DESIGN, DEVELOPMENT AND MANUFACTURING OF THE ALCAS CFRP DOOR SURROUND STRUCTURE

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Abstract

Even though it is unquestionable that continuous fibre reinforced composite structures have an extraordinary potential to increase weight efficiency, it is still an open question if composite structures are competitive when all production and assembly aspects are taken into account. Assembly of composite structures typically means bolting or riveting and this in turn means that geometric accuracy is a dominating factor besides the bare laminate properties. Integral structures like the ALCAS CFRP Door Surround Structure (DSS) are advantageous because they minimise joining activities and reduce the number of critical interfaces. On the other side highly integral structures have the tendency to increase the manufacturing risk because every small local flaw can ruin the complete structural component. The way ahead within the ALCAS project was to generate a variety of possible options and than challenge these options by considering the crucial boundary conditions given within the project. The major steps in the project were the definition of the global design approach, the development of an appropriate preforming concept, the definition of suitable primary and secondary moulds and last not least the set-up of a mature resin infusion curing and demoulding strategy. To analyse the result the structure was mounted on a typical fuselage skin and was successfully tested under representative boundary conditions. The conclusion is, that today even ambitious concepts can be realised with composite structures to demonstrate the feasibility of both design and manufacturing strategies. To achieve a fully competitive low cost high performance CFRP structure, it is most important to link all disciplines together, beginning with systems engineering and design approaches up to production and also certification strategies.

1 Introduction

The future of Composite Structures still seems to be an open story. On one side the automotive industry announces energy efficient serial vehicles with weight optimized carbon body structures for the year 2013 (e.g. BMW i3) [1] and on the other side aircraft manufacturers started to analyze metallic options for future high rate production airframe structures.

Fig. 01: CFRP space frame unit for cars [2]

An unquestionable fact is that energy efficiency will be the dominating factor for all competitive future transport concepts. Taking this into account the more important question might be how to design future transport vehicles with the most efficient structural integrity and of course the maximum level of utilization. Materials and especially their combinations as well as manufacturing and assembling concepts will finally decide if the chosen approach is competitive or not. Fibre dominated, orthotropic materials like e.g. CFRP have their biggest advantage in midsize to large linear or shell like structures with clear load paths. On the other hand isotropic materials like e.g. steal or aluminum are highly independent on stress directions which means that they are more advantageous in volumetric 3D components. The design of most transport vehicles is dominated by the usable volume they can provide and of course how efficient this volume can be loaded and unloaded. Taken into account the above mentioned statement about shells and orthotropic materials transport vehicles should be very well suited for the application of composite materials from a theoretical point of view. What makes the thing far more difficult is the fact that the access doors will spoil the structural concept in a way that load paths get more complex and local stress concentrations have to be taken into account at door hinges, guides and locking devices.

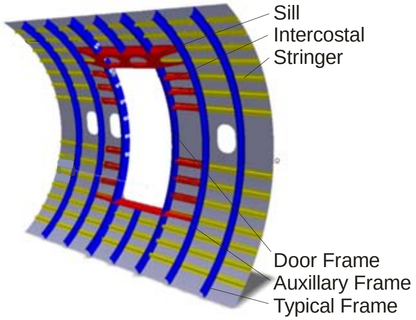

Fig. 02: Conventional DSS layout

Furthermore there is the new problem of fitting tolerances which have to be kept stable within certain limits under all loading conditions. The Door Surround Structure of a commercial aircraft is a very good example for the above described situation. Within the ALCAS project a representative door surround scenario was analyzed in a step by step approach. Step by step in this case means, that starting from highly generic design concepts manufacturing and certification aspects played a more and more important role until the final concept was defined and frozen.

ALCAS (Advanced Low Cost Aircraft Structure) is a research and technology project, which is conducted under the 6th framework program of the European Union. The objective of the ALCAS project is to concentrate on the cost reduction of major structural aircraft components for business jets and airliners. Among those there is the highly loaded wing box structure and typical fuselage sections of a single aisle airliner scenario including their large cut-outs in the door area.

2 Design approach

Since the majority of activities took place within the ALCAS project the major development target was cost efficiency through the use of innovative dry fibre materials (e.g. Non Crimp Fabric (NCF)) and suitable Liquid Composite Moulding (LCM) processes. On the other hand the structural performance of the impact critical door area has to be kept at the level of toughened prepreg laminates.

