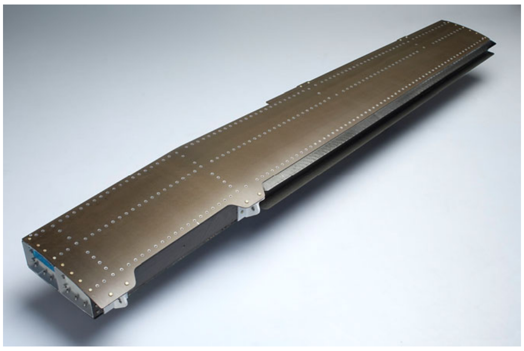
Nationaal Lucht- en Ruimtevaartlaboratorium
National Aerospace Laboratory NLR

Executive summary

Development of a cost effective composite wingbox for small aircraft



Report no.
NLR-TP-2010-047

Author(s)
R. Klomp-de Boer

Report classification
UNCLASSIFIED

Date
August 2010

Knowledge area(s)
Lucht- en ruimtevaart constructie- en fabricagetechnologie

Descriptor(s)
Automated Fibre Placement
Cost price
Automation
Design for Manufacture
Co-bond

Introduction

Composites have become well established within primary and secondary aerospace structures mainly because of their superb performance-to-weight ratio. However production costs and time-to-market are becoming increasingly decisive factors in the design, both for the large and small airplane manufacturers. Composite material raw prices are comparatively high and the key to cost reduction lies in part count reduction and automating manufacture using techniques such as Automated Fibre Placement (AFP).

Within the EU funded project CESAR (Cost Effective Small Aircraft) NLR has helped to develop and manufactured a semi-span composite wingbox representative for small aircraft. This was done together with other partners, being Piaggio Aero Industries, CIRA, MERL, HAI and IoA. VZLU has performed the full scale static test on the assembled wingbox and has manufactured the metal hinge brackets for the wingbox.

Description of work

Several wing box concepts have been created and reviewed resulting in two final concepts recommended for further detail design.
To facilitate this process and minimize the number of design iterations. NLR was responsible for the AFP manufacture and assembly of the wingbox. Therefore, in order to facilitate this process and minimize the number of design iterations NLR created a report containing input for design.
To enable the comparison with the aluminium benchmark wingbox, all costs aspects for the composite wingbox have been investigated and

This report is based on a presentation held at the SAMPE Conference and Exhibition, Seattle (U.S.A.), 17-20 May 2010.

used to create a technical cost model.

Manufacture of the spars and skins and assembly of this composite multi-spar wingbox concept took place at NLR. The Catia models provided by Piaggio were the basis for the AFP tooling design by NLR. The tooling was manufactured at NLR. The skins and spar were manufactured with AFP. The assembly phase consisted of co-bonding cured spars to the uncured, placed lower skin. After machining of the co-bond, the RTM ribs from CIRA and aluminium closing ribs and brackets from Piaggio respectively VZLU were installed. The wingbox was closed by bonding the machined upper skin and installing Composi-Lok blind fasteners.

Results and conclusions

The main result of the CESAR subtask Composite Structure – Wing is that it has proven feasible to achieve both weight and cost reduction for a wingbox using advanced composites and AFP compared to the aluminum version. The design guidelines developed in this project and the experience gathered and documented are essential input for the development of reliable and affordable design tools. The use of these tools such as Input for Design guidelines allows the introduction of concurrent engineering and remote team collaboration shortening the design process as was demonstrated during the CESAR project in the development of the composite wingbox with Piaggio and other subtask partners. Both the time-to-market and development costs will profit from this, contributing to achieving these CESAR goals.

Applicability

The input for design can in general be used for any composite torsion box (e.g. wing, horizontal and vertical tail) to create a design fit for manufacture using Fibre Placement.

The generated technical cost model, production times and cost data are applicable for any composite aerospace structure such as a wing box and help to determine a more accurate cost estimate for both feasibility studies and detailed design.

The manufacturing concept and method developed and experience gathered and documented can be used for any composite wingbox such as wings for small aircraft, or stabilizers on larger aircraft.

Nationaal Lucht- en Ruimtevaartlaboratorium
National Aerospace Laboratory NLR

NLR-TP-2010-047

Development of a cost effective composite wingbox for small aircraft

R. Klomp-de Boer

This report is based on a presentation held at the SAMPE Conference and Exhibition, Seattle (U.S.A.), 17-20 May 2010.

The contents of this report may be cited on condition that full credit is given to NLR and the author.

This publication has been refereed by the Advisory Committee AEROSPACE VEHICLES.

Customer	European Commission
Contract number	AIP5-CT-2006-030888
Owner	NLR
Division NLR	Aerospace Vehicles
Distribution	Unlimited
Classification of title	Unclassified
	August 2010

Approved by:

Author	Reviewer	Managing department
16/08/10	18/08/10	18/8/10
R. Klomp – de Boer	H.P.J. de Vries	H.G.S.J. Thuis

Contents

Development of a cost effective composite wingbox for small aircraft

Ronald Klomp – de Boer
National Aerospace Laboratory NLR
Voorsterweg 31
Marknesse 8316 PR The Netherlands

ABSTRACT

Composites have become well established within primary and secondary aerospace structures mainly because of their superb performance-to-weight ratio. However production costs and time-to-market are becoming increasingly decisive factors in the design, both for the large and small airplane manufacturers. Composite material raw prices are comparatively high and the key to cost reduction lies in count part reduction and automating manufacture using techniques such as Automated Fiber Placement (AFP). Within the EU funded project CESAR (Cost Effective Small Aircraft) NLR has helped to develop and manufactured a semi-span composite wingbox representative for small aircraft. This was done together with other partners, being Piaggio Aero Industries, CIRA, MERL, HAI and IoA. VZLU has performed the full scale static test on the assembled wingbox and has manufactured the metal hinge brackets for the wingbox.

This paper describes the development and manufacture of this composite multi-spar wingbox concept, with specific details on design for manufacturability when using composites and AFP, design and manufacture of AFP tooling, AFP manufacture of spars and skins, assembly of the composite wingbox and cost - weight comparison with the aluminum benchmark wingbox.

1. INTRODUCTION

The percentage of fiber reinforced materials (composites) in primary aircraft structures continues to grow. With this growth comes demand for continuous improvements in manufacturing technology. The most common manufacturing technology for composites used today involves manual stacking of pre-impregnated sheets of material followed by cure in an autoclave. It uses complex tooling and precludes a high level of part integration, increasing assembly effort. Hand lay-up of cut prepregs is labor intensive and a highly trained technician can place just about over 1kg per hour. With AFP this could be increased to 6.5 to 11kg/hour for complex tools and for cylindrical parts even up to more than 20kg per hour [1]. The capital investment of a few hundred thousand to several millions Euros for AFP machinery can be more than compensated by this increase in lay-up rate, whereas the costs of labor will only increase in future. Combined with other advantages of AFP over hand lay-up such as very precise ply thickness control, in-process compaction, high consistent quality, low void content (typically < 1%), unlimited fiber angles (tow path optimization) and low material scrap rate (5 to 20%). To summarize the above, the Boeing 787 would very likely not have been built without the development of AFP [7].

