ICAS 2021 SHANGHAI
International Council of the Aeronautical Sciences
32nd Congress of the International Council of the Aeronautical Sciences
September 6-10, 2021
Pudong Shangri-La, Shanghai, China

THERMOPLASTIC APPLICATIONS FOR AEROSTRUCTURES: TOWARDS SUSTAINABLE AND WEIGHT EFFICIENT APPLICATIONS

Mélanie HERMAN[1], Eric DUPUY[1], Christophe PARIS[1], Emilie PETIOT[2], Jean-Pierre CABANAC[1], Chantal FUALDES[1], Guillaume MASSE[3], Marc-Antoine CELLI[3]

[1]Airbus Operations, Toulouse, France
[2]Airbus Operations, Nantes, France
[3]Airbus Helicopters, Marignane, France

Abstract

Thermoplastic composite materials are of increasing interest to the aerospace industry, which is mainly related to some numerous assets compared to thermoset composites. Thermoplastic materials have been successfully implemented on some key Airbus structural applications, taking full benefit of their specificities. This paper details the innovative aspects of some thermoplastic structural applications within Airbus Group:

- by Airbus Commercials aircraft: NEO generation of air inlet acoustic panel
- by Airbus Helicopters rotorcraft: H160 helicopter main rotor hub.

Keywords: Thermoplastic, Materials, Structures, Applications

1. INTRODUCTION

Airbus is committed to improve environmental performance by cutting emissions throughout the commercial unit's operations, raising the fuel-efficiency of its aircraft and, over the longer-term, designing a new generation of cleaner passenger jets. Whilst aviation as a whole represents approximately 2% of global human-induced GHG emissions and around 12% of the transport sector emissions, work to reduce the impact of aviation is required [30]. Flightpath 2050 and the ACARE SRIA have dedicated targets by 2050, compared with year 2000 levels:

- CO2 down by 75 %
- NOx down by 90%
- Noise down by 65%

Implementation of advanced composite materials to aircraft primary structures has been continuously growing, and projects like Airbus A350XWB - in the field of commercial aircraft - or Airbus H160 - in the field of civil rotorcraft - are new references of how far composite technology can be implemented. The usage of high-strength materials such as Carbon Fiber Reinforced Polymer (CFRP) has enabled achievement of weight efficient structures - with induced aviation emissions reduction - in the aviation industry while reducing significantly maintenance costs when compared with metal structures.

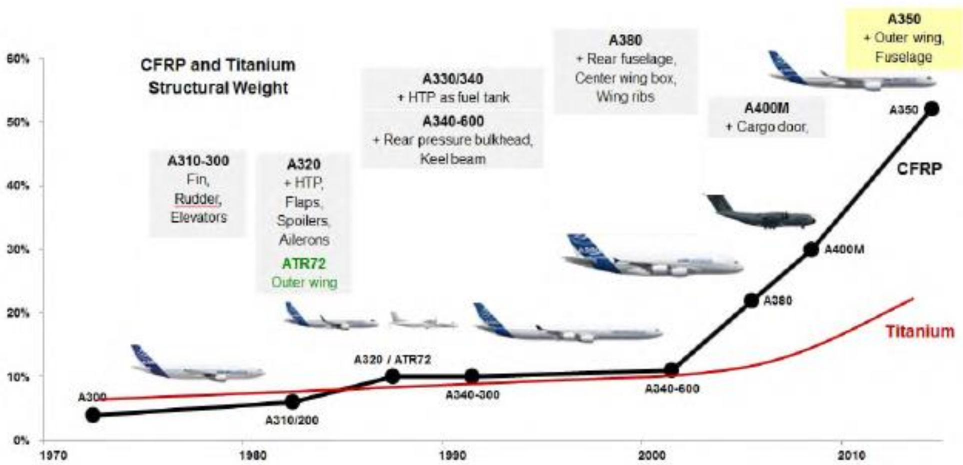

Figure 1 - Evolution of CFRP and Titanium Structural Weight on Airbus aircraft

One challenge for Airbus is yet to reach sustainable growth. As a consequence, reduction of operational costs and environmental footprint represent the main objectives for next generation of aircraft and rotorcraft. Digital, smart design, advanced materials, manufacturing and service support are key for Airbus competitiveness. It requires revised manufacturing supply chain supporting sustainability. This should include:

- High performance materials, allowing functions integration
- Advanced manufacturing capabilities supporting high rates
- Reuse and recycling capabilities

2. THERMOPLASTIC APPLICATIONS WITHIN AIRBUS GROUP

Past developments of composite materials part within Airbus Group were mainly related to the thermoset matrix composites. As exposed in *Figure 2*, few applications are actually made with thermoplastics in comparison with thermoset applications. The use of thermoplastics materials and welding has been done progressively on structural applications on each aircraft range: A340, A380, A350 and military applications.