2.1 Large SPS concept

A feasible way to meet cost and performance demands seemed to be the application of a non load bearing Sacrificial Protection Shield (SPS) covering the complete door area.

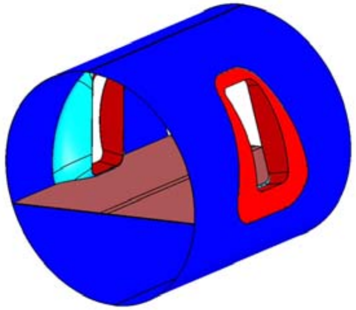

Fig. 03: Large SPS concept

The fuselage skin was drawn to the inside of the fuselage and reinforced to build the door frames. Analytical pre-sizing showed that this approach would be applicable to protect the brittle LCM Laminate but the reduced inner fuselage diameter and the additional weight due to non optimal load paths were not acceptable.

2.2 "Donut" sandwich concept

In the second step the SPS was significantly reduced and positioned at the most critical area on the floor level.

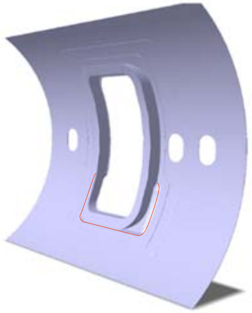

Fig. 04: "Donut" +SPS

The doorframe was designed in an O-shape local sandwich structure around the cut-out ("Donut" Sandwich Concept). Even though a comparable concept (Combined-Prepreg (toughened)-Infusion (CPI) instead of SPS) was successfully demonstrated together with the CTC GmbH in full size it was difficult to integrate the Donut concept into the typical fuselage structure.

Fig. 05: "Donut" +CPI

2.3 Cruciform sandwich concept

In a parallel workgroup of ALCAS, a new toughened NCF/LCM laminate (developed by Hexcel) showed a comparable performance to toughened prepreg laminates. From that time on the SPS was no longer necessary. While keeping the production cost advantages of the foam core sandwich doorframe elements, the architecture was adapted to the typical frame-stringer-grid configuration.

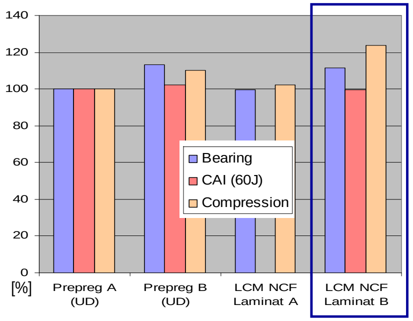

Fig. 06: Innovative toughened NCF material [3]

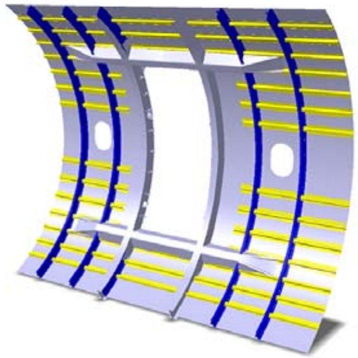

Fig. 07: Cruciform sandwich concept

The solution was acceptable from a design and manufacturing point of view but the requirements for keeping the door in place and emergency door opening (door stops and guides) showed that a sandwich doorframe is not reasonable because of the plenty holes that need to be drilled through the sandwich structure and the costs of special bolts with extended length. Furthermore the sealing of the applied foam cores with potting mass or comparable material would significantly increase the total weight of the assembly.

2.4 Final monolithic integral concept

In the end it turned out, that the requirement to open the door - even though the cabin is pressurized - leads directly to the certified "Door Stop" concept with discrete load introduction points and this in turn limits the design options to something that looks like the conventional C-shaped Door and Auxiliary Frame and monolithic Intercostal arrangement used in today's aircrafts. The only option left was to change the differential design into a completely integral CFRP design in order to minimize assembly effort. Unlike the manufacturing driven design concepts introduced before this rather conventional Door Surround Structure has massive undercuts and hidden volumes when realized as an integral component and therefore it was clear that the manufacturing concept will be a challenge.