1.1 CESAR project

CESAR is focused on increasing the competitiveness of European manufacturers of small-size aircraft and their supply chain. A way of achieving this is thru the development of a new concept for this type of aircraft using improved technologies reducing the time-to-market and lowering the costs, while considering safety, environmental impact and comfort. In order to sufficiently cover all these complex issues, CESAR consists of five RTD areas, namely aerodynamic and structural design, propulsion integration, aircraft system optimization and design integration aspects. The goals of the CESAR project are to reduce the current time-to-market of 6-7 to 4 years, reduce the development costs by 20-25% and the manufacturing and assembly costs by 16-20% depending on the type of propulsion [2].

The project is partially funded by the European Commission under the 6th Framework Program and coordinated by VZLU.

1.2 CESAR subtask Composite Structure - Wing

The aluminum front wing of a small canard business aircraft (Piaggio P180 Avanti) serves as a model in this study, see figure 1. The aluminum front wingbox consists of two spars which have been split up, 15 ribs and an upper and lower skin with integrated stringers. Flaps are connected to the rear spar. The front wing is joined to the fuselage using fittings at the front and rear spars. The general front wingbox dimensions are span 3230 mm, chord 314 mm and height 100 mm.

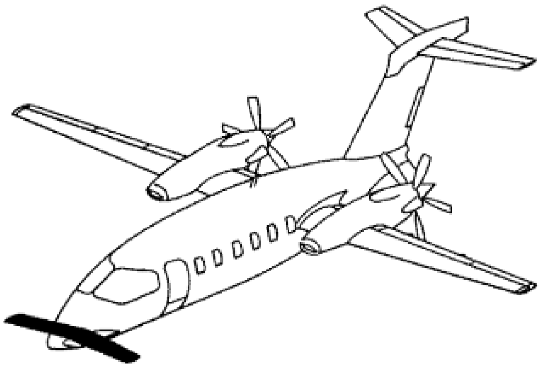


Figure 1. Piaggio P180 Avanti showing location of the forward wing [source Piaggio]

This paper describes the work performed by NLR on the development and manufacture of a composite multi-spar wingbox concept, with specific details on design for manufacturability when using composites and AFP, design and manufacture of AFP tooling, AFP manufacture of spars and skins, assembly of the composite wingbox and cost - weight comparison with the aluminum benchmark wingbox.

First step in the development of the composite wingbox was a feasibility study with the aim of selecting the basic structural concept and manufacturing method. A multispar concept with monolithic skins manufactured using AFP was considered the best choice based on the evaluation performed. This is considered the starting point of the wingbox development described in this paper.

The detailed CATIA design and stress analysis were performed by Piaggio and HAI, whereas MERL and IoA were responsible for the composite material, adhesive and mechanical joints testing and VZLU for the full scale wingbox static test. CIRA has developed the composite ribs using RTM technology. These aspects will not be described in this paper.

2. INPUT FOR DESIGN

2.1 Wingbox sub-concepts

AFP offers advantages, but there are some hurdles to overcome before it can be successfully integrated. Besides the investment cost, there is a learning curve. Designers will have to learn to design composite structures that work and integrate or in other words are compatible with AFP software, requiring engineers to learn the fundamentals of automated fiber placement and how it works with the design [1]. To facilitate this process and minimize the number of design iterations NLR being responsible for the AFP manufacture and assembly of the wingbox created a report containing input for design. An essential part of CESAR is cost effectiveness. The input for the design is therefore mainly manufacturing driven consisting basically out of two parts. First part covers the material selection and further development of sub-concepts for the multispar wingbox. This is followed by specific design, manufacture and assembly issues related to AFP and composites. Part of this Input for Design will be described in this paper.

The input for design started with the selection of the material for manufacturing the skins and spars. Two major aerospace prepreg suppliers are Cytec and Hexcel. They can supply a wide range of epoxy resin and carbon fiber combinations in slit tape configuration. Important selection criteria for CESAR are costs and availability both in lead time as well as minimum order quantities. As a baseline material Hexcel’s AS4/8552 has been selected. This material has been used in various aerospace structures and is well known. It was used in a cost-weight study performed by NASA [3] it has been recently used in for example Dassault F7X horizontal tail plane, A380 Tail Cone & Fixed leading Edge Lower Panel, B787. It is also directly available in slit tape. The AS4/8552 slit tape (HexPly AS4/8552 RC34 AW194) has been successfully used in the A380 Tail Cone. It is important to note that the NLR has good experience with AS4/8552 slit tape. It has shown good process ability which helps in creating a robust product.

Figure 2 shows the basic cross section of the forward wing with three spars, the structural concept following from the trade-off study. The location of the three spars in chord direction is assumed to be relatively fixed and no major relocating is allowed or possible considering the relatively small chord as this would have a large impact on the overall stiffness and loading of the structure.

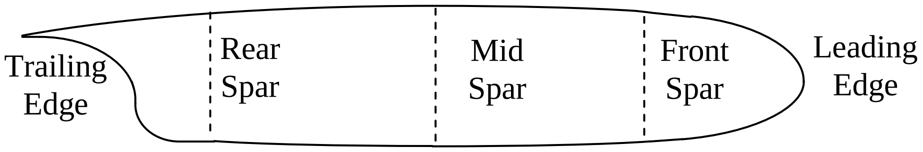


Figure 2. Basic cross section of the forward wing

Starting with this basic cross section, sub-concepts for the wingbox can be created. The following boundary conditions and requirements were applied.

- Outer contour of upper and lower skin panels fixed and determined by aerodynamic requirements.

- Leading edge (LE) is removable allowing installation & inspection of the de-icing system and fastening areas.
- Contour of trailing edge (TE) is fixed and determined by the specially contoured slot required for an effectively working single slotted flap with fixed hinge.
- The spars are continuous from tip to tip and the ribs are split.

Like many other aircraft the Avanti P180 has a removable leading edge which contains the de-icing equipment. For ease of access, maintenance, repair or replacing the leading edge needs to be removable. This requirement has implications for the design of the front end of the wing box. In general it is preferred to keep the geometry of the LE simple and to avoid a step (joggle) at the interface with the wing box, but to incorporate this at the wing box side. The step in surface profile at the wing box side required to enable installation of the leading edge can be made in the skins themselves. This is a common approach in composite skins of wings, flaps, horizontal stabilizers etc. for example the Airbus A320 composite flap [4]. Also doublers or the front spar flange can be used for attachment, with the flange facing either outward or inward. In general the same concepts can also be generated for the trailing edge, with the exception that the trailing edge is often fixed and could become an integral part of the skins. Besides having to accommodate for attachment of the leading and trailing edge, the skins, spars and ribs also need to be attached to one another. Joining methods considered for this wingbox were co-curing, co-bonding, secondary bonding and fasteners.