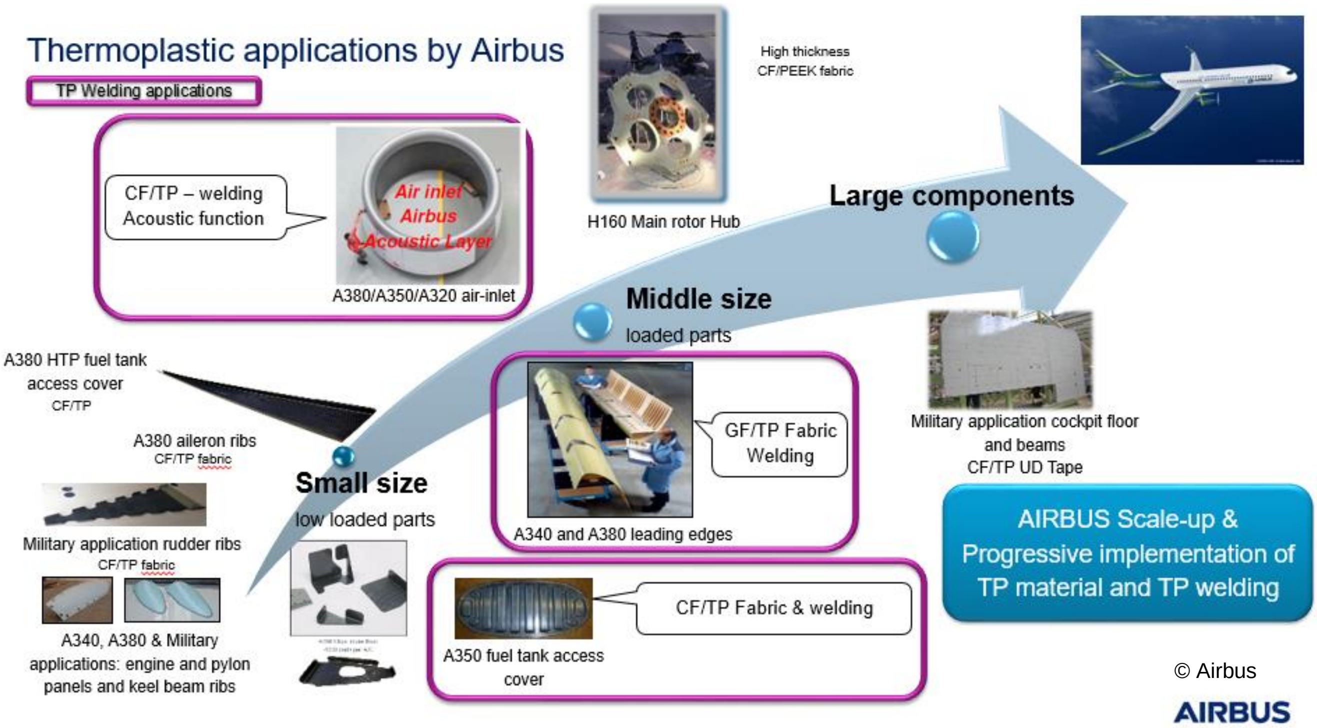

Figure 2 - Overview of Thermoplastic applications by Airbus

Larger implementation of thermoplastic composite materials in aerostructures is being investigated by Airbus and some other major aerospace actors through some research activities (e.g. CleanSky2 Multi-Functional Fuselage Demonstrator [21]).This interest in thermoplastic applications is mainly related to some benefits compared to thermoset composites, which are detailed in the following paragraphs.

3. THERMOPLASTIC VS THERMOSET PREPREG MATERIALS

3.1 Material chemistry and reactivity

Thermoset and thermoplastic are two families of polymer materials, which can be used for the processing of composite structural parts by combining the polymeric matrix with fibers. The high performance thermoset matrices are constituted of complex formulation of different epoxies with hardeners and catalyzers, which need to be stored at low temperature to prevent the exothermic reaction of polymerization from starting. During the part processing, the uncured material is heated at a temperature close to 180°C to create a reticulated network to obtain the requested mechanical properties. This chemical reaction of polymerization, which needs to be controlled by the part manufacturer, is nevertheless irreversible. Concerning thermoplastics, the formulations have the advantages to be so far away of REACH regulations and to be supplied already polymerized by the material supplier. The polymers supplied are constituted of liner chains of macromolecules arranged in amorphous and crystalline phases in the case of semi crystalline polymers. This involves that a thermoplastic can be transformed several times without heat generation related to chemical reaction, enabling also an almost infinite shelf life and storage conditions at room temperature. The processing of thermoplastic parts with high performance matrices such as semi crystalline polymers (PAEK, PEEK) is nevertheless constrained by an elevated temperatures that needs to be reached to enable a decrease of matrix viscosity and a melting of the crystalline phases (400°C for PEEK). This processing temperature has been significantly reduced on the new generation of PAEK polymers, allowing a lower energy consumption during the process.

3.2 Damage Tolerance Behavior and Fracture Toughness

Lower relaxation thermoplastic matrix vs thermoset is leading to better detectability of impact damage. This is induced by higher matrix toughness. Literature underlines also a significant higher stress intensity factor K_{1C} value for TP when compared to TS resin, as shown in *Figure 3*.

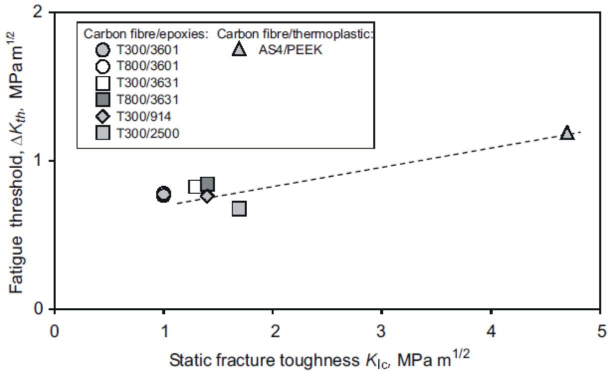

Figure 3 - Relation between effective thresholds for crack propagation ΔK_{th} and static fracture toughness of carbon-fiber laminates, with TS or TP resins [8]

This observation is consistent with improved behavior of TP materials regarding damage tolerance and reduced sensitivity to delamination in comparison with TS materials.

3.3 Influence of Environmental Conditions

Composite structures can be exposed to severe environmental conditions in service, including high moisture environment which may be combined with elevated temperature. The presence of moisture within a polymer composite can lead to significant changes in the physical and chemical characteristics of the polymer matrix. The following effects are observed at coupon level [22].

- Swelling of the matrix, leading to a change in stress state
- Decrease of Tg
- Degradation of the fiber-matrix interface
- Strength decrease regarding microcracks and delamination development

It is observed that for epoxy matrix composites the matrix properties can be significantly affected by the moisture content, whereas the fiber mechanical properties, i.e. strength in fiber direction, are not affected. The moisture absorption in PAEK matrix composites, up to 0.3 wt%, is much lower than in epoxy matrix composites, up to 2.5 wt% [11]. This can explain that the effects of moisture on the mechanical properties and the Tg are negligible for PEEK matrix composites [11] [12]. In addition moisture content does not significantly affect their fracture toughness [14].

These effects of moisture and associated reduction of Glass transition for CF/Epoxy fabric can be clearly evidenced on out-of-plane mechanical characteristics when compared to CF/PEEK fabric. Whereas CF/PEEK fabric properties are not significantly affected after exposure to moisture, a more important reduction is observed on CF/Epoxy fabric for both ILSS Static and Fatigue behavior as shown in Figure 4 and Figure 5. This was an important aspect in the selection of Thermoplastic resin PEEK for H160 main rotor hub. Effect of elevated temperature in dry conditions is found lower for CF/PEEK fabric than for CF/Epoxy fabric in static, which has been also observed for notched and unnotched coupons in tension as described in [1].

