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CLEANSKY2/ CLEAN AVIATION LARGE PASSENGER AIRCRAFT FOR MORE SUSTAINABLE COMMERCIAL FUSELAGE TECHNOLOGIES – MAJOR ACHIEVEMENTS

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Abstract

In the framework of CleanSky2 (CS2) - Large Passenger Aircraft project, a consortium led by Airbus consisting of universities, research centers and industrial partners across Europe investigated various fuselage system, cabin & airframe technologies for commercial aircraft. The goal has been to strongly contribute to the environmental objectives of 20-30% CO2 reduction whereas at the same time performance increase through weight reduction and improved competitiveness through less recurring cost and industrial ramp up capabilities had to be demonstrated.

In total, more than 40 different technologies have been further developed by the European consortium consisting of 14 partners in order to finally deliver an 8m large scale flagship in 2024: the Multifunctional Fuselage Demonstrator. Novel fuselage design and built concepts are demonstrated as well as thermoplastic composite material testing & modelling, elementary parts manufacture and assembly for large scale fuselage structures incl. "zero airframe customization" concepts for cabin installation.

Final results and major achievements of this European funded program will be presented and discussed in this paper.

Keywords: CleanSky2/ CleanAviation, large passenger aircraft fuselage technologies, thermoplastic composites, sustainability

1. Introduction and framework

The European funded CleanSky2 (CS2) Research & Technology program has been kicked-off in 2014 and comes to an end in 2024. The initiative aims to develop cleaner air transport technologies capable of reducing CO2, NOX and noise emissions by 20-30% compared to "state-of-the-art" aircraft. CS2 activities have been structured in "Innovative Aircraft Demonstration Platforms/ IADPs", "Integrated Technology Demonstrators/ ITDs" as well as "Transverse Activities/ TAs". IADPs have been broken further down into “Fast Rotorcraft”, “Regional Aircraft” and “Large Passenger Aircraft/ LPA”, whereas the objective of LPA is to *“mature and validate technologies for the next generation aircraft through large scale integrated demonstration*” [1]. Three platforms have been established: Advanced Engine & Aircraft Configurations/ PF1 [2], Innovative Physical Integration Cabin-Systems-Structure/ PF2 [3] and Next Generation Aircraft Systems, Cockpit and Avionics [4].

Major achievements of the 10 years program in CS2 LPA PF2 Innovative Physical Integration Cabin-Systems-Structure will be discussed in more detail. Results have been elaborated by the European aeronautics eco-system represented by industrial partners, small and medium sized enterprises, research institutes and universities whereas the CS2 Joint Undertaking public-private partnership coordinated funds. Airbus took the lead of platform 2 consisting of 14 leaders and core partners incl. related consortia organized in “Call for Proposals/ CfPs”.

A typical single aisle aircraft has been selected as a reference structure for the R&T investigations and high ambitions with regard to significant weight and recurring cost reduction at high production rates have been defined. The whole program has been designed to maximize learning and technologies discussed and matured up to a technology readiness level 6 representing essential building blocks for future applications.

The CS2 platform 2 has been organized in 4 streams/ demonstrators:

- **Multifunctional Fuselage Demonstrator/ MFFD**
  Demonstration of an integrated, low-cost typical fuselage with industrial aspects by applying thermoplastic opportunities, using high degree of pre-installation and modularization
- **Cabin & Cargo functions**
  Demonstration of weight, recurring costs, and lead-time benefits of highly integrated cabin elements, designed for automation
- **Lower Center Fuselage**
  Demonstration of new center fuselage in composite material with design to manufacturing improvements
- **Non-specific cross functions**
  Development of innovative materials, automated industrial means, virtual tools and testing technologies for platform 2 demonstrators

In this paper, leaders and partners of the European consortium discuss and highlight their major achievements contributing to the success of this program.

2. Multifunctional Fuselage Demonstrator

The Multifunctional Fuselage Demonstrator (MFFD) represents a typical single aisle passenger aircraft fuselage section. With 8 meters of length and 4 meters in diameter, the goal was to demonstrate the potential of thermoplastic composites in terms of structural weight reduction, further economic competitiveness improvements, production rate increase and contribution to ecological targets like recycling or reduction of fuel burn, waste and greenhouse gasses [5, 6] In this context the use of thermoplastic composites combines the benefits of Carbon Fibre Reinforced Polymers (CFRP), as far as light weight design is concerned, with manufacturing methods, which are not available for thermoset composites with epoxy matrix.

2.1 Overview

The objective of the Multifunctional Fuselage project was to mature and validate technologies for the next generation commercial aircraft through a large scale integrated demonstration, on one hand, to pave the way to meet the environmental objectives, on the other hand, to enable the European aerospace industry to prepare the future by working on significant recurring cost and weight reduction as well as on increased production rates of 70 to 100 aircraft/ month [7, 8], which can satisfy the growing air transport market.

The Multifunctional Fuselage Demonstrator (MFFD) was set up in 2014 as a flagship demonstrator to deliver a large-scale section referring to a typical single aisle passenger aircraft. Key elements investigated were new fuselage built concepts using pre-equipped modules and thermoplastic composites for the airframe structure enabling innovative manufacturing like high rate forming processes, injection molding and assembly technologies like dustless joining through welding.

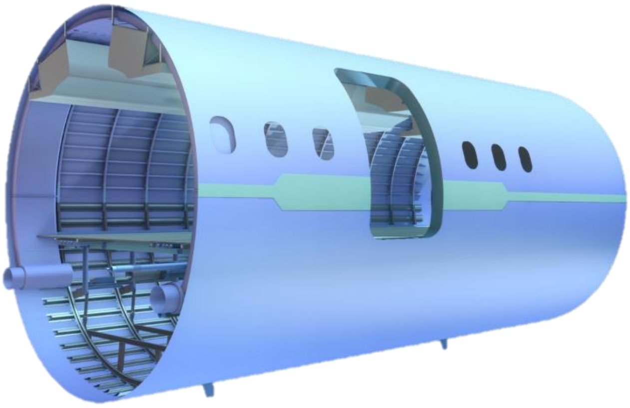

Figure 1 - The Multifunctional Fuselage Demonstrator/ MFFD

In the following chapters, an insights will be provided about the major technologies demonstrated in the MFFD by the European partner network and integrated by Airbus. The key elements are:

- The MFFD built concept, which is characterized by 2 half shells: the upper and lower fuselage shell. Half shell pre/equipping and modularisation of systems installation allows parallelisation of the fuselage assembly reducing lead time for the future products.
- Thermoplastic composite material has been selected enabling innovative manufacturing and assembly technologies such as thermoplastic welding. Various welding technologies have been investigated and matured in different fuselage applications underlining the crucial role for "dustless joining/ assembly" of the composite airframe. LM-PAEK has been selected as a thermoplastic composite material to be used. Characterization of mechanical properties at coupon level has shown fracture toughness benefits and damage tolerant behavior compared to thermoset reference composites [12].
- A new cargo door concept will be discussed proposing a novel actuation system based on an electromechanical innovative latch & lock principle.
- The marriage of upper and lower fuselage shells in the major component assembly (MCA) station produced the airframe of the Multifunctional Fuselage Demonstrator with two competing designs for longitudinal joints as well as two different welding technologies will be compared: ultrasonic welding for the overlap and laser welding for the butt strap design [11].
- Innovative cabin functions have been developed and the "Crown Module" integrated in the MFFD to enable less airframe customization concepts prior to validation & verification activities [8].
- Key performance indicators (KPI) have been closely monitored during the maturation of the manufacturing and assembly technologies at partner facilities supported by Airbus in order to better understand the key drivers for performance data. Weight reduction will be the key contribution of the MFFD technologies to meet the CS2 environmental targets of 20-30% CO_2 reduction in emissions whereas rate capability will be assessed at the same time in order to ensure competitiveness [5, 6, 8].
- Technologies matured in CS2 will be further developed in follow-on programs, e. g. CleanAviation which represents an essential initiative to meet climate neutrality for the aviation sector in 2050.

All above mentioned points are part of the perception that progress can only be achieved by a strong interaction between structure, cabin and systems already in the design phase. A multidisciplinary approach is essential to master the challenging ambitions.

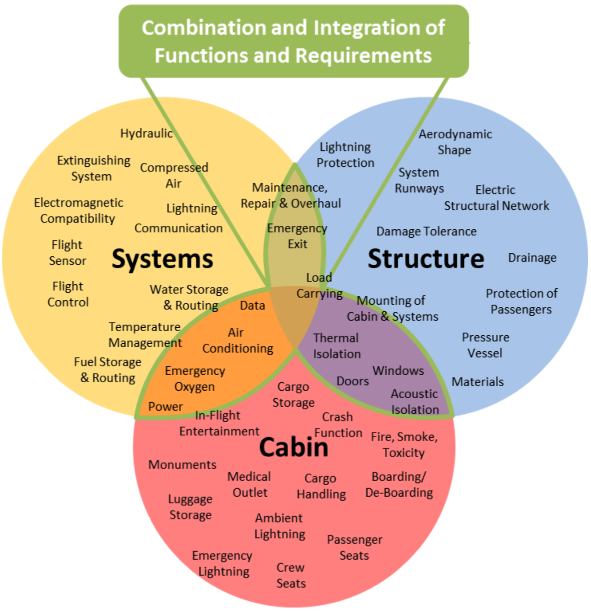

Figure 2 - Interdisciplinary approach for achieving the goals

Therefore, the MFFD is finally a flagship demonstrator for engineering, manufacturing, assembly and integration and will serve also in the future as a platform for further research and technology development.

Dedicated examples of technologies investigated and major achievements of this MFFD flagship demonstrator will be elaborated by the partners in more detail in the following paragraphs starting from smaller size elementary parts, joining technologies using thermoplastic welding up to major component assembly of large scale pre-equipped upper and lower fuselage modules. Ultimately, the European consortium delivered the world's largest R&T fuselage demonstrator made out of thermoplastic composite materials.

2.2 Elementary Parts

AERnnova developed four different technology streams with the target to achieve TRL 4/ TRL 5 – ground demonstrator- of new thermoplastics materials LM-PAEK. The activities were performed for selected structural components in the Cargo Door Surrounding Structure (cDSS), Tapered Butt Straps (BUSTI) and Co-consolidated Fuselage Panel, that included a static load testing validation, and the Upper Shell Stringers.

Cargo Door Surrounding Structure (cDSS)

This technology stream included the tooling design and manufacturing, the actual parts manufacturing, and the welding. The work was developed by AERnnova, mainly within its affiliated AERnnova Composites Illescas, ACI in collaboration with partners in the Call for Proposal, CFP, DEWTECOMP for the welding activities. Multiple geometries were considered to explore different manufacturing processes. The best results were obtained with the press forming technologies.

Upper Shell Stringers

These stringers were Z cross-section, 8 m length stringers, both straight and with joggles. The activities included the tooling development, design and manufacturing and the actual parts manufacturing. The work was developed by AERnnova ACI. The key technology matured in this stream was based in continuous compression molding.

Tapered Butt Straps (BUSTI)
These structural components, flat tapered straps, are required to weld and to join the upper and lower semi-fuselage shells. The tooling design and manufacturing and the straps manufacturing were the main activities. The work was developed by AERnnova ACI.

Fuselage Panel and testing
The entire process was completed for these components: the material screening characterization, the stress calculation, sizing and parts design, the tooling design and manufacturing, the actual parts manufacturing and assembly and the structural testing [13, 14]. The press forming for stringers and frames was followed by one shot in-situ co-consolidation of the panel. These works were developed by AERnnova Engineering Division, AE, ACI and FIDAMC in collaboration with CfP DELTA (Element) for testing. Tooling developments were the key element for the fuselage panel project success. The in-situ co-consolidation of the thermoplastic fuselage panel has provided experimental evidences that it is capable of meeting the static strength requirements of typical pressurized fuselage components.

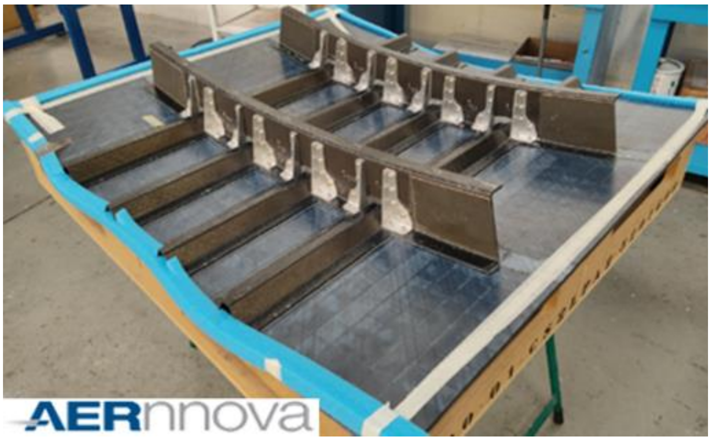

Figure 3 - Curved fuselage specimen

2.3 Integral Frames for MFFD upper shell

Airbus Aerostructures (ASA) and Premium AEROTEC (PAI) had a strong motivation to further develop the manufacturing concept for the production of thermoplastic (TP) integral frames made out of UD-CF tape material (TC1225 / T700 "LM-PAEK" with an areal weight of 194 gsm, supplied by Toray Advanced Composites) within the scope of CS2. The biggest drivers were shorter forming cycle times of about 6 minutes compared to hours-long autoclave processes for the curing of thermoset frames as well as reduced assembly efforts for the integration of frames into fuselage shells due to the integral design, which results in an elimination of a significant amount of attached parts.
ASA and PAI were successful in transferring the knowledge gained in other research projects with a focus on stamp forming of TP unidirectional integral frames to a satisfyingly robust concept that was implemented to provide frames for the MFFD upper shell to the DLR ZLP in Augsburg for a first-time integration by applying a resistance welding process.
Principally, the manufacturing concept for TP integral frames is set up as follows [15,16]:

- The preform is manufactured by applying an Automated Fiber Placement process (AFP), in which 8 UD tows with a width of ¼" are laid up in parallel via a steered head. A lay-up speed of 0,2 m/s was selected and the laser power was set to reach a nip-point temperature of 380-400°C. This work was conducted in cooperation with the Fraunhofer IGCV in Augsburg.
- For the stamp forming process itself, rigid upper and lower forming tools made of 1.2312 hardened tool steel were used, which can be heated to 200°C by means of heating cartridges to allow proper material crystallization during the press holding phase. Also, the spring-in behavior that lies in the nature of such CF-TP integral frames was compensated by adjusting the tool surfaces.
- Pre-drying of the AFP-preforms according to guidelines published by the material supplier ensures that a critical moisture content is avoided [17]. After that, the preform is mounted into a holding frame by means of aluminum holding stripes. This holding frame can then be transferred linearly from an infrared oven, where the frame preform is heated to a processing temperature of about 390°C (figure 1, left) before it is moved above the lower forming tool.

When the press closes, a pressure on the part of about 350 bar is applied for 120 s.
- After final NC contour trimming, the part quality is checked via ultrasonic inspection.

From a technical standpoint and with regard to a potential serial application, main issues requiring further investigations and improvements are an increased lay-up rate in the AFP process and a concept allowing a robust stamp forming of integral frames with thickness variations (that were not in the scope of the CS2 activities).

Figure 4 – Molten frame preform in active IR oven, shortly after reaching TMelt (left) and integral frames ready for assembly (right)

In total, more than 200 thermoplastic integral frames were manufactured for the MFFD upper shell and other related projects with different radii, thicknesses and surface plies. Thickness ramps are needed in order to achieve a load-optimized design and therefore to target the lightweight ambitions within Airbus. Different thicknesses come with different radii to respect the forming abilities and restriction of the material. Some integral frames must be electrical insulated by a glass surface ply to prevent corrosion of aluminum parts. Appropriate strategies are developed to apply glass surface plies onto the related preforms using the AFP process with adjusted KPIs. New milling concepts and tools are used to trim large scale parts to achieve a maximum in geometrical accuracy.
Finally, 28 integral frames have been delivered for assembly in the MFFD upper shell.

2.4 MFFD upper shell module

Advanced Fiber Placement (AFP) with in-situ consolidation has reached a level of maturity where it is now employed for crafting the MFFD upper shell's skin. Utilizing TC1225 UD tape, the process achieves full consolidation as it is applied, eliminating the need for additional equipment such as vacuum bagging, ovens, or autoclaves. DLR-ZLP in Augsburg manufactured the MFFD upper fuselage shell. 141 kilograms of tape were meticulously placed, equating to 52.7 kilometers of ½“ tows. However, the absence of a secondary consolidation stage heightens the demands of the procedure. Any gaps or voids that arise during placement cannot be rectified post-application. This not only impacts the consolidation quality of the final laminate but also affects surface smoothness and temperature regulation throughout the placement process. The intricacies of AFP with in-situ consolidation reveal a significant interplay between various process parameters, including temperature, pressure, and robot end effector speed [18, 19]. These factors directly influence the thickness and width of the tape post-consolidation, known as the Consolidated Tape Width (CTW). The alignment of tapes with one another and thermal imaging for closed-loop control of laser power are also contingent on these parameters. Within the project, DLR has advanced an inline inspection system dubbed the Tape Placement Sensor, integrated into the AFP end effector. This system monitors and logs any occurring gaps and overlaps during production, ensuring precision and quality throughout [20].
The automatic alignment of all 44 stringers was achieved through an automatic positioning system utilizing the weld bridge. Subsequently, the stringers were fixated via ultrasonic spot welding at 500 mm intervals. To counteract the spring-in effect of the skin during spot welding, additional stamps on the end-effector were implemented to ensure the reproducibility of the welding process [21, 22]. The process further entailed fully automated robot-based continuous ultrasonic welding of stringers with camera-based path correction, ensuring precise welding at the stringer's edge [23]. Structural welds were executed at a net weld speed of 1.44m/min, translating to a net weld time of 11 minutes per stringer.

Airbus Aerostructures (ASA) and Premium AEROTEC (PAG) manufactured integral frames, frame couplings, cleats, and connecting parts using AFP followed by a Press Forming Process and final milling. Resistance welding played a crucial role in the upper shell assembly for integrating integral C-frames, frame couplings, and cleats. This decision was driven by factors such as exceptional mechanical performance, resilient process characteristics, consistent reproducibility of welded joints, and the practical feasibility derived from its accessibility.

A custom-designed welding jig, called weld bridge, facilitated the integration of C-frames/ integral frames with a total of 730 welds, along with 12 frame couplings using resistance welding [24]. This tooling served as the central apparatus for positioning clips and integrating frames and frame couplings. Due to tolerances in the skin, stringers, and frames, precise programming of the positions for the 300 cleats to be welded was unattainable. To address this challenge, a system combining an industrial robot with a cobot was devised. The cobot, equipped with force moment sensors, guided the resistance welding end-effector mounted on the industrial robot. Cleat-frame welding was completed within approximately 40 seconds for both heating and cooling phases, totaling approximately 3 minutes per weld, inclusive of robot movement and cleat pick-up from the magazine.