The above described creation of basic concepts for structural elements in the wingbox allows for a methodological design approach. Combining these different concepts in a morphologic table helps visualizing the possibility of combining sub solutions to create several overall concepts. Five basic concepts were created with joggles, doublers, outward and inward facing spar flanges, etc. These concepts in turn were evaluated using weight factors and scoring on costs of material, AFP programming & operating, tooling, assembly, wingbox to fuselage attachment, weight and repairability. Figure 3 shows the outcome, which is a combination of the two best scoring concepts. At the leading edge a doubler is preferred minimizing the gap and step between leading edge and skins. The trailing edge has a much smaller thickness allowing the use of a small joggle in the skins. Inward facing flanges on the front and rear spar allow the manufacture of two mirror C-section spars on a single tool, which are easy to release with corner angles greater than 90deg.

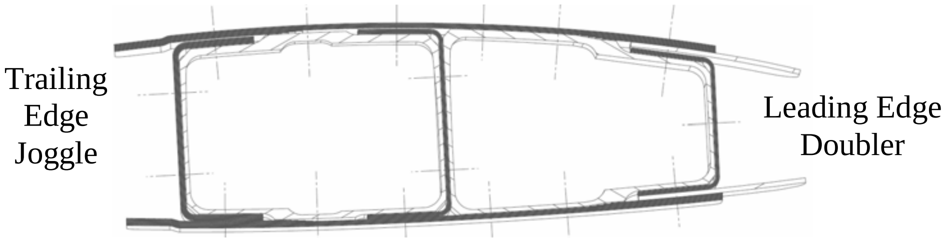


Figure 3. Cross section of the wingbox showing combination of preferred concepts

Although the evidence is incomplete on whether co-bonded joints develop the same structural performance levels as co-cured joints at the present it is generally assumed that co-bonding is not inferior to co-curing [5]. With secondary bonding still posing many quality and certification issues, it was decided to co-bond cured spars to the lower skin and mechanically fasten the upper skin to the framework of spars and ribs. The ribs were originally designed using a RTM resin with insufficient Tg, preventing co-bonding these as well to the lower skin.

2.2 Link between wingbox design and manufacture

The resulting wingbox design with its nomenclature is shown in figure 4.

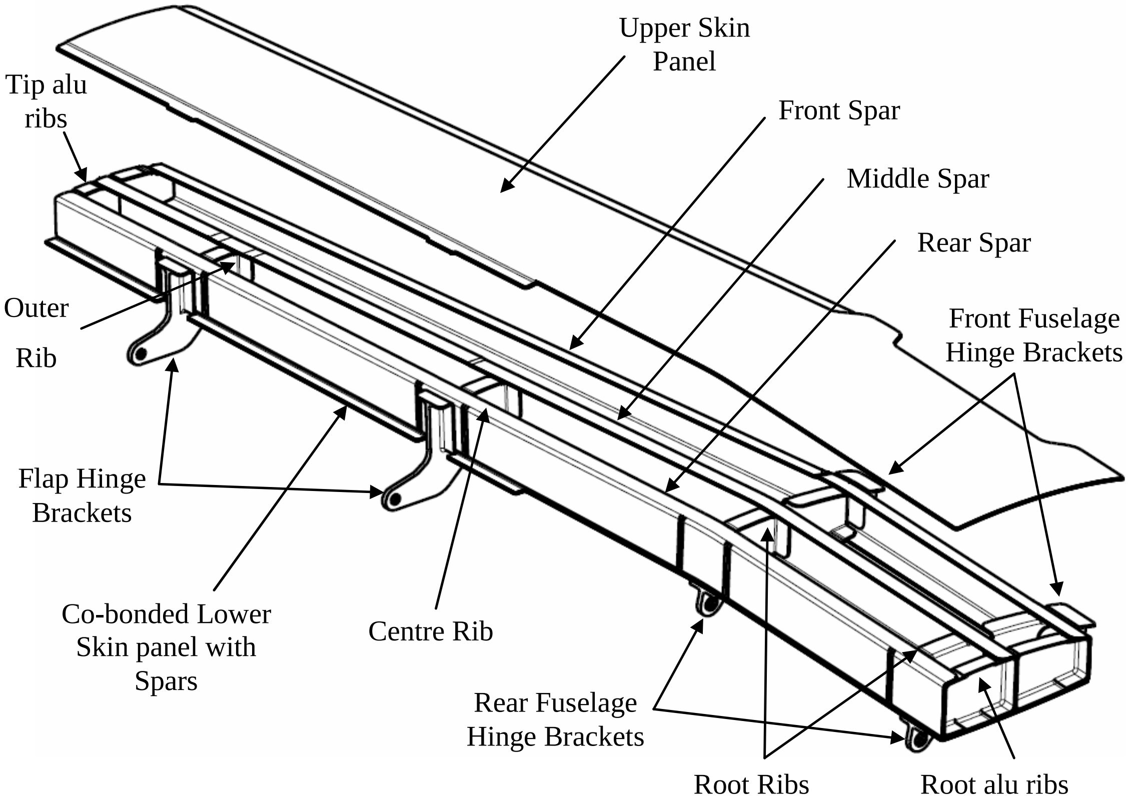


Figure 4. The CESAR forward wingbox running from center box to port side tip with aluminum root and tip ribs added for testing

The CESAR wingbox has been limited from port tip to center wingbox because of the current autoclave and AFP machine limits at NLR, but is still representative for all the design and manufacture features. For the detailed design of the spars, skins and assembled wingbox NLR provided input establishing the link between design and manufacture using AFP.

The wingbox has a small sweep back and anhedral angle, resulting in kinks in the spars and skins. The kink angle that can be manufactured is limited by the maximum slope angle the AFP deposition head can overcome before the torch collides with the tool surface. This proved no problem with a maximum anhedral angle of 5 deg.

An important consideration in the laminate lay-up scheme design is that the spars can be manufactured on a mandrel in a way that resembles filament winding using symmetric rotation moulds. This approach minimizes the number of cuts, stops and starts and maximizes the efficiency of the fiber placement process. The ply build up for the spar web and flange should then preferably be such that the 45 and 90 deg plies are continuous.

Another important design consideration is that fiber placement machine at the NLR places tapes with a total width of 12.7 mm (4x 1/8 inch) without individual tow management. In combination with the limited spar web height and flange width, this eliminates the design of local 45 deg plies in these spar elements otherwise creating unacceptable large triangular gaps. The spars are perfectly suited for placing local 0 deg plies, allowing stiffening the spar flanges increasing the wing bending stiffness.

The distance between the roller and the cutter blade, also known as “cut distance” determines the minimum length of the tapes, and as mentioned above the tapes have a fixed width of 12.7 mm. These two determine the dimensions of local reinforcement pads as shown in figure 5.