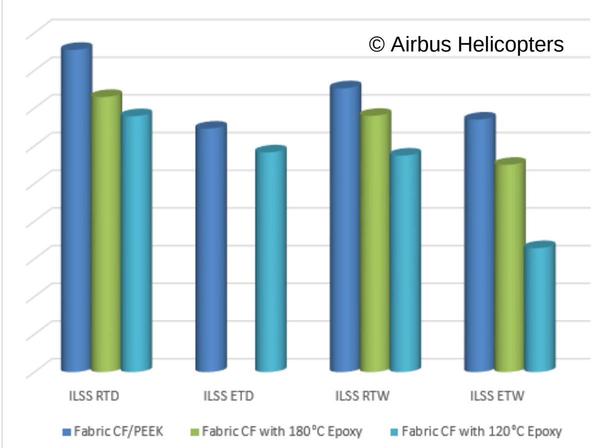

Figure 4 - Static ILSS comparison between CF/Epoxy fabric and CF/PEEK fabric for various environmental conditions

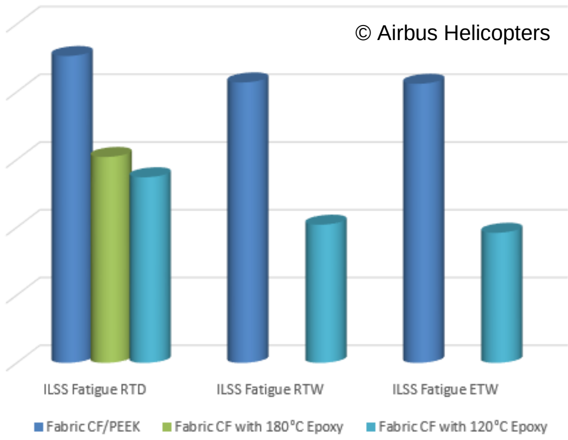

Figure 5 - Fatigue ILSS (R=0.05) comparison between CF/Epoxy fabric and CF/PEEK fabric for various environmental conditions

3.4 Properties involved by the material transformation reversibility

The reversibility of the thermoplastic transformations involves key properties. The first one is the capability to assemble thermoplastic parts by welding. Welded structural parts are already flying today however welded thermoplastic parts are made of carbon or glass fabrics and not with UD carbon thermoplastic tapes for which the maturity of welding technologies is lower. The second advantage of the reversibility of the material transformation is the capability to reprocess or to reuse the production scrap, and the potential for end of life thermoplastic parts to be easier recycled. This is a key enabler to reach more sustainability in aerospace industry. Grinding and compression molding process can be used to manufacture parts with discontinuous short fibers from the recycled composite materials genuinely made of continuous fibers. Implementation of recycling and reuse is yet linked to the development of the suitable supply chain organization aiming at collecting and sorting the materials before transformation.

4. BENEFITS IN MANUFACTURING OF THERMOPLASTIC PROCESSES

As Airbus investigates processing solutions that will enable high production rates, TP composite technologies have emerged as powerful candidates. All along the production line, TP manufacturing is offering benefits in comparison with TS solutions. Starting from the laminates lay-up, the recent progresses from the thermoset AFP machines can be transferred to the Thermoplastic applications [15]. Moreover the TP AFP is offering the capability for high-speed processing of large structural components with an Overall Equipment Effectiveness (OEE) potentially improved by:

- no intermediate debulking cycles during lay-up
- a reduced maintenance of the AFP machinery due to the non-sticky TP resin,
- a final laminate stiff enough to be moved with a light vacuum gripper to the next manufacturing step (forming or consolidation). For high rate production, the dedicated metallic mold can stay at the AFP cell which is avoiding some moves through the factory.

Nevertheless the AFP machines remain a high investment, have a minimum length for lay-up and introduce some recurring costs from the TP material slitting. An alternative is the “Pick and Place” which is more affordable, offers wide possibilities for the plies contour design and directly handles the tape material. More adapted to small or simple parts, the “Pick and Place” can be implemented in a fully integrated manufacturing line [16] [17] using a robotized and digital platform from the plies cutting up to final stamping. When addressing the TP part consolidation, hot-press stamping achieves a part in a few minutes with a high process repeatability (*Figure 6*), allowing an adapted control plan supported by process monitoring. Already qualified process, this technology used for the A350 clips manufacturing is now cycling through various part references with tool change operations and would be even more adapted for high rate processing of standardized part design.

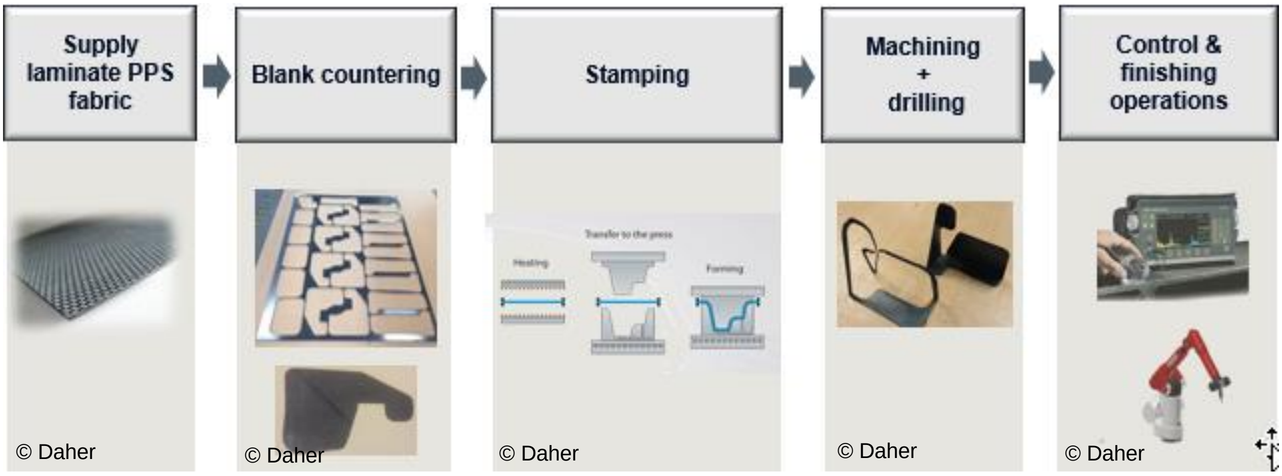

Figure 6 – Description of manufacturing process for clips (Courtesy of Daher)