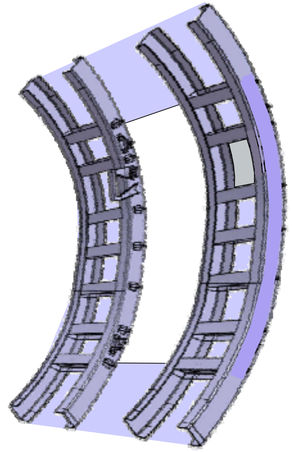

Fig. 08: Monolithic integral DSS

To maximize the results that can be elaborated within the given project budget the decision was made by airbus to scale down the Door Surround Structure in length down to two Door Stops (normal length is 7 Door Stops) while the fuselage diameter was kept at 4m. The width of the structure was also adapted. A FEM based sizing of the structure was conducted by Airbus with realistic Door Surround load cases which led to representative laminate thicknesses between 4 and 10 mm. Finally, a complete CAD Model of the Door Surround Structure was generated to support the generation of Flat Patterns and the generation of the required mould elements.

2.5 Lessons learned: Design approach

- The whole development chain needs to be synchronized to find a reasonable compromise in the development phase.
- Innovative Ideas have to be prepared early and in a professional way I order to get the chance to be chosen for a new aircraft program.

3 Preforming strategy

Since the final integral design consisted out of four straight I-beam Intercostals with flat ends connected with two curved C-shaped frame segments, it was necessary to decide how the different elements should work together. In addition the best way to transfer the loads within the integral component had to be identified. From a structural point of view it was clear that a maximum of interleaved plies would be the safest way to guarantee the structural performance in the final component test. By accepting this rather conservative approach it was clear that the preforming sequence would get even more complicated. Furthermore the Intercostal preforms with their flat head faces needed complex ramping to make them compatible with the C-shaped frame segments.

3.1 Flat pattern generation

To generate the Flat Patterns a CATIA-Composite Part Design (CPD) model was suggested where all plies could be generated auto-matically.

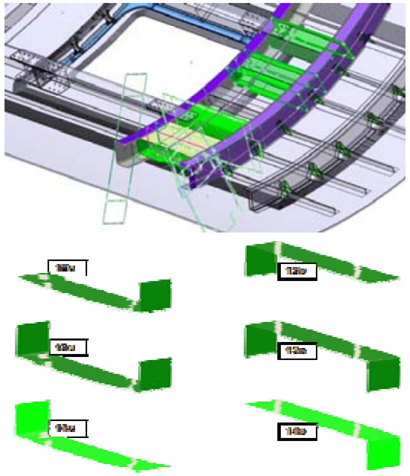
Fig. 09: CATIA CPD, Flat Patterns

Unfortunately the available early version of the software was not able to handle the complex arrangement of draped, interleaved and folded plies directly. After the problem was understood a few modifications in the ply arrangement and some virtual unlocking of the different plies helped to get the program running. What was supposed to be done by just pressing a button turned out to take several weeks until a sufficient result for the Flat Patterns was available.

3.2 Intercostal preform

To avoid structural deformations in the Intercostal a standard fabric with active binder (Hexcel G0926 Injectex) and a symmetric lay-up has been chosen. The Flat Patterns were transferred to the cutter system and cut out with a passive wheel cutter. The plies were than identified and equipped with a sticker. Since real draping (shearing of fiber reinforcement) was only required in the ramping section the basic task was to fold the cut plies around a brick-like preform tool.

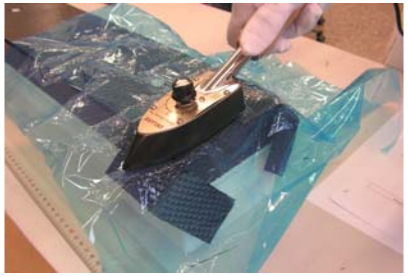
Fig. 10: Binder activation, intercostal preform

Activation of the binder was done manually with an ironing device and after a couple of layers a debulking step was necessary to stay within the thickness limits. Two of the mentioned brick-like preform tools together formed one Intercostal. For global referencing of the Intercostal preform the brick-like perform tools and also the Flat Patterns were equipped with guiding holes and appropriate guiding rods (Punch Card Concept).

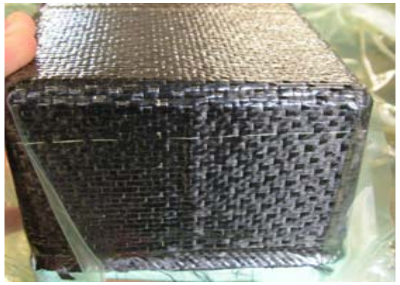
Fig. 11: Debulking, intercostal perform

The decision to interleave all layers slowed down the process enormously. Furthermore most of the Flat Patterns had to be trimmed to avoid overlaps. Gaps were considered to be less critical because their impact on adjacent layers is less critical in the chosen mould configuration. Inductive preform activation (Heating by generation of local eddy currents in the preform) showed excellent results even for high laminate thicknesses but the acceptance of this highly innovative technology among the project partners was limitted [4].