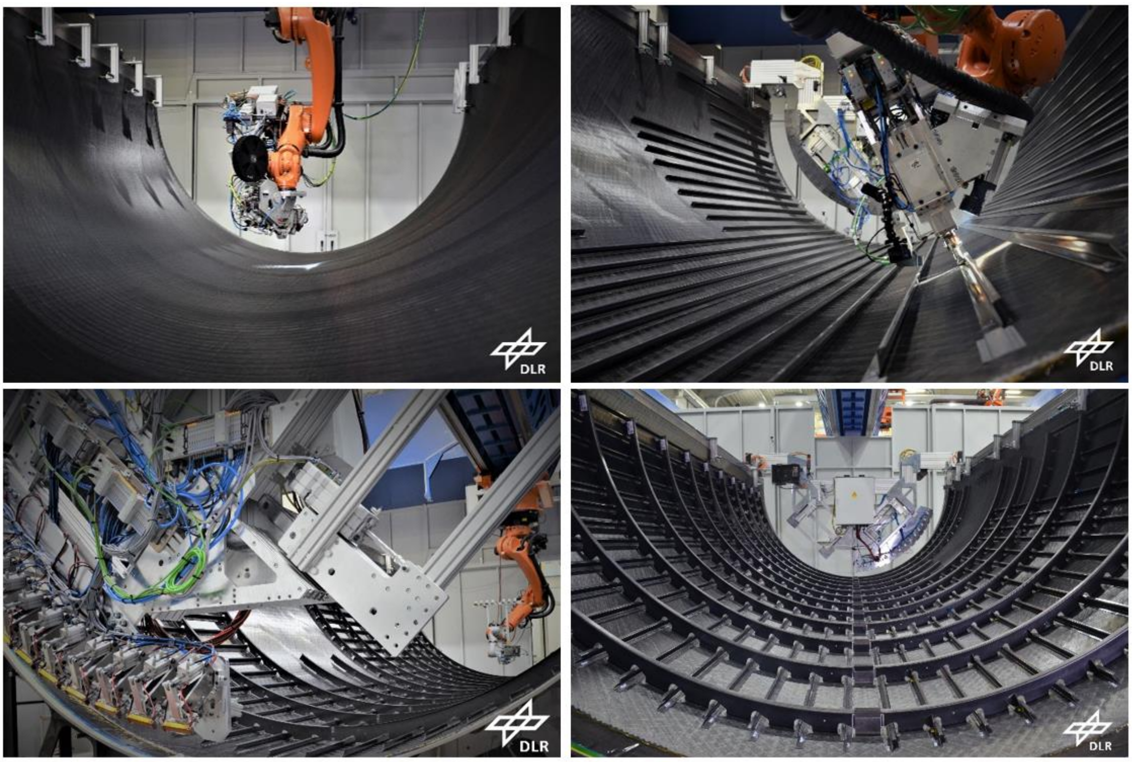

Figure 5 – MFFD upper shell production: in-situ lay-up of skin (top left), continuous ultrasonic welding of stringers (top right), resistance welding of frames with welding bridge (bottom left) final MFFD upper shell section (bottom right)

2.5 MFFD lower shell module

The Lower Shell Module [25] was built by the STUNNING consortium, which consists of the following partners: GKN Fokker, Royal Netherlands Aerospace Centre (NLR), Delft University of Technology (TUD), SAMXL and Diehl Aviation. The STUNNING project & consortium were supported by several CfP projects: TCTool, ECOCLIP, MECATESTERS, TORNADO, MISSION, EMOTION and MAYA.

Design of the Lower Half

The material selection for the Fuselage was performed by Airbus. The Toray CETEX® TC 1255 LM/PAEK thermoplastic material was used for all composite parts in the lower fuselage shell. In the beginning of the project, a decision was made to change the diagonal fuselage split into a horizontal split.

For the lower half this meant that the design consists of a 1-piece skin with varying thickness, sticking out above the passenger floor. The skin is stiffened with omega stringers. Twelve C-shaped frames are connected to the skin by means of clips on each stringer location. The frames form a sub-assembly with the cargo floor beams. To join the 3 sections of the frame a Titanium additive manufactured (AM) connection bracket is used.

The floor structure consists of 12 floor beams connected to each other by the seat rails and L-profiles. Connection to the frames is made by means of Z-struts connected through energy absorbers. The X-paddles distribute the forward loads (in DOF) from the floors to the stringer in the lower shell module and eventually into the lower fuselage skin.

Several systems (electrical, water, air, fuel) are installed as pre-assembled modules into the demonstrator. The electrical system demonstrator consists of nine (9) electrical units (supplied by MISSION), and several wiring assemblies. System installation was done by using the existing structure or by means of specific designed brackets. Most systems are installed in the floor structure, so that a fully equipped floor could be installed as a module.

Around the cargo door aperture a separate cargo door surround structure (CDSS) was designed by Airbus.

Parts manufacturing for the lower half of the MFFD

As a result of the design change to a horizontal split in the fuselage, the majority of the work of Diehl (cabin) could not be integrated anymore in the lower half. Diehl added their demonstrator parts to the MFFD when it was delivered in ZAL Hamburg.

Diehl developed and manufactured thermoplastic sidewall sandwich panels (see figure 6, left), thermoplastic interior panel structural clips (through project MAYA) and integrated multi-system ports. The side panels were made using a press technology with powdering and infrared field heating (figure 6, right)

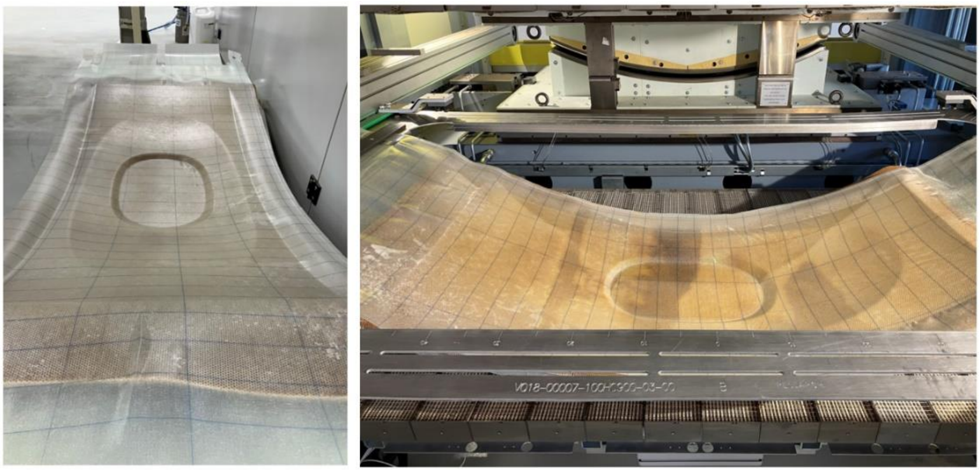

Figure 6 – Pressed sidewall panel (left), pressed panel at the thermoplastic press at Diehl (right)

The NLR manufactured the lower half skin by means of laser automatic fibre placement (figure 7) and autoclave consolidation in female moulds. The two 90 degree parts with a scarf/taper shape at the keel were joined during consolidation in the mould delivered by project EMOTION.