For larger or thicker parts, press-forming process is found more adapted. Even though the processing temperature is much higher than for TS, TP consolidation time can be shorter as consolidation cycles only require a controlled cooling from the melting temperature to the crystallization. A challenge of such process for very large thin parts – as for fuselage shells - is the scale-up of the thermal and pressure uniformity while keeping competitive cycle duration. It is also important to consider the differential thermal expansion between the metallic tooling and the TP part. If not managed properly, it may lead to a lack of applied pressure and prevent from a complete part consolidation. One alternative to the press with hard molding dies is the membrane-press which enables pressure and heat to be applied evenly on large smooth parts. Another cheaper solution is the oven. With lower industrial footprint and operating cost compared to press or autoclaves, the vacuum-only process has been achievable thanks to the recent development of Out-Of-Autoclave materials. Nevertheless, this OoA process will be fully cost-efficient if the bagging operation is simplified with low cost ancillary materials.

Figure 7 - L-stringer molded using Continuous Compression Molding, Courtesy of CETMA, CleanSky2 KEELBEMAN project [18]

In the field of high rate production, continuous compression molding [19] and pull-forming processes can produce straight regular and complex profiles of unlimited length. They are also offering the opportunity to get a netshape part controlled by on-line monitoring system. Currently in development, the curved pultrusion enabling a high fiber content looks very promising for applications such as fuselage frames manufacturing [20]. Overmoulding is another technology of high interest when combined with thermal-press forming. It can produce in one-shot a netshape part and offers plenty of design possibilities for some reinforcement integration to enhance rigidity or some functional features. No doubt that the TP welding property is also a key enabler for high volume production. In the current sequential approach, the structure assembly generates dust from the drilling and fastening either in a metallic or in a thermoset design. Therefore this operation needs to be completed before any systems or cabin features installation. The TP welding produces no chips or dust that could damage pre-installed systems. This technology is key to develop some pre-equipped structural elements and system modules and aims at reducing the overall cycle. Moreover, in addition to some good mechanical performance when compared with other rivet less joining technologies, TP welding process provides a continuous structural joint up to 10 times faster than conventional drilling and fastening processes. Some TP processes are being explored through the CleanSky2 Multifunctional Fuselage Demonstrator [21], made of TP material in full-scale with automated TP assembly processes.

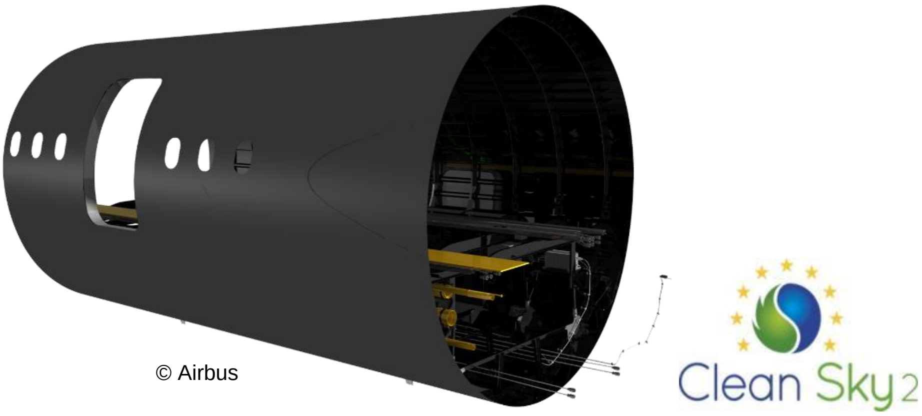

Figure 8 - Illustration of the intermediate overall Multi-Functional Fuselage Demonstrator design [21]

Although there is still much to be developed and validated for large scale applications, Thermoplastic composites are offering some substantial advantages for an aircraft high rate production factory.

5. AIRBUS AIRCRAFT AIR INLET ACOUSTIC PANEL

By Airbus, the serial manufacturing of thermoplastic welding started actually more than 20 years ago on acoustic panels of air inlets. In 2018, more than 800 air inlets have been manufactured with thermoplastic acoustic layers welded for a large range of Airbus aircraft (A350XWB, A320neo, …), including a strong level of automation in Nantes plant.

Figure 9 - Air Inlet Acoustic Panel (Airbus Nantes)

The main innovation of acoustic panel has been the integration of high efficient acoustic function obtained with welding of resistive layers made of CF/PEI (so called “zero splice” acoustic liner or acoustic layer, which is under Airbus patent). This offers high tailored acoustic performance, manufacturing and in-service robustness and an excellent cosmetic aspect.
The indirect benefit with thermoplastic welding is the zero splice acoustic skin leading to air inlet aerodynamic improvement and increased acoustically treated surface.

5.1 Nacelle Air Inlet Context

Air inlet is essential for propulsion system regarding:

- aerodynamic performance,
- anti-icing function and
- noise reduction (Air inlet contribution for engine noise reduction is more than one third of total engine noise)

Air inlet inner panel provides the contour for the airflow entering the engine - securing engine performance and minimizing aerodynamic drag and air flow instabilities; for all flight conditions (roll-out, take off, cruise, cross wind, …). Second function of air inlet inner panel is noise attenuation – which is a key success factor vs competition, according relevant ICAO regulations, ref [23] [24]. Maximum noise levels are defined for each flight phases – in effectively-perceived noise levels (in EPNdB) [28]. These two main functions shall be achieved in the stringent environmental conditions such as vibrations, high temperature / rain / ice / de-icing fluids (glycol) / maintenance damages / in service damages …etc. Airbus develops and implements highly efficient air inlet design since A380 program using thermoplastic technology for acoustic layer. This air inlet acoustic layer design remains the one used today on A350XWB, A320neo and A330neo programs.

