parts as well as to verify the guidelines specified in the design guide.

A bottom shell as a typical shell element was designed to test the AFP machine parameters established in the test series explained above. Honeycomb cores with non-perpendicular edges and core filler have been introduced as challenges in the core area, as well as reinforcement plies in monolithic areas in order to obtain sufficient material strength for riveting.

For spherically curved surfaces, it is not possible to place all fibers with the same orientation without gaps. Using the layup strategy "Angle Offset", a direction is defined for one position. Each tow is then placed adjacently to the neighboring tow, leading to angle deviations in heavily curved areas. When using a "Constant Angle" Layup Strategy, all tows are placed with the same orientation. In spherically curved geometries, this leads to gaps or overlaps. The amount of gap/overlap can be defined during the programming stage. Further strategies are possible and can be defined i.e. by combining the two strategies through a maximum angle deviation. If a maximum deviation is exceeded, the original orientation is restored. Using this strategy, gaps and overlaps only occur at the borders of sectors.

To be able to evaluate the effects in reality after the curing, the bottom shell has was designed and manufactured, using both "Angle Offset" and "Constant Angle" strategies.

Parts have been built using the “Constant Angle” strategy with 50% gap/50% overlap as well as 0% gap /100% overlap. The “0/100”-strategy makes for a gapless layup and thus guarantees all points of the part to be covered by at least the specified number of plies (within tolerance). This strategy shows spots with notably higher thickness due to overlapping carbon fiber tows.



Gaps and overlaps appearing at constant angle with 50% gap/overlap

In an iterative process, both machine parameters and layup programs have been optimized in order to obtain most constant and satisfying layup results.

6. CONCLUSION

The demonstrator has fulfilled the expectations to prove the general feasibility of complex helicopter sandwich parts to be produced by Automated Fiber Placement.

Cured AFP H/C bottom shell

The key potential of the technology was found in a considerably higher layup rate compared to manual layup and more consistent part quality as well as largely reduced scrap rates since no cutting is done until the part is cured, thus reducing both cost economic and ecological impact..

Dealing with an automated process sets up also the demand for adapted data interfaces between the sub process chains. Stepping into the perimeter of manufacturing, the principal interaction between material suitability for processing, design requirements and machine performance were investigated to develop a first robust parameter set to an optimized one.

The advance from a manual CFRP layup process to the automated AFP can contribute to a more automated and highly repeatable composite part production. For complexly shaped helicopter sandwich structural parts, AFP has been found to be the best fitting automated process of today’s range of technologies. It has been proven possible to build larger helicopter sandwich shell parts like bottom or side shell elements using this approach. The process has been optimized and most risks and challenges identified, making series production of AFP-parts conceivable.