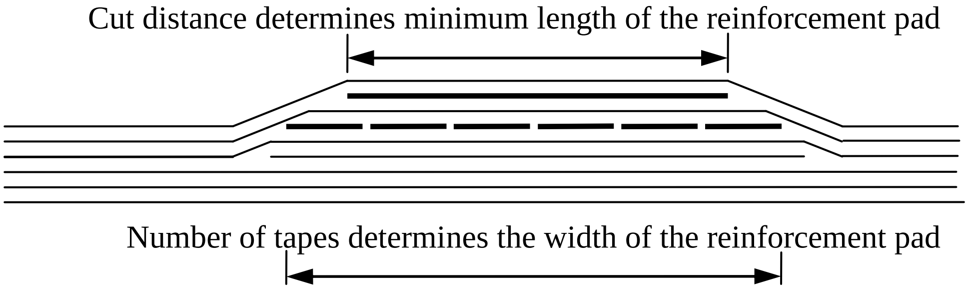


Figure 5. Link between cut distance, tape width and dimensions of reinforcement pads

A consequence of working with tapes with a fixed width is that unless they can all be placed parallel to the part contour, gaps and overlaps will occur. Vice versa if the tapes are only placed parallel to each other over the entire part surface, part of the tapes will not run parallel to the part contour. This is schematically shown in figure 6 as option 2 respectively option 1. This also highlights the importance of defining clearly the ply orientation in each part of the product. The CESAR wingbox has a limited sweep back angle and the majority of the plies have been placed according option 1. Only from the center to tip rib, where the skin was locally reduced in thickness, the skin was provided with local 0 deg plies parallel to the front and trailing edge over the width of the spar flanges. In the lay-up for the skins a minimum thickness was used to accommodate for the countersunk head and to provide sufficient cylindrical height for the shank of the fastener.

The same situation occurs in an even more challenging way for the AFP manufacture of the spars. Whereas for the placement of the skins there is room for placement outside the net contour, the spars manufacturing concept was to place these as two mirror C-section on a single mandrel. The contour of the spar web within which has to be placed is fixed and. Starting from the top using fiber steering to create parallel tapes as far as possible, this results in gaps at the other side as shown in figure 7 (red tapes). Excessively large gaps need to be covered by an additional tape to meet the full lay-up requirements, but in the case of the spar web results in overlaps as shown in figure 7 (blue tape). By changing the placement strategy stacking of overlaps at one location and consequent irregular laminate thickness can be avoided, which is especially of importance at interface locations such as at the fuselage and flap hinge brackets mounting areas.

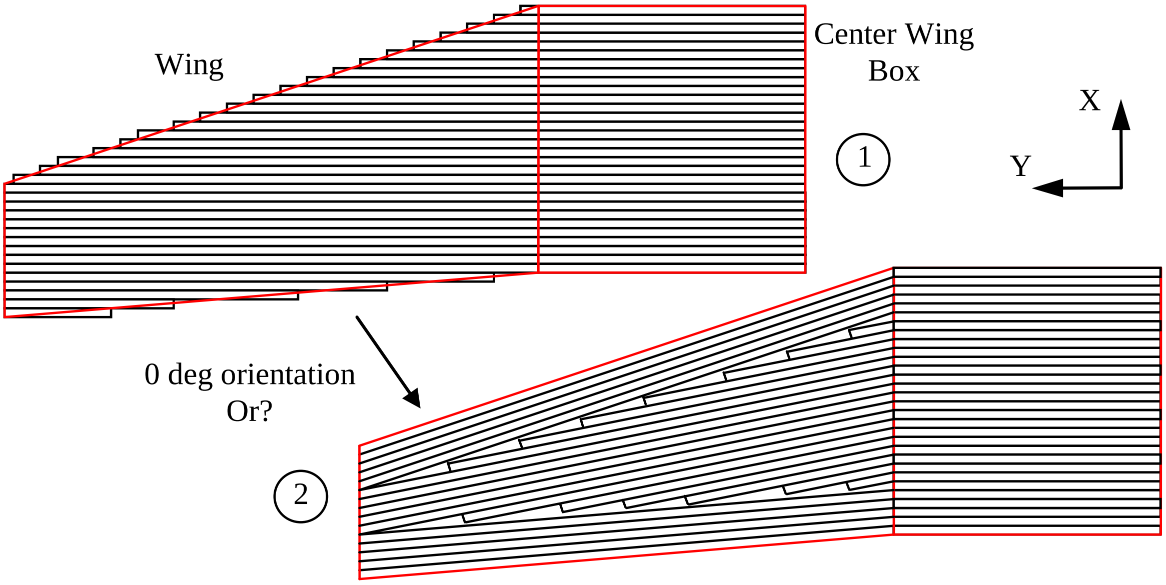


Figure 6. Effect of placing tapes parallel or steering to follow wing contour

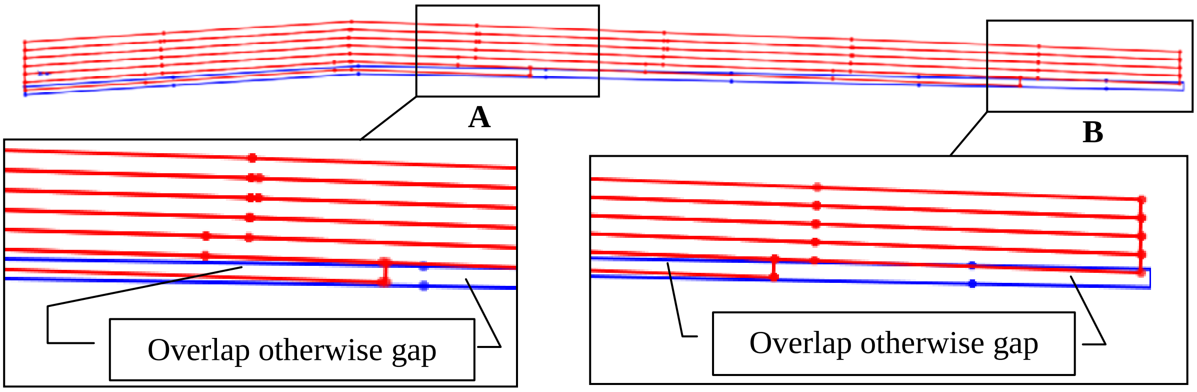


Figure 7. Effect of fixed tape width on spar web lay-up resulting in overlaps or otherwise gaps

3. MANUFACTURING

3.1 Spars and upper skin manufacture

For the manufacture of the spars and skin tooling the low costs, ease of manufacture, light weight and quick availability of aluminum were decisive in this research project. The aluminum spar tool could be quickly and easily machined from standard available aluminum 2024T3. The skin tool is made of aluminum 5083 enabling to manufacture a welded egg crating backing structure with skins on both sides. The egg crating allows gas to flow thru the tooling while the skins on both sides create a torsion stiff box. The aluminum spar and skin tools are provided with removable steel end fittings. Both the spars and skins were to be placed and cured on the same aluminum tool. The main disadvantage of aluminum is the large difference in coefficient of thermal expansion (CTE) with composites. In the design of the aluminum tooling this has been accounted for.