Figure 10 - A350XWB Rolls Royce Engine (Trent XWB) and air inlet acoustic layer

5.2 Airbus Air Inlet Main Issues

Before implementation of thermoplastic acoustic layer, Airbus in-service return of experience highlighted some robustness issues, in particular for acoustic layer to honeycomb assembly. The list of the mains acoustic layer issues is provided in table 1:

In service	-Wire mesh dis-bonding (air flow suction): wire mesh bonding low strength (with thermoset) -Rain / ice / erosion -Corrosion risks (thermoset vs steel wire mesh) -High temperature -Damages
Maintenance	-Accidental damages (tool drop, …)

Table 1 – List of main issues for acoustic skin in previous design

To improve in service robustness, Airbus develop new thermoplastic technology with Airbus Nantes plant and a new acoustic layer design.

5.3 Air Inlet Design Evolutions

Acoustic layer Aerodynamic surface used on air inlet before A380 program is made of pure metallic wire mesh (A340 program) or perforated composite or metallic sheet (A320ceo). Several longitudinal splices were needed for such acoustic skins, reducing the acoustically treated area as in Figure 11.

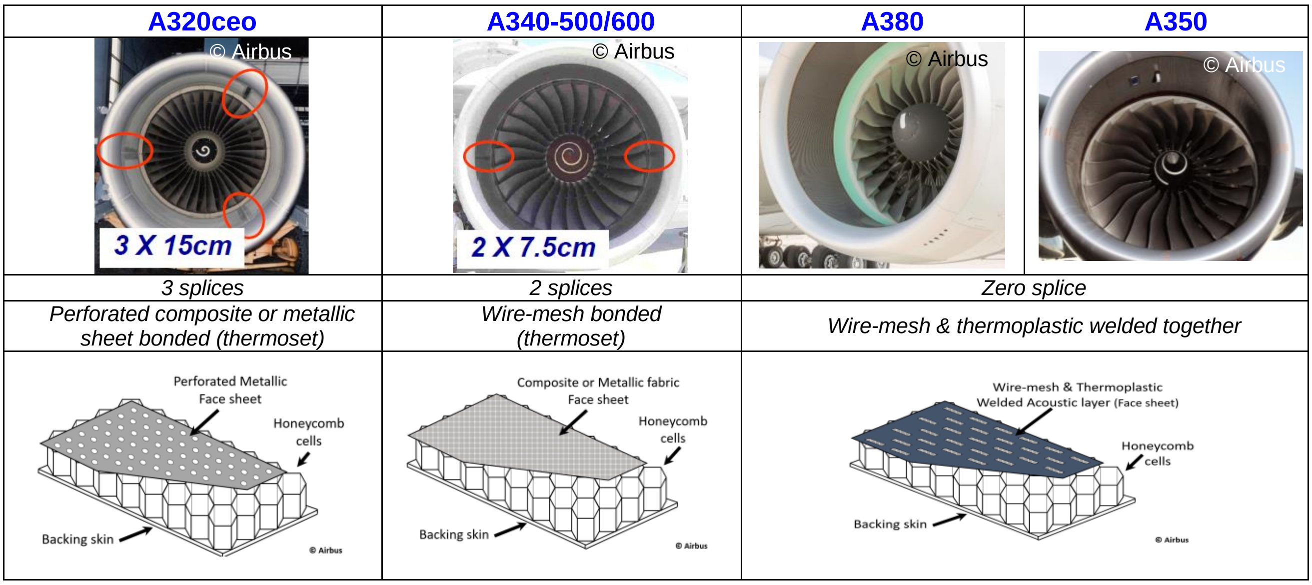

Figure 11 – Overview of different concepts for Airbus Air inlets [25]

The thermoplastic acoustic layer allow junctions removal [25]. On A380, the zero splice concept was developed and implemented improving noise reduction (treated area) [26].

5.4 The use of Thermoplastic for Inlet Acoustic Layer

Acoustic layer is made of one wire mesh layer and thermoplastic layers welded all together. Thermoplastic welding automatic process is developed by Airbus Nantes plant. This acoustic layer is then bonded on thermoset and on honeycomb to create air inlet inner panel. Honeycomb cells are acting as noise damping cavities – resonator [27]. This new thermoplastic acoustic layer concept drastically reduces the acoustic skin dis-bonding in-services events. Indeed, jet engine suction combined with delaminated / de-bonded surfaces (mainly linked to in-services damages) was leading to wire mesh de-bonding and engine ingestion. The acoustic skin new concept also reduces the manufacturing defects and then secure the target acoustic skin Percentage of Aperture (PoA) [28]. The thermoplastic acoustic damping layer was developed to meet aerodynamic requirement, to sustain erosion and also to meet Airline cosmetic requirements.

5.5 Thermoplastic Acoustic Layer Manufacturing & Quality Control

Once the acoustic layer is finalized, thermoset are setup and a first cure cycle is applied. Then thermoset adhesive film and honeycomb are installed on top (with thermoset backing skin) for the final cure cycle. The thermoplastic welding allows a significant higher performance in fracture toughness compare to former technology. In addition, thermoplastic welding creates small “bridges” with the wire mesh. The key process parameters for thermoplastic welding were defined through process simulation and manufacturing trials, and using Airbus Nantes plant past experience. Rigorous and quite heavy process fine tuning during development phase was needed for welding automatized industrial process. The same effort was done for thermoset and adhesive film cure cycle optimization of the bonding of TP acoustic skin on TS and honeycomb. All in all, final acoustic layer quality and robustness is improved. Design and tolerancing play also a key role. Airbus Nantes plant develop and implement thermoplastic automatic welding process and associated real time process parameter monitoring, using statistical approaches. This welding quality control means consist in numerical picture analysis. In addition to Statistical Process Control (SPC), a systematic Visual inspection and sampling Process Control Specimens are also done.

5.6 Conclusion for the thermoplastic use on air inlet

Airbus air inlet acoustic layer is made of thermoplastic since A380 program. This innovation allows significant robustness improvement in service and indirectly improve noise reduction capability (zero splice design). This technology is also offering durability of cosmetic aspect for our Customers. Acoustic layer development will continue to anticipate future noise reduction requirements (develop acoustic layer compatible with hot air inlet lip area for example). Acoustic panel further improvements are also needed to reduce air inlet manufacturing recurring costs [29]. New design – function integration – and process steps reduction are under development. Use more thermoplastic will simplify panel manufacturing and re-use. For future program, thermoplastic could be used for other propulsion system components, such as fan cowl, thrust reverser or pylon structurally loaded parts.