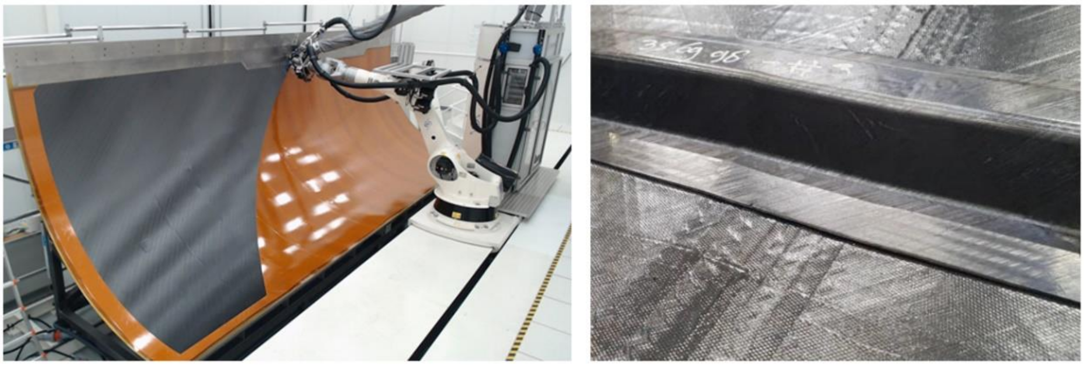

Figure 7 – Automated fibre placement of a 90° part of the lower skin of the MFFD (left), Stringer

joggled for ramp-up at lower skin of the MFFD at NLR (right)

The MFFD lower half skin was delivered net size to the final assembly shop at SAMXL. The stringers were delivered by Xelis and made with the continuous compression moulding. NLR joggled the stringers that had to run over steep ramp ups (figure 7).

Clips were short-fibre injection moulded delivered by the ECOCLIP consortium.

The C-frames were manufactured by GKN Fokker using the butt-joint technology. Pre-forms for the floor beams were manufactured by laser automatic fibre placement and consolidated in an autoclave by GKN Fokker. The seat rails were delivered by Airbus. The connection brackets for the frame parts were manufactured using titanium additive manufacturing (AM) with Laser Metal Deposition by wire. As well AM and final machining was performed by GKN Fokker.

X-paddles, cargo-, vertical- and side struts, tandem clips, L-profiles and seat rail brackets were made using press forming from flat consolidated laminates by GKN Fokker. The cargo floor beam was made by Xelis with the continuous compression moulding process.

Sub-assembly and final assembly of the lower half of the fuselage

Several sub-assemblies were delivered to the final assembly line located at SAMXL.

- Frame sub-assembly: At GKN Fokker the 3 frame sections and the cargo floor beam were joined by the Titanium AM connection parts. The cargo struts were conduction welded to both the cargo floor beam and the middle frame section (figure 5). This together formed the frame sub-assembly.
- Floor beam sub-assembly: At GKN Fokker the floor beams with the vertical and side struts were joined by conduction welding (figure 5). The seat rail brackets were also conduction welded to the floor beams.
- Integrated system modules: In the GKN Fokker Wiring facility all wiring harnesses, systems and tubing were assembled into modules.

Figure 8 – Sub assembly by means of conduction welding (left), MFFD lower skin module with all clips ultrasonically spot welded to skin with stringers (right)

Next to the final assembly line the floor beam sub-assemblies, the seat rails and integrated system modules were assembled to a floor grid module. As the systems were already part of this floor grid module, the fuselage was already pre-equipped for a large part. The final assembly of the Lower Half demonstrator started with building the skin module, existing of skin, stringers and clips (Figure 9, left). The tooling results from project TCTool are used to position the lower skin and automatically place and ultrasonic tack-weld the stringers (executed by SAMXL). Welding of the stringers was done by GKN Fokker using conduction welding. Positioning of the frame clips was done by GKN Fokker with a dedicated fixture which was positioned on each frame-station. In collaboration with TUD, SAMXL ultrasonically spot-welded the clips to skin with stringers. The frame sub-assemblies were positioned against the welded clips and ultrasonically spot-welded by SAMXL (Figure 9, right).

Figure 9 – MFFD lower shell skin module with all frames ultrasonically welded to the clips (left), assembled lower half hoisted out of the welding/ assembly jig (right)

After installation of the lower part of the cargo door surround structure by GKN Fokker, the pre-equipped floor grid could be installed. Connections of the floor grid to the frames were established using conduction welding by GKN Fokker. In this stage also the connection between the X-paddles with the skin and floor grid was conduction welded. The project MECATESTERS supported with a test campaign of welded specimens and project TORNADO supported in assessing Disbond Arresting Features (DAF).

The final assembly of the cargo door surround structure was done using traditional fasteners and supported by the Cobot drilling technology developed by GKN Fokker. The hinge for the cargo door was installed with a special fixture to ensure the correct hinge line position.

After lifting the Lower Half demonstrator out of the assembly jig some final activities took place.

MFFD lower fuselage module conclusion

Building this full-scale demonstrator as shown in figure 10 accelerated the maturation of many new technologies (published in [26-33]) and provided a framework for validation and testing. Exploitation of the various matured technologies will be focused on parts for fuselages, wings and empennages.

All technologies highly contributed to the demonstration of an entirely new, advanced fuselage structural concept in alignment towards next-generation cabin-cargo architectures, including relevant aircraft systems.

Figure 10 – MFFD lower shell module as delivered to the major component assembly facilities

2.6 MFFD major component assembly

The Major Component Assembly (MCA) process of the MFFD was performed using the PARAMONT assembly research setup [34] which was developed in previous aircraft assembly research projects and now further optimized for the MFFD (figure 11, left). The setup allows highly automated handling of full-scale fuselage segments. It possesses industrial robots on linear axes equipped with end effectors for assembly processes and several parallel robot kinematics - so called hexapods - for the handling of fuselage structures. With their vacuum-gripper-end-effectors the hexapods were able to handle and manipulate the large fuselage shell structures of the MFFD. The high-precision, automated positioning was supported by real-time measurement with laser trackers.