Using a rectangular shaped aluminum mandrel with a 3 mm corner radius similar to the wingbox spars, test spars were placed to determine the springback angle and laminate quality. Figure 8 shows the basic spar lay-up with the local 0 deg reinforcement plies in the flange stopping before the radius, squeezed to a nice taper.

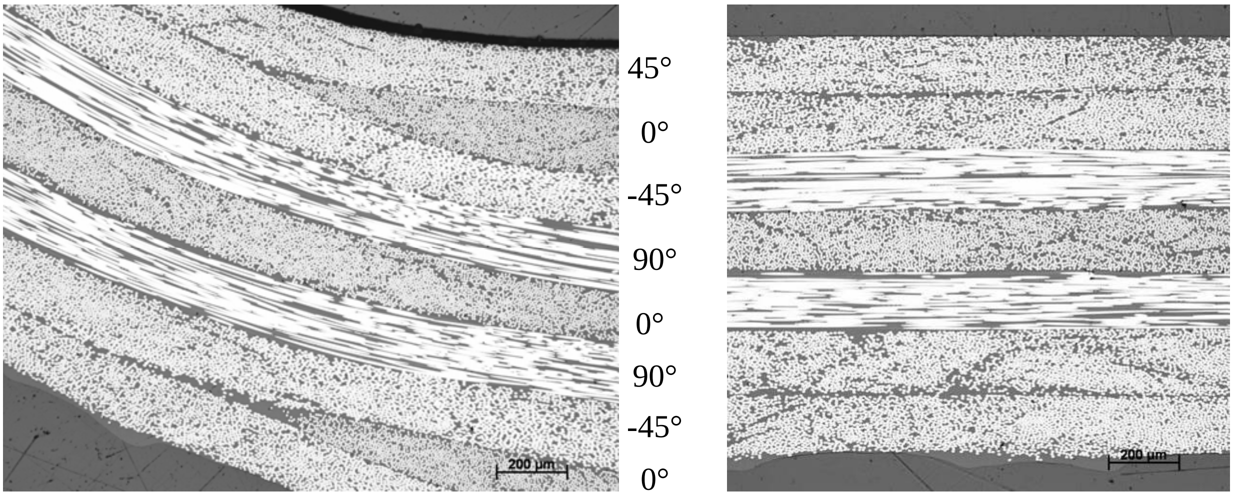


Figure 8. Cross sections at radius spar flange and of spar web lay-up

The Catia models provided by Piaggio and the springback angle formed the starting point for the spar and skin tooling design in which the difference in CTE has to be compensated for. However unlike with hand lay-up tooling, AFP tooling poses extra challenges. For example the AFP machine has a machine zero point and limits within which parts can be placed. Tooling including the spindles should be designed such that the entire gross laminate fits within these machine limits. Also to ensure proper alignment of machine head with tool and part additional tool features such as the markers for location of the Y-axis and machine zero point were incorporated. Machining of the parts required separate tooling and moving parts from the AFP-cure tool to machine tools. For proper relocating the parts on the machine tools, small markers (dimples and cones) were incorporated in the AFP-cure tools.

The AFP skin tool needs to be transported in several occasions, from mould storage into the AFP machine and after placement and bagging into the autoclave. To facilitate handling of the AFP skin tool, four fittings were designed, two on each of the longer sides. These fittings were provided with thread for installing threaded lifting lugs on which standard lifting hooks can be attached. Combined with a lifting traverse this enabled moving the AFP skin tool around the workshop. The four fittings were designed as round bars also allowing easy placement on the autoclave cart which was modified with four vertical supporting beams.

For the manufacture of the skins there are several options. One could place the skins on a dedicated AFP mandrel and cure them on a separate female tool ensuring the skin outer surface is smooth. In the CESAR project it was decided to use a single tool for placing and curing of the skins minimizing number required of tools. This however implied solving two problems. Part release after cure requires the use of a release agent, however this non-stick layer also prevents proper placement of the first ply especially on a concave tool. To solve this first a tacky layer needs to be applied. For this contact spray adhesives were tested, but not with satisfactory results. Eventually as most aircraft wings need to be provided with lightning strike protection, first a ply of bronze wire mesh with the same 8552 resin from Hexcel (HexPly CuSn6/8552 AW80) was applied providing sufficient tack. AFP manufacture of the skin and spars is shown in figure 9.

Figure 9. Fiber placement of lower skin and last 45 deg ply on middle spar

Secondly to avoid the need for separate curing and machining steps, the doubler should be integrated in the skin placement and cure. The doubler was made separately on a flat tool with AFP and cut to net contour using an automated cutter. Using a 0.2 mm teflon strip between the skin and doubler, positioned 3 mm away from the skin net contour, allowed contour machining of the skin with a 6 mm mill to the predetermined depth removing part of the skin and exposing the net shaped doubler. This approach avoided unfavorable planform milling of a step in the skin. The above described concept and resulting machined upper skin at leading edge are shown in figure 10.

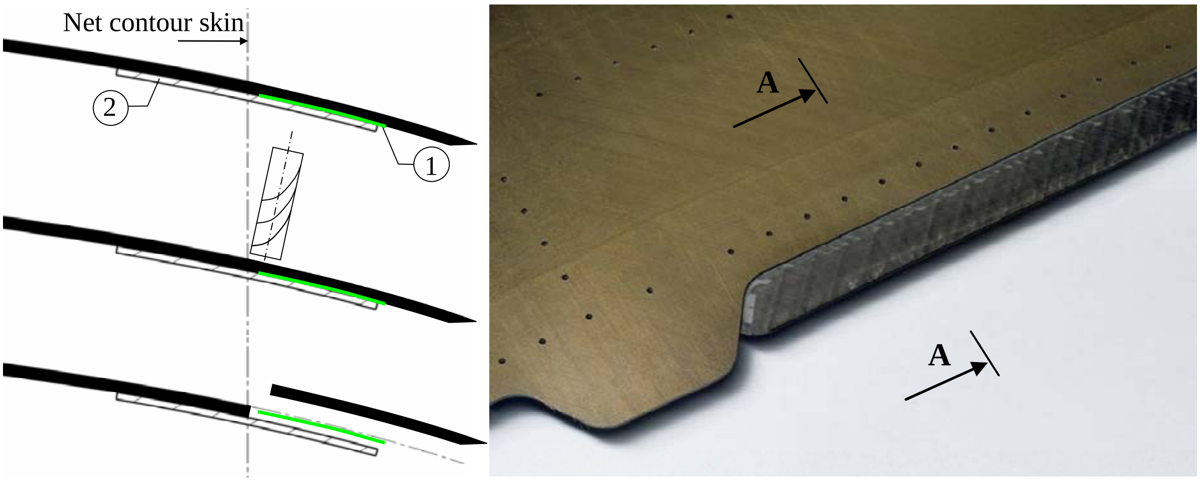


Figure 10. Concept for manufacturing skins with integrated doubler, 0.2mm teflon strip (1) and (2) doubler strip, and resulting machined upper skin at leading edge

It should be noted that the spars required joggles to accommodate the thickness changes in the skins at the pockets and doubler. Although these joggles should be part of the hardware, these do not have to be part of the virtual mandrel used in the AFP programming. The AFP process with thermoset tapes makes use of a flexible compaction roller which can follow the joggles without the machine head actually having to follow these steps. Incorporating these joggles as part of the programmed placement trajectory would unnecessarily complicate the placement process and reduce the efficiency.