6. H160 HELICOPTER MAIN ROTOR HUB

On H160 helicopter has been introduced a main rotor hub made of carbon fiber in fabric with thermoplastic resin PEEK: a first innovation for such significantly loaded rotor part. Thermoplastic has been motivated by 3 aspects:

- Enhanced out-of-plane mechanical properties with low sensitivity to ageing effect, leading to weight efficiency of rotor hub
- Improved fatigue and damage tolerance behavior under out-of-plane loading, leading to enhanced reliability and operability
- Environmentally friendly properties, in particular regarding storage conditions being less stringent than for thermoset material.

Figure 12 - H160 thermoplastic hub (5 blades)

6.1 Fabric CF/PEEK out-of-plane mechanical properties

Thermoplastic resin PEEK has been selected for H160 main rotor hub according to material out-of-plane mechanical characteristics improvement in comparison with known TS resin (180°C resin system). As detailed in [1] and [2], AH has experienced improved ILSS performance for CF/PEEK when compared with some CF/Epoxy in static and fatigue mode. Out-of-plane loading is significantly contributing to static and fatigue stress state for main rotor hub applications. Therefore improved performance of CF/PEEK material is a key asset to improve reliability and performance of such critical component. In addition, it has been observed by AH that for the ILSS fatigue behavior of fabric CF/PEEK, two different areas have been evidenced in S-N curve ([1] and [2]):

- From 1 cycle up to around 30 000 cycles there is a significant effect of fatigue, characterized by a steep slope
- From 30 000 cycles up to 10^7 cycles the slope is smoother and similar with thermoset behavior.

The behavior is illustrated in Figure 13..

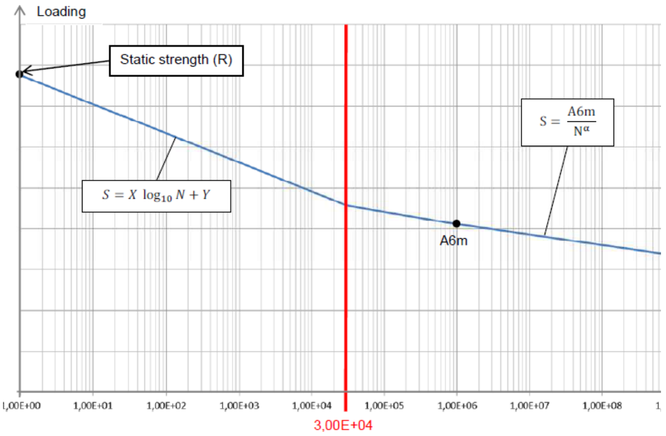

Figure 13 - Fabric CF/PEEK ILSS Fatigue curve shape as S-N data [1] and [2]

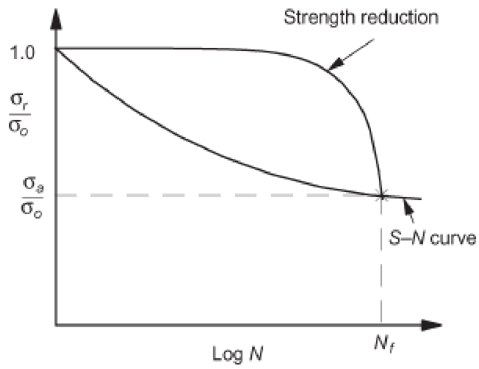

Figure 14 - Strength reduction of composite materials under fatigue loading [8]

6.2 Effect of Fatigue Loading on Static Residual Strength

Residual fatigue strength after fatigue is generally not a concern for thick composite parts. Actually fatigue tests on composite components are performed with amplified dynamic loads until some damages, degradations or loss of stiffness appear. Objectives of component fatigue tests is to derive a fatigue limit and further investigate growth behavior of damages. In flight the maximum dynamic load level applied on the hub is much lower than mean fatigue limit level [3]. Effect of fatigue loading on static residual strength has been explored through numerous papers [7] [8]. Authors have demonstrated [8] that residual strength (after fatigue) was directly function of the physical damage in the plies. The damages are:

- Microcracks and cracks in the resin
- Micro-delamination and delamination

The strength reduction can be illustrated as shown in Figure 14.

Based on Airbus experience and test results, it has been evidenced:

- Some slight decrease (10%) of residual strength after fatigue for fabric GF/Epoxy on Starflex® hub [3]
- Non detrimental effect of fatigue on residual strength for fabric CF/Epoxy and CF/PEEK [2]

No detrimental effect of loading rate has been also evidenced for fabric CF/PEEK [2].

6.3 Damage Tolerance Evaluation

One benefit of thermoplastic material has been highlighted with H160 rotor hub through damage tolerance and fatigue evaluation. For Airbus fuselage applications, the “no detrimental growth” approach is generally preferred, as found more appropriate for non-removable or non-easily inspectable structures. For H160 hub, adaptation to some particular out of plane loading conditions induced by dynamic bending moment is leading to fatigue damage in composite. For applications such as rotor hubs and sleeves, there is evidence of sensitivity to fatigue. For the first time on such rotor hub application, the damage tolerance evaluation could be based on Slow Growth evaluation. It could be achieved thanks to thermoplastic enhanced behavior in presence of delamination.

In AC29.573 f.(6)(iii) [6] is proposed an approach for Damage Tolerant Fail-Safe (Residual Strength with Detectable Damage) Evaluation, based on Slow Growth Evaluation. *“This method is applicable when the damage grows in the test and the growth rate is shown to be slow, stable, and predictable. Inspection intervals should be established so that the damage will have a very high probability of detection between the time it becomes initially inspectable and the time at which the extent of the damage reduces the residual static strength to limit load (considered as ultimate), including the effects of environment.”* This approach is leading to definition of inspection intervals, to ensure that in case of presence of detectable damage there is no detrimental effect on residual static strength. Delamination growth may occur as a consequence of significant level of interlaminar shear stresses. Probable events that may induce such undesired stresses are numerous: local buckling, free edges and notches such as holes, ply drops, impact damage, … or, in thick structures, high level of out of-plane stresses. For such applications it is then important for damage tolerant evaluation to make characterization of delamination growth both theoretically and experimentally.