Figure 11 – Major Component Assembly facility at Fraunhofer (left) and MFFD after successful welding of longitudinal joints ready for shipping to ZAL

The MFFD contains of two longitudinal joints. To be able to compare different joint designs the demonstrator's left-hand side joint is a butt strap joint whilst the right-hand side joint is an overlap joint. The more complex butt strap joint geometry of the left-hand side is necessary since the door surround in this area leads to a skin thickness variation that can be handled by this special joint design. On the right-hand side the skin thickness is constant, allowing a less complex overlap joint design. A CO_2 laser welding process was used to join the left longitudinal seam. The laser beam was guided via a linear axis and a high-precision mirror system. Laser welding can be used to achieve high process speeds without introducing significant thermal distortion into the components. This left joint represents a so-called butt-strap design, where several strips are placed in corresponding shafts in the upper and lower shell. These vary in width and are up to four meters long. Gaps on both sides of the strip were filled with matrix material - the thermoplastic material without carbon fibers - to avoid moisture pooling in the weld. This process was performed by a gap filling end effectors which was guided on a linear axis along the longitudinal joint. Ultrasonic welding was selected for the less complex overlap joint to develop and demonstrate a fast, highly automated welding process for high production rates. In ultrasonic welding, vibrations are introduced into the component by a sonotrode which is creating dynamic shear stress and is then transformed to heat [35]. The thermoplastic shells were then be joined under additional pressure. Since ultrasonic welding is a well-established, fast, and very energy efficient technology, a highly productive process is possible [36]. After welding the longitudinal seams, the frames of the upper and lower shell had to be connected with so called frame couplings. Resistance welding was the technological choice for the joining of the frame couplings, giving the possibility to weld different frame coupling geometries on the left-hand and on the right-hand side with the same technology. The heat was generated by electricity passing through the insert (resistance heating) during the welding process. The process is fast, simple to control, generates a homogeneous temperature distribution in the seam and can be easily applied for large structures. The ultrasonic and resistance welding processes were performed by WELDER project partners.

A rigid tooling inside the fuselage segment was used to absorb high loads during the thermoplastic welding processes and thus reduced the load on the fuselage segment itself. So-called inner positioners were installed on the tooling. They supported the fine positioning of the segments for the welding process and absorbed the forces. The welding pressure was generated during the welding process from the outside by the welding end-effectors that press the fuselage shells against the inner positioners.

The successful Major Component Assembly (MCA) significantly contributed to the success of the MFFD, particularly through the application of innovative thermoplastic welding techniques such as laser, ultrasonic, and resistance welding, complemented by highly accurate measurement and positioning through automation technologies, enabling high precision and efficiency in sustainable aircraft manufacturing.

2.7 Cargo Door

Saab's work started in 2018 with the following objectives:

- Integration and demonstration of two cargo doors in the single aisle aircraft fuselage & MFFD respectively
- Demonstration of flexible lightweight assembly jigs for cargo door assembly

Regarding to these objectives, the technical highlights Saab chose to work with are listed below:

- Electromechanical actuation: Lift, latch & lock without a handle
- New cargo door design with lock & latch mechanism in fuselage
- New sensor types (proxy)
- Flexible reconfigurable assembly jigs
- Vacuum Infusion manufacturing process
- Additively Manufactured Thermoplastic Tooling
- Complex forming of Tri-Axial Composites

In 2021, the metallic TD4 cargo door was completed and shipped to Germany where it was installed in a single aisle type fuselage demonstrator. It was successfully demonstrated together with the fully operational electromechanical latch, lock and lift system (figure 11, left). The TD4 cargo door was assembled in a flexible assembly jig.

As for the TD5, the original intention of a Composite Resin Infused skeleton with integrated frames did not succeed as planned, and the door was produced with pre-preg, still with the same curing tools and the Tri-Axial lay-up. The flexible lightweight assembly jig was used also for the composite cargo door, only modified as the door was smaller, and thus Saab fulfilled both objectives described earlier, but had to mitigate the risk of not being able to deliver a cargo door which meant change to pre-preg material cured in autoclave.

The result of the TD5 demonstrator can be seen in figure 11 (right) which was shipped to Germany in March, 2024 and was installed in the MFFD in April. It was also successfully demonstrated together with the electromechanical system.

Figure 12 – The metallic TD4 cargo door installed in a single aisle demonstrator (left), composite TD5 cargo door mounted in the flexible assembly jig (right)

2.8 MFFD summary

The MFFD consortium with 11 main partners from industry and research organizations, supported by further partners from academia and SMEs, have matured and validated more than 40 technology bricks for the next generation commercial aircraft. Although partly competing, all the technologies were chosen for a better evaluation of their potential application.

The Multifunctional Fuselage Demonstrator provides a broad knowledge on how future aircraft structures from thermoplastics could be designed and manufactured, considering a large range of very different functions such as load carrying, passenger and cargo transport, as well the need for a large variety of electrical, mechanical, pneumatic and hydraulic systems. These are part of the cost and weight driving elements which have to be considered from a manufacturing as well as an operational point of view. The technology bricks demonstrated in the MFFD project have given a much better understanding of thermoplastic composites as a material for fuselage primary structures.

At the end of the project, all of this has been achieved through a close collaboration between the project partners, working together on concepts, technology bricks and their maturation, production of parts and assembly. This approach was applied across the pre-equipped lower shell including the floor module and the upper shell, the elementary parts, the novel cargo door demonstrator and finally by integration of a cabin crown module.

The MFFD stands now for the largest thermoplastic civil aircraft components, which in turn built up the largest passenger aircraft fuselage R&T demonstrator from this material class. With the wide range of design solutions, manufacturing and assembly concepts, based on novel joining techniques and automation technologies, the MFFD's industrial partners are enabled to choose the most appropriate technology for achieving the improvements in performance and reduced ecological footprint required for future aviation.

Figure 13 – The Multifunctional Fuselage Demonstrator at it's final position in the ZAL Center for Applied Aviation Research, Hamburg

3. Cabin and Cargo Functions

The Cabin and Cargo R&T demonstrator has been dedicated to integrating and testing the next generation of large passenger aircraft cabin and cargo functions and technologies. A number of smaller test rigs and component demonstrators have also been part of the program, confirming the assumptions taken and proving the technical maturities of the technologies developed. Figure 13 shows some dedicated examples of technologies investigated.