Because of time and budget limits it was not possible to adapt the AFP lay-up and cure tooling for dimensional deviations using an iterative process of manufacturing parts and measuring them and adapting tooling. To avoid mismatches between parts and machine tooling, for the machining of the spars and upper skin, PUR casting resin was used to make plugs. The use of these plugs ensured that the cured parts would fit firmly on the machining tool contour, which is essential for proper machining of thin composite laminates.

Manufacture of high quality laminate composite spars and upper skin with integrated doubler using AFP proved feasible. The fiber placement of the local reinforcement pads on the rear spar was however difficult because of their limited dimensions and the need for local 90 deg plies. It was concluded that for the manufacture of spars for small aircraft with limited web height, the overall lay-up can be created using AFP but the local reinforcement pads are more efficiently placed by hand using a laser projection system for correction positioning.

3.2 Lower skin co-bonding and wingbox assembly

The design of the composite wingbox allowed the application of co-bonding, hereby replacing the fasteners in the skin-spar connection by a structural adhesive joint. Compared to the aluminum wingbox this could result in significant fastener count reduction. It was preferred to use cured spars on an uncured lower skin allowing the use of light tooling. After placing the lower skin on the AFP-cure tool, the machined spars needed to be positioned at their final location. For this aluminum fixtures were developed compensated for the difference in CTE. These fixtures pushed the spars apart to their final chordwise position, but also allowed the spars to remain there while the aluminum fixture pitch reduced when cooling down from the 180 °C cure temperature. With the limited chord dimensions and resulting small expansion this could be achieved by using thin silicon rubber at the outer side of the spar fixture clamps. After successfully curing the first lower skin with spars, unacceptable geometric deviations were observed hampering the installation of the cured RTM ribs and aluminum end ribs. Geometric inspection of the spars revealed a secondary springback effect in spanwise direction probably due to the presence of the kink and deviating corner angles. As mentioned above the spar tooling could not be adapted within this project. To ensure the test wingbox could be assembled, the spars needed to be placed sufficiently apart to allow installation of the ribs. This was achieved using low cost tool made of standard aluminum L-profiles. By using a pin - slotted hole connection between the two L-profiles the aluminum tooling could be designed such as to push the spars apart at heating up to the 180 °C cure temperature and contracting without pulling at the spar webs. Figure 11 shows the spars installed on the lower skin for the second co-bond.

For the machining of the co-bonded lower skin with spars it was considered impractical to use PUR plugs after the experience with making plugs for the spars and upper skin. Therefore a

MDF tool was developed supporting the lower skin all round and in between the spars, hereby also fixing its position. See figure 11. Placing the co-bond in the MDF machine tooling required no undue force and despite the geometric deviations caused by the spars, both co-bonds were machined satisfactorily.

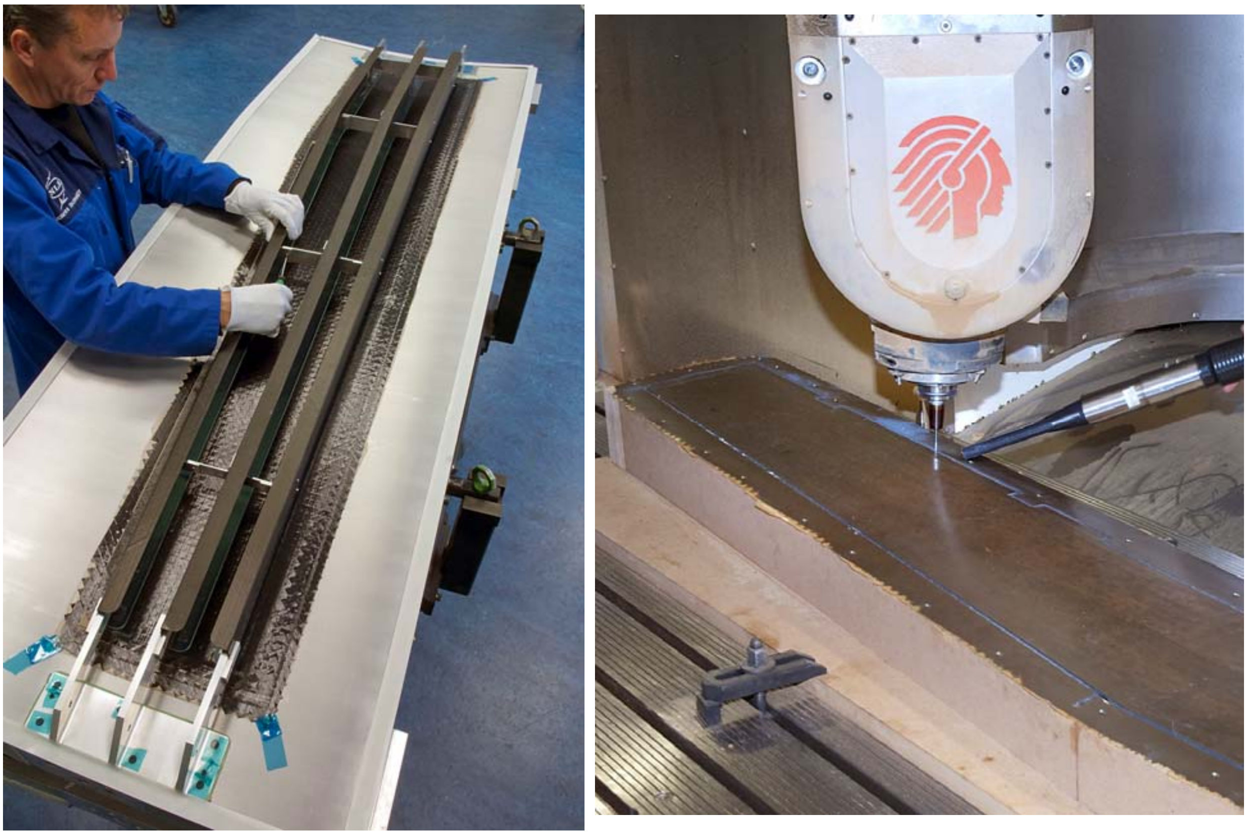


Figure 11. Spars installed on lower skin to be co-bonded and machining of the co-bond

After curing and machining of the second co-bond, assembly started with the installation of the machined RTM ribs, with three ribs provided with strain rosettes on the web, followed by installation of the fuselage and flap hinge brackets using Hi-Loks. The separately cured and machined upper skin was provided with a 3.2mm pilot hole pattern, which was taken over manually in the substructure. For series production it is recommended to drill these CNC ensuring a high constant hole quality. With the hole pattern in both mating parts, the upper skin was bonded using Hysol EA9394 and temporary fasteners. The Hysol EA9394 functions as a liquid shim eliminating gaps and differences between mating parts. The vacuum bag outer side of the spar and vacuum bag inner side of the upper skin are mating surfaces. After curing overnight, the hole pattern was manually reamed up and countersunk after which the countersunk Composi-Lok blind fasteners were installed. The final assembled wingbox is shown in figure 12.