3.3 Frame segment preform

The C-shaped frame segments were made from a mixture of specialized low areal weight NCFs and unidirectional reinforcements. Because of the geometrical shape the cut plies had to be draped from a rectangular layer into the curved c-shaped perform. Unidirectional reinforcements (Hexcel G1157) were added mainly in the inner flange area. Binder activation was also done with ironing devices. The final preform assembly where all subpreforms were integrated was done manually. All four Intercostals together with their preform tool were aligned side by side and provisionally fixated with sticky tape.


Fig. 12: Bladder forming, frame preform

3.4 Global door surround preform

After that the two frame seg-ments were positioned at the two sides of the Intercostal preform block. Gusset fillers were used to close the gaps in the radius area.

3.5 Lessons learned: Preforming

- Draping simulation will be very powerful if software problems can be eliminated.
- CAD/CPD and manufacturing must be harmonized to achieve a global optimum
- Net shape Flat Pattern accuracy is still problematic
- “Punch Card Concept” proved to be applicable and efficient.
- Inductive activation is a highly effective solution for volumetric preform consolidation

4 Mould concept

The mould concept often decides if the later production will be successful or not. Successful means that the produced laminate is free of voids and the local fibre content or respectively the local laminate thickness is correct and reproducible. Another important criterion is the global component accuracy.

4.1 “Spring-In” phenomenon

Apart form process induced deformations due to lack of laminate symmetry or warpage effects all curved composite components especially if they are continuous carbon fibre reinforced will show “Spring-In” effects in a way that angled laminates will show a 1 to 2 degrees deviation compared to the dedicated mould. The reason for this can be related to significant differences in the laminate’s “In-Plane” and “Out-of-Plane” properties. During the process the laminate thickness decreases through shrinking effects of the resin and it’s Coefficient of Thermal Expansion (CTE). “In Plane” the fibre reinforcement suppresses these effects. In an angled laminate this means that the inner and the outer (constant) arc lengths get closer together which in turn causes the deflection.

An optimized mould should be able to compensate this problem by providing an adapted geometry that leads to a correct shape in the produced composite component.

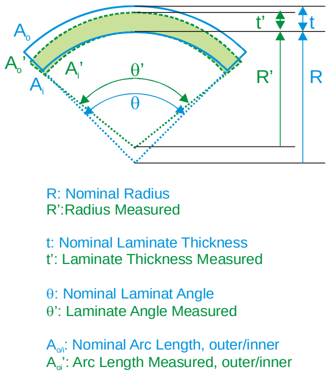

Fig. 13: “Spring-In” phenomenon

To predict “Spring-In” deformations there are two dominating laminate characteristics that need to be determined in the design phase and kept constant in the later production environment. These parameters are point of gelation and local fibre content in the corner area. In case of the integral DSS the deformation effect in the laminate corners is less critical because the local structural interaction of the different sub structures (e.g. the intercostals) reduces the deflection

4.2 Primary mould

Since the outer loft of the component is of highest priority an available female fuselage shell mould was chosen to be the mould concept reference. The female mould is a simple welded steel structure with a constant radius of 2m. To adapt the steal mould to the required shape a carbon slip sheet was manufactured with the given CAD data. As mentioned before the manufactured CFRP slip sheet showed the typical “Spring-In” effect meaning that in this case the radius is smaller than that of the steel mould. To cope with this problem a vacuum bag was used to pull the slip sheet against the steel mould. Even though this arrangement is risky it was the only solution within the project budget. The risks are that vacuum leakages can occur that will lift -up the slip sheet during the autoclave process and that the surface quality may be reduced because of wrinkles in the membrane. To provide a second referencing plane a metallic profile was positioned on the primary mould in the area, where the Door Stops had to be mounted later on.