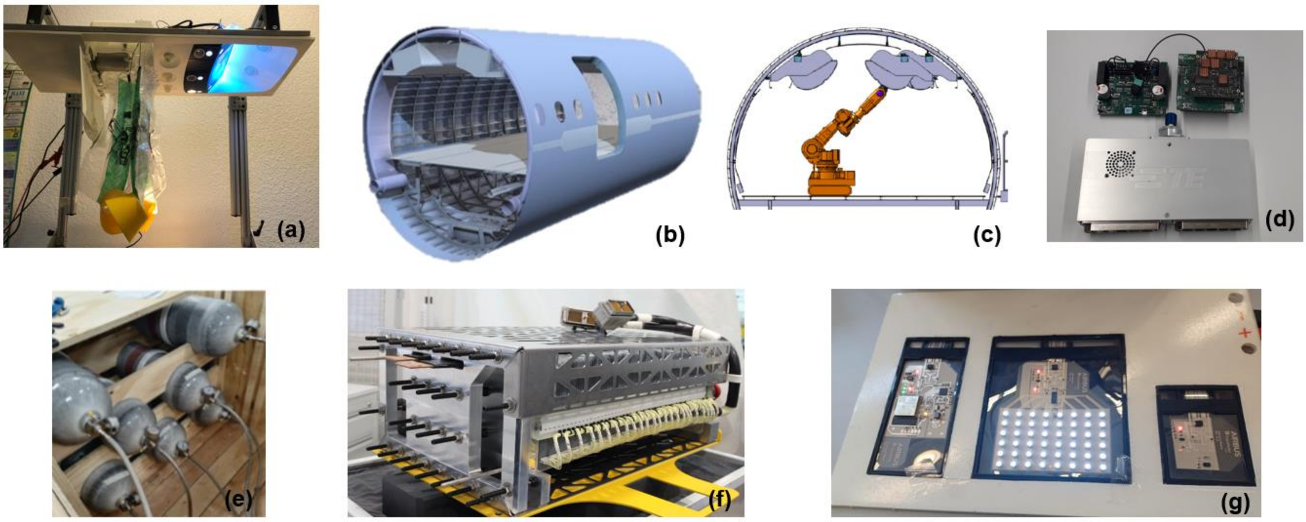

Figure 14 – Examples of Cabin & Cargo technologies: customizable passenger service unit (a), platform concept (b), automated installation technology for linings and hatracks (c), universal cabin interface (d), environmentally-friendly fire protection (e), energy optimised cabin (f), printed electrics (g)

The target has been to accomplish technology readiness level up to 6, for a number of technologies that are key enablers for the Cabin & Cargo of the future.

These have included the following:

- Customizable Passenger Service Unit (PSU) by SAFRAN with improved functionalities. This technology has reached TRL 4.
- A new platform concept by Airbus, which aims at significantly reduced customization in airframe with customization on the cabin side. This shall be achieved by fewer interfaces to the airframe, modularization and standardization ("decoupling" of structure and cabin). This technology has reached TRL 6.
- Universal Cabin Interface by Airbus, or an optimized electr(on)ic & mechanical architecture with system components through Multi-ATA chapters. This technology has reached TRL 4.
- An environmentally-friendly fire protection system by Airbus, that is halon-free, inside the cargo hold. This technology has reached TRL 6.
- An Energy Optimised Cabin by Safran, through a Fuel cell technology as an enabler new power source of the cabin. This technology has reached TRL 4.
- Specific automated installation technology for linings and hatracks for a faster cabin and cargo assembly by Fraunhofer. This technology has reached TRL 5.
- Printed Electrics technology by Airbus, as a solution to replace dedicated routings made of multiple wires by developing the technology of „printing" data and power lines with a minimum customization effort. This technology has reached TRL 6.

4. Lower Center Fuselage

The main goal was to introduce the manufacturing (both elementary parts production and assembly) in the heart of the early design phase. This to secure compatibility with lower cost and high ramp up objectives.

On the primary structure, the project focuses on the possibility to replace historical "fastenings forest" by simple pins/lugs type junctions that enable clean and fast assembly at sub-component level.

The same principle has been proposed on the link between seat rails and center wing box/main landing gear bay structure. On top, it allowed also to reduce the number of interfaces to, then, reduce the time of assembly.

For the production of the sub-components, the focus was on the capacity to use low-cost processes for elementary parts and assembly. The design had to match with these constraints. Here under, proposals in accordance with these objectives:

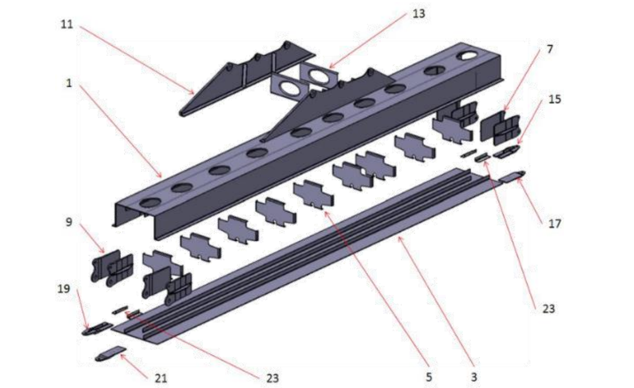	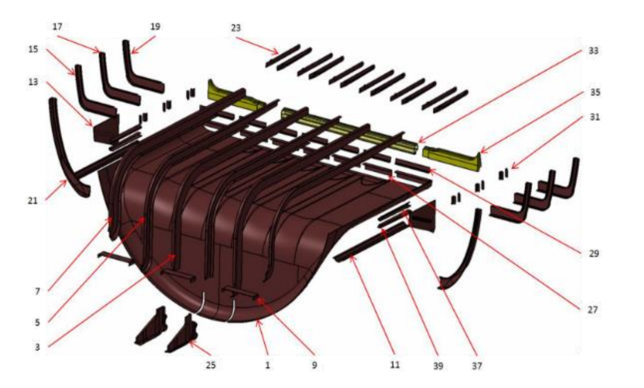
Metallic keel beam integrating elementary parts production with low cost and high volume capacity processes (extrusion, stamping).	Main landing gear bay in composite showing a high level of integration

Figure 15 – Lower center fuselage technology examples for low-cost processes for elementary parts and assembly

The project allowed to push the existing mindset limits to other boundaries, where the manufacturing constrains can be beneficial for the overall product if the integration is made at the early architecture design phase.

5. Non-specific Cross Functions

The work on Non-specific cross functions was oriented on materials and processes, testing development and predictive virtual simulation to support the requirements of the Platform 2 demonstrators, and future aircraft development and operation. Three aspects of this work are described here: Fatigue Digital Twin, Structural Health Monitoring, and detailed experimental characterisation and simulation of thermoplastic materials.