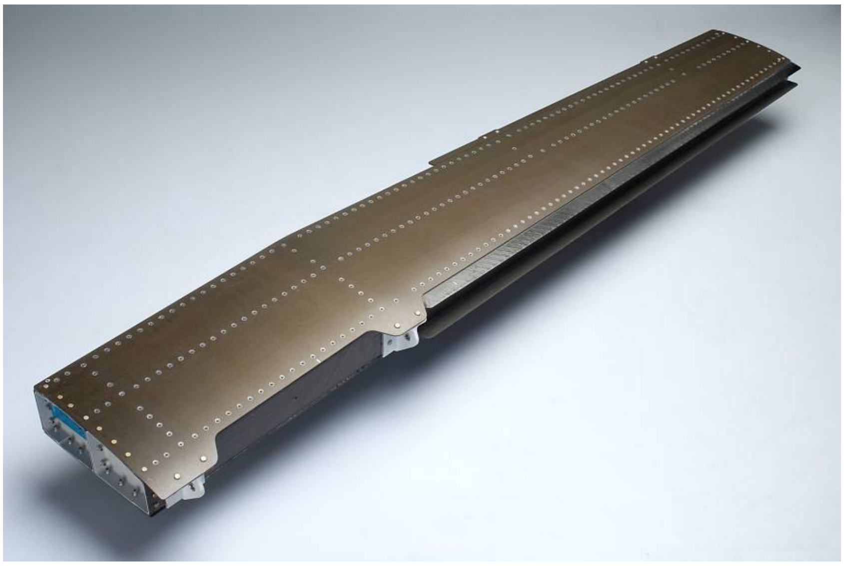


Figure 12. Assembled CESAR composite wingbox

3.3 Non-destructive inspection composite parts and assembly

Throughout the parts manufacturing process, the laminate quality was checked using NDI. For the separate parts the C-scan immersion technique was used, see figure 13. Full immersion in water provides a good and constant coupling between transducer and the part. This technique provides the highest sensitivity of inspection because of the possibility of applying focused transducers. The NDI results, see figure 14, match the high laminate quality found in the test part in figure 8. For the inspection of the liquid shim between the upper skin and substructure the C-scan squirter method was applied. Although this method is less sensitive than the immersion technique this choice was made to prevent water ingress in the wing box, see figure 13. The NDI result is shown in figure 14, revealing a proper liquid shim between spar flanges and skin. The missing backwall echo between rib flanges and skin turned out to be caused by laminate problems in the RTM ribs.

Figure 13. Squirter and immersion inspection at NLR of wingbox respectively co-bonded lower skin

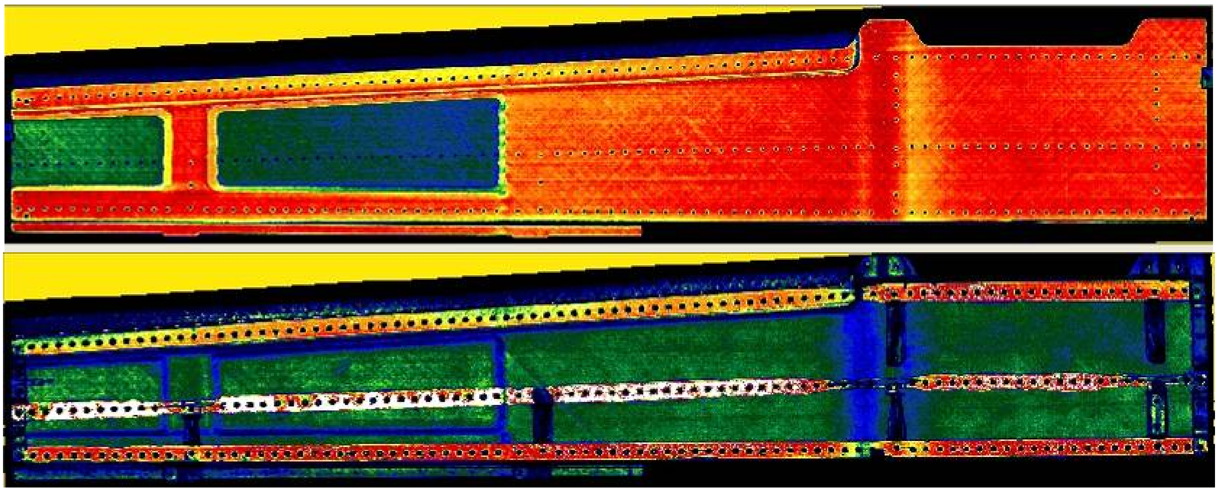


Figure 14. Attenuation C-scan of machined upper skin showing the two thin tip zones and of wing box assembly with gate setting for liquid shim between upper skin and lower framework

4. COST AND WEIGHT

4.1 Wingbox costs

The cost estimation is based on a technical cost modeling technique [6] in which each of the elements that contributes to the total cost is estimated individually, differentiating between fixed and variable costs. Development of a production flowchart is an essential tool in creating a technical cost model. For each production step the time and costs involved were determined. The fixed costs such as machine investments are based on a mix of internal NLR and supplier data. The same applies to the variable costs such as materials for which suppliers also have been contacted to provide industry relevant cost rates. The current cost analysis and production planning is based on the assumption that the composite production facility has sufficient manufacturing capacity. The cost has been estimated for a production rate of 40 wingboxes per year for a total period of 10 years. The total cost consists of 70% variable and 30% fixed costs. Figure 15 shows the cost breakdown for these two cost components. The costs for the RTM ribs and metal brackets have not yet been included.

One of the most obvious substantial cost components are composite materials, contributing nearly 20% to the total cost. It should be noted that the current composite material costs are based on minimum order quantity. If for example the prepreg materials were ordered in the amounts as used by Airbus, the price could be halved. Other major contributors to the total cost are fasteners, being nearly 16% of the total variable costs, and the whole process of drilling, reaming, countersinking and installing the fasteners.