Fig. 14: Manufacturing set-up on primary mould

4.3 Secondary mould elements

Large composite components like the Door Surround Structure are usually manufactured in an open mould process which means, that a flexible vacuum membrane covers the manufacturing set-up. The manufacturing set-up is positioned on the primary mould which serves as positioning reference. Secondary mould elements are more or less floating structures within the manufacturing set-up that give shape to local functional or hidden surfaces. In case of the Door Surround Structure secondary mould elements are necessary to realize the integral structure with their undercuts at the frames and at the Intercostals. Possible concepts to realize undercuts are modular or lost cores. Modular cores made from 3 metallic sub-cores were e.g. used for the first Airbus A310 CFRP Vertical Tail Plane. The undercuts of the Door Surround Structure component are even more critical because access is even more limited.

Fig. 15: PMI foam cores, Intercostal preform

The only reasonable solution to manufacture the component were lost cores, which means that the cores have to be considered as non load bearing “Flying Tool” or they have to be destroyed and removed after the curing process. Smaller, manually positioned casted profiles with a defined radius were applied to form the radius sections of the CFRP component.

Due to the typical process condition of 180°C and 5-10bars only selected Lost Core materials were available. Water soluble cores have successfully been applied in series process but casting and sealing of the core elements needs to be done in a specialized process which causes further costs. Since only a single component was planned the application of machined high temperature foam core elements was the most cost effective approach. To avoid the weight penalty of a large “Flying tool” and because access was needed later on to install the Door Stops and Door Guides the foam core elements were machined out after the process. To optimize the release properties the foam core elements were coated with a water soluble filer and standard release agent.

4.4 Vacuum membrane

A conventional polyamide membrane was used to cover the manufacturing set-up. The membrane was sealed against the vacuum membrane that was applied to fixate the slip sheet of the primary mould. To ensure process safeness it was decided to use a combination of two membranes. Because of the rather simple outer shape of the manufacturing set-up wrapping was less problematic. Sealing on a vacuum bag was a compromise that increased the manufacturing risk, because the sealing line is difficult to check.

4.5 Lessons learned: Mould concept

- Accuracy of improvised mould is much better than expected
- An improvised mould is very risky for vacuum tightness sensitive LCM processes
- Foam core proved to be a cost efficient, quick and viable solution for a single prototype

5 Processing

Cost reduction was one of the major criteria within the ALCAS project. Therefore it was decided right from the start to investigate LCM processes instead of Prepreg or Thermoplast based concepts. Closed Mould Resin Transfer Moulding (RTM) would have been a viable option but the costs of a RTM mould were far beyond the projects budget limits. To minimize processing costs usually out of autoclave LCM strategies are preferred. Since the limited pressure reduces the maximum flow distance (free flow without flow aids) and the option to reduce laminate porosity by applying elevated pressure is also limited the decision was made to infiltrate the manufacturing set-up in an autoclave environment.

5.1 Infusion concept

The high complexity of the laminate architecture can be a problem because all ramps and all gusset fillers may become runners for the resin. This in turn makes it very difficult to predict the flow front formation and to reproduce the results. Furthermore application of flow aids is limited because most component surfaces are defined by primary and secondary moulds.

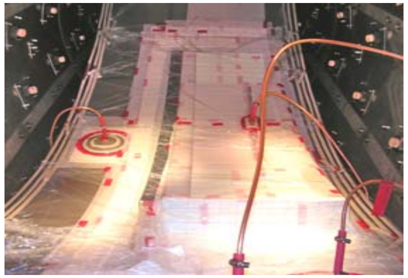

Fig. 16: Manufacturing set-up in autoclave

The infusion strategy was set-up in a way that infusion lines are located where possible runners may build up. By doing this the flow fronts are far more predictable.

5.2 Flow simulation

To set-up the final infusion strategy a simple but efficient 2D flow simulation (3D structure but no out of plane resin flow effects) has been conducted taking into account the flow properties of the different preform components. Possible runners where also simulated to check the maturity of the infusion line network. Vacuum ports where not needed because the applied Single Line Injection (SLI) process requires no vacuum in the infusion phase.

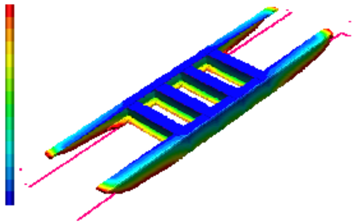

Fig. 17: Polyworx flow simulation

5.3 Infusion control

The mass of the resin needed to fill the preform was estimated and stored in a pressurized container. After opening the resin valves the infusion process and later on the fiber volume fraction of free surfaces were controlled by applying a designated difference in pressure between the autoclave and resin container. Temperature was increased to curing level after the resin flow had stopped at the appropriate pressure difference.