Airlines are faced with high cost of aircraft operations, which is partly driven by maintenance on airframe structures. Airbus is investigating solutions that could provide usage monitoring and enable structural maintenance optimization. The promising solution is the hereafter-called Fatigue Digital Twin. The global aim of Fatigue Digital Twin is to optimise the Maintenance Program, by exploiting the data recorded by the Flight Data Recorder on the aircraft.

The aircraft data recorded for each flight can be processed through various engineering models (load models, stress models, life models…) to evaluate the real aircraft usage compared to the theoretical aircraft usage defined for certification. Due to the high volume of data to be exploited, Machine Learning algorithms are required to enable high performance, which is not possible to achieve with “standard” approaches. For the stress module, the Loads to Stress Transfer Function (LSTF) has been developed in this project, in order to process loads definition and evaluate associated stresses at key airframe locations. The LSTF determines the stress at every instant of the flight and this output enables the evaluation of the fatigue and damage tolerance (F&DT) behaviour based on the actual utilisation of the individual aircraft. The structural maintenance plan can be fully optimised using the outcome of this evaluation [37].

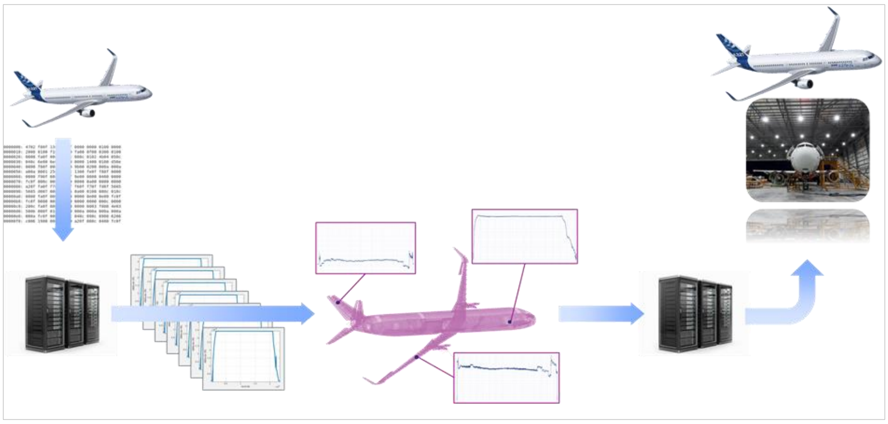

Figure 16 – Illustration of Fatigue Digital Twin Concept [37]

Airbus also developed innovative tools to reduce the inspection time on aircraft structure for structural test and aircraft operation. An ultrasonic phased array sensor (US PA) was developed for crack detection at a fatigue initiation site for Structural Health Monitoring. The sensor would be permanently installed on metallic structures in positions where scheduled inspections for cracks are required. The interrogation of the sensor will allow easy inspection of the area. For Test Structures, this will produce time savings leading to a reduction of lead time and costs. For In-Service, scheduled maintenance time and costs will be reduced. The work involved developing the ultrasonic phased array to fulfil the detection, environmental and durability requirements identified for installation on the aircraft. For the final optimized sensor design, a large number of tests were completed on the probability of defect detection, before environmental & durability tests were successfully performed [38].

ONERA's activities in the project included the experimental characterization and modeling of a thermoplastic matrix composite. An extensive test campaign was carried out at ONERA to characterize the mechanical properties of the TC1225 material made of carbon fibre and thermoplastic matrix. Firstly, tensile tests on cross-ply laminates, with different 90-ply thicknesses have been analysed to determine that the onset of damage is insensitive to the ply thickness (unlike carbon/epoxy materials) while the damage kinetics increases as a function of the ply thickness (like carbon/epoxy materials). Moreover, some tensile tests on [±45]s laminates with regular unloads have allowed us to study in depth the plasticity inherent in this material with a thermoplastic matrix. Interlaminar shear strength tests have been analysed using both analytical models and finite element simulations and the S13R and S23R strengths have been extracted from tests carried out on respectively a unidirectional laminate and a quasi-isotropic laminate. Finally, to determine the fracture toughness, delamination propagation tests, such as DCB, ENF and MMB, were performed. The fracture toughness identified are extremely high compared to those of the classical carbon/epoxy matrix and can explain the specific transverse crack damage pattern. After quasi-static tests, impact tests, at different moderate impact energy levels, and then compression after impact tests were carried out at ONERA on two different quasi-isotropic laminates, in order to assess the influence of impact damage mechanisms on residual properties (both stiffness and strength). Finally, the analysis of cross-ply CT and CC specimens, considering two different sizes, was performed in order to estimate the fracture toughness associated with the fibre failure in tension and in compression. In addition, at the ply scale, the material behaviour was modelled using the Onera Progressive Failure Approach, a model originally developed for epoxy matrix composites, and extended in this study in order to consider the specifics of this composite material. The comparisons with experimental data are in very good agreement and very promising [12].

6. Conclusions

Airbus took the leadership role for the 10 years Large Passenger Aircraft program Platform 2 dealing with innovative fuselage technologies with reference to a next generation single aisle commercial aircraft. This program has been funded by the European CleanSky2 Joint Undertaking public private partnership and consisted of a consortium of 14 leaders & core partners including a large number of "Call for Proposals (CfPs). This set-up in platform 2 covered a large group of the European aeronautical eco-system from universities, research centers, small and medium sized enterprises, suppliers and an

aircraft manufacturer.
More than 40 technology bricks have been developed for new fuselage materials and structural applications as well as cabin & cargo functions. The maturity has been assessed using the Horizon Europe rules [39] whereas TRL 6 level has been successfully achieved for some bricks.
The strong contribution to the scientific community has been widely published with more than 70 peer reviewed papers, PhD and Master thesis and intellectual property rights have been protected by 35 new patents.
The CS2 program aims to develop cleaner air transport technologies capable of reducing CO2, NOX and noise emissions by 20-30% compared to “state-of-the-art” aircraft. Amongst other objectives e. g. the stengthening of the competitiveness of the European aeronautical eco-system and improved sustainability through the use thermoplastic composites, a main contribution of platform 2 has been the reduction of CO2 emissions through weight reduction by innovative fuselage technologies. Each kg of weight saving can be directly translated into less fuel burn. Depending on the combination of technologies on fuselage level, a CO2 emission reduction in the range of 180kg – 540kg for one typical single flight has been found. The overall environmental potential can easily extrapolated considering 1,600 flights per year for a single aisle aircraft which clearly underlines the positive impact.
In a nutshell, CS2 LPA platform 2 successfully matured fuselage technology bricks for next generation aircraft and the European consortium delivered the world’s largest fuselage demonstrator manufactured with thermoplastic composite material.

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8. Copyright Statement

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