One of the major targets in the CESAR project is a reduction of manufacturing and assembly costs by 16% to 20%. Based on cost data from Piaggio for the metal wingbox the cost reduction with the CESAR composite wingbox will achieve the 20% target. Further costs reductions are possible through reducing part and fastener count by using Out-of-Autoclave materials and adhesive bonding. In many process steps automation of hand labor will result in higher accuracy, increased repeatability and quality and shorter production cycles enabling further cost reductions.

The conclusion is that “Design for Manufacture” will become more and more “Design for Automated Manufacture”.

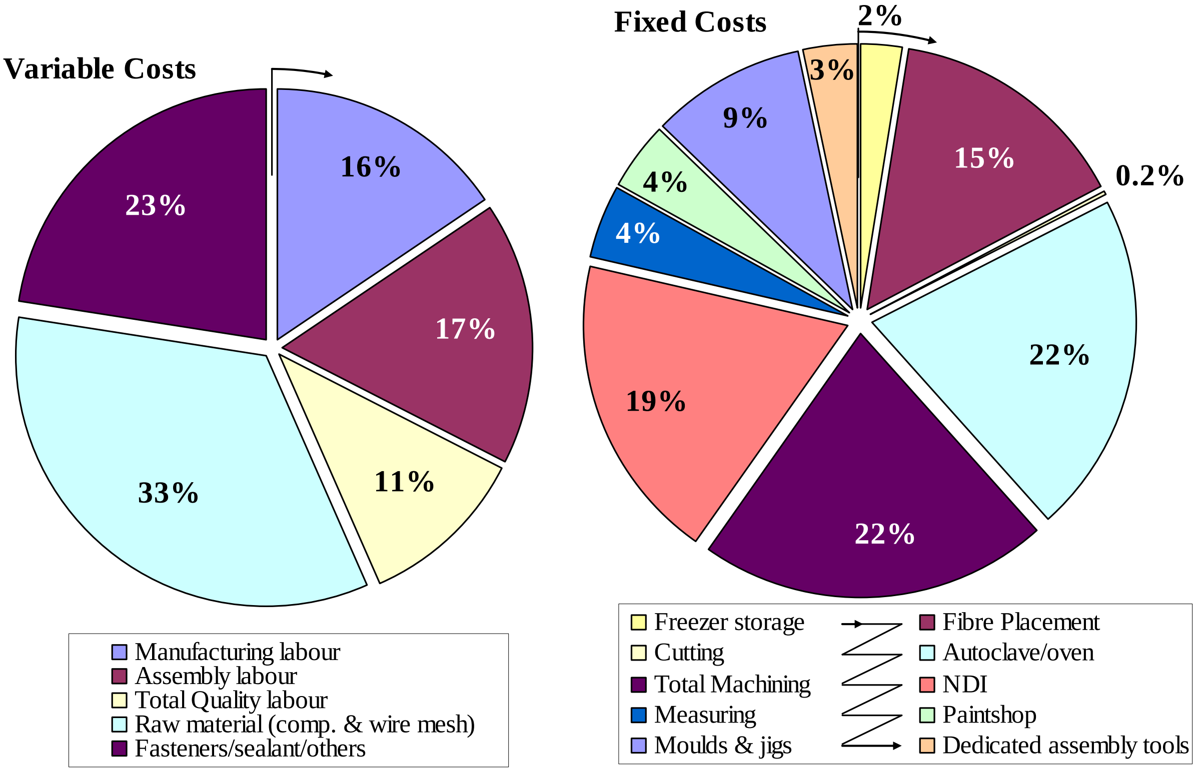


Figure 15. Overview of variable and fixed costs for composite wingbox excluding RTM ribs and metal brackets

4.2 Wingbox weight

The weight of the full size composite wingbox (tip-to-tip) is 10.4 kg and consists of 13 structural parts. Compared to the aluminum counterpart a weight saving of 24% and a part number saving of 22% has been achieved with the composite redesign. The part saving is mainly due to application of the three, continuous spars concept reducing the number of required ribs. Co-bonding of the spars to the lower skin resulted in a reduction of 45% of required Hi-Loks. The part and fastener count reduction greatly contributed to lowering the assembly labor costs.

5. CONCLUSIONS

The main result of the CESAR subtask Composite Structure – Wing is that it has proven feasible to achieve both weight and cost reduction for a wingbox using advanced composites and AFP compared to the aluminum version. The design guidelines developed in this project and the experience gathered and documented are essential input for the development of reliable and affordable design tools. The use of these tools such as Input for Design guidelines allows the introduction of concurrent engineering and remote team collaboration shortening the design process as was demonstrated during the CESAR project in the development of the composite wingbox with Piaggio and other subtask partners. Both the time-to-market and development costs will profit from this, contributing to achieving these CESAR goals.

The most substantial component of expenses, hence of the price for an aircraft are the production (manufacturing & assembly) costs. The production effectiveness depends on materials used and on particular production technologies, joining processes and on assembly itself. The majority of these production factors, related primarily to the airframe of the aircraft, are already determined at the early stages of the aircraft design. The cost model developed for the wingbox can facilitate both detailed design and feasibility studies in more accurately predicting the cost and determining important cost drivers. This in turn well help to identify risks and robust design reducing the overall development costs.

6. ACKNOWLEDGEMENT

Instrumental to the success of this project was the team effort and great technical pleasure shown by all colleagues and partners involved, with a special thanks to Piaggio Aero Industries for the successful collaborative engineering of the wingbox design. Also I thank the suppliers for their support during the design and manufacture of the composite wingbox.

7. REFERENCES

1. Sloan, Jeff. “ATL & AFP: Signs of evolution in machine process control.” *High-Performance Composites* September (2008): 41-47
2. *CESAR – Cost-Effective Small Aircraft, Annex I Description of Work*, Final Version, May 2006
3. Polland, D.R., Finn, S.R., Griess, K.H., Hafenrichter, J.L., Hanson, C.T., Ilcewicz, L.B., Metschan, S.L., Scholz, D.B. & Smith, P.J. “Global Cost and Weight Evaluation of Fuselage Side Panel Design Concepts”, NASA Contractor Report 4730, The Boeing Company, April 1997
4. Niu, Michael C.Y., *Composite Airframe Structures, Practical Design Information and Data*, Conmilit Press Ltd, Hong Kong, 1992
5. “Composite Materials Handbook MIL-HDBK-17-3F”, United States, Department of Defense, Philadelphia, June 2002
6. Rudd, C.D., Long, A.C., Kendall, K.N. & Mangin, C.G.E. *Liquid Moulding Technologies: Resin Transfer Moulding, Structural Reaction Injection Moulding and related processing techniques*, Cambridge, Woodhead Publishing Limited and the Society of Automotive Engineers, 1997
7. “Ingersoll wins best supplier award for 787 fuselage work”, CompositesWorld, 1/11/2010, Gardner Publications, Inc., 1/14/2010