6.4 Delamination Growth Characterization

Some activities have been led to characterize delamination growth behavior in I+II and II opening modes. Studies have been done on coupons in mixed mode I+II as presented in [2], and tested in 4 points bending. The energy release rate (ΔG) obtained is a combination between mode I and mode II propagation (GI and GII). ENF coupons have been tested [2] to characterize pure mode II growth behavior law. A delamination growth law has been established, with representation of Energy Release rate ΔG as a function of crack growth rate (da/dN). The regression law is leading to linear relationship between energy release rate and crack growth rate, based on compliance method (1).

$$\frac{da}{dN} = C.\Delta G^{m} \quad (1)$$

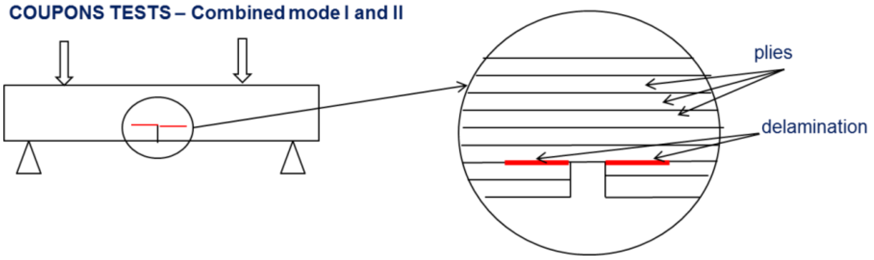

Figure 15 - 4 points bending coupons with saw cut (mixed mode I+II)

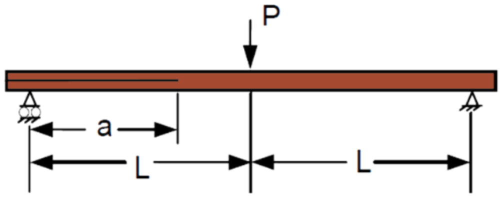

Figure 16 - ENF coupon (pure mode II)

Growth behavior has been investigated on fabric CF/PEEK material regarding combined opening mode I+II and mode II. Results are presented in Figure 17.

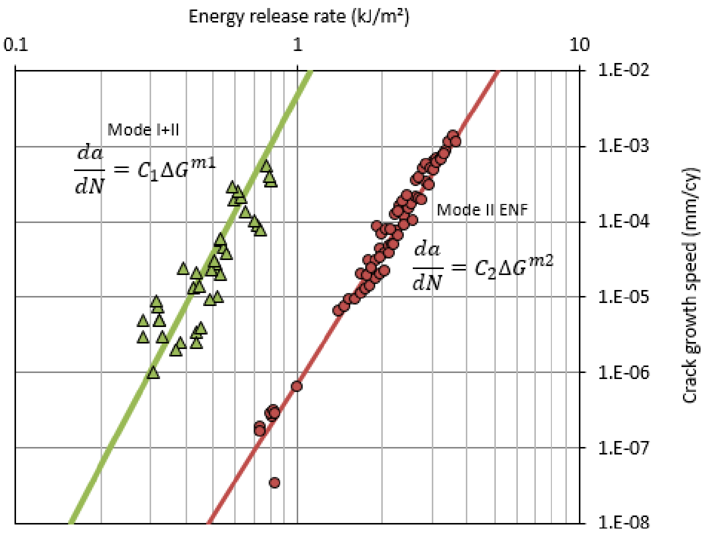

Figure 17 – Fabric CF/PEEK delamination growth law in mode I+II (green) and in mode II (red)

The established laws in mixed mode I+II and in pure mode II are used to monitor growth behavior of delamination which may be present initially on the component (e.g. manufacturing flaws), or which may have initiated because of fatigue loading or accidental damage.

6.5 Environmental Effect on Delamination Growth behavior

Effect of environmental conditions on delamination growth behavior has been investigated on Starflex® materials (fabric GF/Epoxy) [3] and H160 hub (fabric CF/PEEK). Environmental ageing is leading to plasticization of epoxy matrix [8]. As a consequence, delamination growth rate is lower after ageing for epoxy matrix. This has been confirmed on some CF/Epoxy as shown in Figure 18. For a value of energy ΔG the crack growth rate is lower for the laminate in water than in air. Transverse Crack Tension tests have been performed on fabric GF/Epoxy (Figure 20, [3]) to investigate effect of environmental conditions on fabric GF/Epoxy. Effect of ageing at room temperature has been established as negligible. Hot temperature was observed as beneficial however effect of cold temperature has been evidenced detrimental for crack growth rate [3]. Influence of temperature on fabric GF/Epoxy delamination growth rate (mode II) is shown on Figure 21.

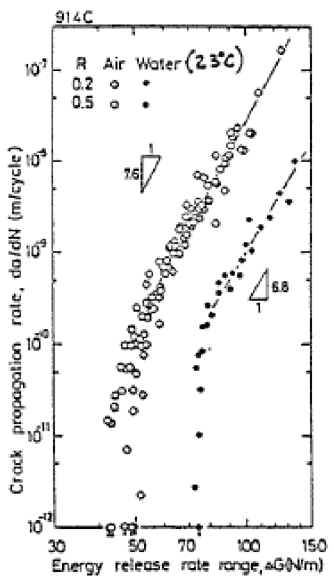

Figure 18 – Crack growth rate for CF/Epoxy in air and in water [9]

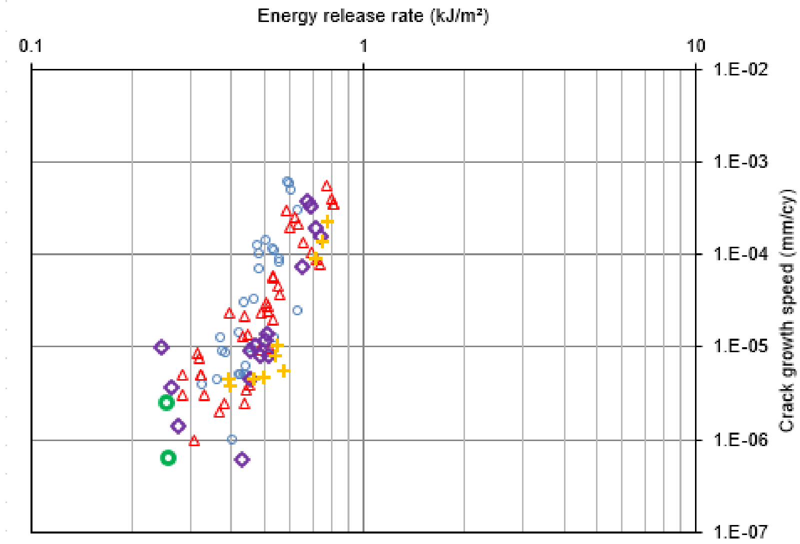

Figure 19 - CF/PEEK delamination growth tests results in mode I+II at RT, ECC and EHC