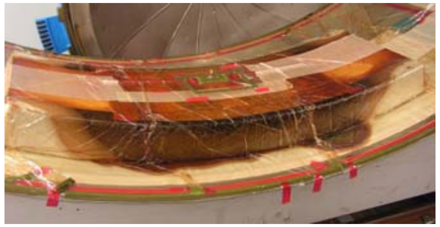

Fig. 18: Failed first infusion

The first trial went wrong possibly because of a non tight vacuum bag or problems with the infusion line coupling. Even though the door surround structure was only partly filled with resin the formation of flow fronts were as expected. Together with airbus the decision was made to infiltrate a second structure and this time everything worked out as planned. The structure was filled correctly and no voids were found. Removing the foam cores was more time consuming than expected but was not critical. Machining of the integral component was a standard operation without any problem.

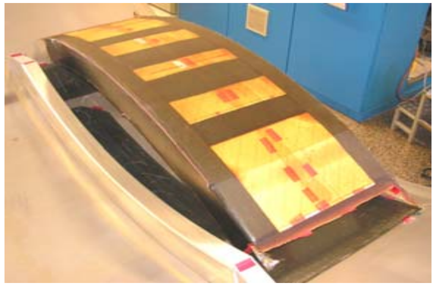

Fig. 19: Successful second infusion

5.4 Lessons learned: Processing

- In case of the geometrical complex DSS Structure a multidisciplinary, stepwise approach accompanied by manufacturing trials was highly efficient.
- A simple 2.5 D flow simulation proved to be viable to predict resin flow even at the high level of complexity
- The Lost Core concept based on PMI foam cores seemed to improve the process maturity by exerting pressure to the web areas though thermal expansion

6 Evaluation

After machining of the large integral component the local laminate quality and the global shape accuracy were analyzed before the Door Frame was bolted to the skin of the test structure. The Non Destructive Inspection (NDI) of the laminate proved that the quality was within the certification limits as expected. The extremely high global shape accuracy of the integral component was far more supprising, since no “Spring-In” compensation measures had been applied and the extreme stiffness of the Door Surround Structure would not allow any corrective actions. It turned out that even though the mould concept was highly improvised the maximum gap between the locally reinforced prepreg fuselage skin and the Door Surround Structure was less than 0,3mm over the hole contact area.

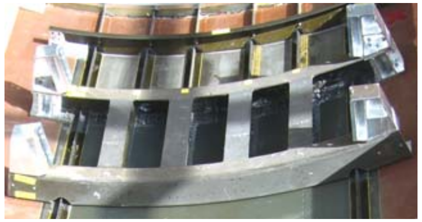

Fig. 20: Assembly of DSS and skin

This excellent result was possible because “Spring-In” effects like the bending of the flanges were suppressed by the integral Intercostals. Since the flange bending could be neglected also the kinematically coupled global fuselage radius was highly accurate. Access to the inside of the integral structure was sufficient to install the Door Stops and other fittings.

Fig. 21: ALCAS Door Surround test panel

Together with a differential Door Frame on the opposite side of the cut-out and other fuselage skin components (frames, stringers) the complete test panel was successfully tested until limit load at the IMA in Dresden under representative load conditions (shear loads and inner pressure).

7 Conclusion

The target of the ALCAS Project never was to find the one and only “Silver Bullet” strategy that will solve all future problems related to composite structures. Instead the key to success was, that all relevant disciplines worked together on a reasonable compromise that took into account up to date materials, reliable design strategies, innovative manufacturing and assembling processes and last not least the comparably small budget. The high level of structural complexity forced all disciplines to find innovative solutions but unlike many other projects the identified measures were discussed and harmonized within the project team. There is still a long way to go until highly integral structural components like the investigated Door Surround Structure are accepted in a serial production scenario but on the other hand it might be true that the missing competitiveness of some of today’s composite structures can be found just there.

8 Outlook

From an engineering point of view the ALCAS approach was quite conservative which in turn increased the manufacturing effort. In a variety of follow-up projects a more manufacturing driven design was investigated. The basic Idea was to minimize undercuts and to reduce interacting plies as long as it is justifiable from engineering side. New global design concepts for future passenger doors have also been developed but today’s requirements leave only very limited space for innovations. Some of the ideas generated within ALCAS and the follow-up projects might make their way into the newly developed Airbus A350-1000 as long as they can pass the Technology Readiness Level (TRL) reviews.

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