For fabric CF/PEEK, due to low sensitivity of fracture toughness to moisture, delamination growth behavior is not significantly affected by environment conditions. In Figure 19 is shown the delamination growth behavior of fabric CF/PEEK for RT, ECC and EHC. Coupons of Figure 15 have been used (Mixed mode I + II). A single population is established with reference values obtained at

RT dry. This confirms the low sensitivity of fabric CF/PEEK fracture toughness to environmental conditions (moisture and temperature effects), as observed in [13] by some authors. Environmental conditions (moisture and temperature ageing) have no detrimental effect on delamination growth in case of fabric CF/PEEK.

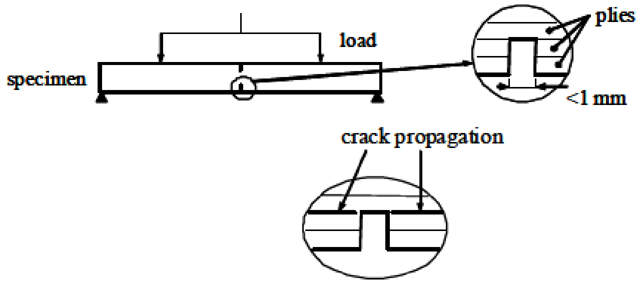

Figure 20 – Transverse Crack Tension (TCT) specimen for fabric GF/Epoxy delamination growth evaluation in mode II [3]

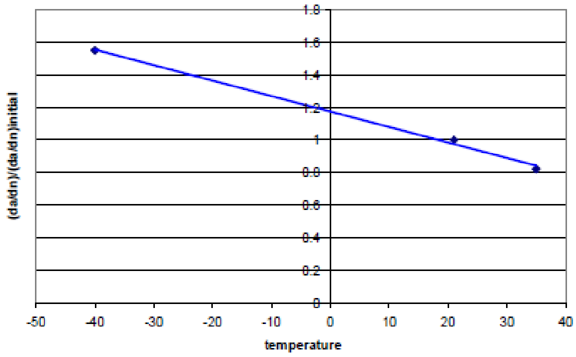

Figure 21 - Influence of temperature on fabric GF/Epoxy delamination growth in mode II [3]

6.6 Delamination Growth Evaluation through Component test

Delamination propagation rate has been evaluated through full scale component for H160 hub in fabric CF/PEEK. The propagation rate observed was low. Furthermore a threshold was observed under which there was no propagation. Components tests performed have evidenced that delamination growth was slow, stable and predictable, in presence of severe delaminated areas, much larger than the expected damages in service. These tests demonstrated a damage tolerant design.

6.7 Conclusion for the thermoplastic use on H160 main rotor hub

Implementation of thermoplastic materials on H160 main rotor hub has contributed positively on several key drivers:

- Enhanced out-of-plane fatigue performance and behavior regarding damage tolerance, when compared with thermoset materials, with positive impact on maintenance and customer value;
- Sustainable aspect and highly reproducible manufacturing processes supported by online monitoring;
- Reduced manufacturing costs in comparison with metallic technologies for such applications.

Civil certification of H160 helicopter, including thermoplastic hub, has been successfully achieved by Airbus Helicopters with EASA in July 2020, and recently in Japan.

7. CONCLUSIONS

During past decades, Airbus has successfully implemented thermoplastic materials on some key structural applications. The selected applications were taking full benefit of thermoplastic properties for functions integration (air inlet) or out of plane mechanical properties (hub). Nevertheless several challenges are remaining to further implement thermoplastic materials on large structural applications such as fuselage shells. Some of them are detailed below:

- Material cost

Due to different factors, in particular linked to the volume of material currently used, price of thermoplastic materials remains higher than for thermoset materials. The capacity to the market to reduce the general cost of the thermoplastic materials and associated technologies will be of course decisive for the future developments of aerospace structures.

- Competitiveness vs Thermoset applications

Some high performance thermoset materials have been implemented on A350XWB fuselage and wings. Mechanical properties between those structural thermoset materials and PAEK composites are found very close on the sizing drivers. Significant weight savings are then not expected for those applications with only a change to thermoplastic materials. Integration of functions, smart design and structural welding for assembly are needed to counterbalance material cost difference between thermoset and thermoplastic. In addition, due to invests needed to move industrial means to thermoplastic processes, significant cost savings have to be assessed in business cases with thermoplastic when benchmarked with thermoset materials.

- Thermoplastic Technologies Readiness

Low readiness of some key technologies, such as structural welding on CFRP UD Tape and out of autoclave processes, is a challenge for implementation of thermoplastic materials in aerostructure to reach function integration and high rate applications. A step forward on those aspects is needed.

- Reuse and Recycling Development

Reprocessing capability of thermoplastics is a key asset of those materials. Sustainable structures should be designed and manufactured to recycle. The supply chain organization should also be revisited to implement reuse and recycling in the industrial flows. On top, materials with short fibers cannot replace continuous fiber materials for structural applications without weight penalty or impact on design.

As a conclusion, there is a clear maturity of thermoplastic which has been evidenced through several innovations by Airbus for structural applications. Some challenges remain to further implement thermoplastic technologies on large applications. Support of all stakeholders is needed to develop readiness of those technologies, such as material suppliers, academics, research institutes and automotive industries, to position thermoplastic as the challenger of well-established technologies.

8. Acronyms

AC: Advisory Circular
ACARE: Advisory Council for Aeronautics Research in Europe
AFP: Automated Fiber Placement
AH: Airbus Helicopters
BD: Bidirectional
CF: Carbon Fiber
CFRP: Carbon Fiber Reinforced Polymer
ECC: Extremely Cold Conditions
EHC: Extremely Hot Conditions
ENF: End Notched Flexure
EPNdB: Effectively Perceived Noise levels
ETD: Elevated Temperature in Dry Conditions
ETW: Elevated Temperature in Wet Conditions
FCV: Fracture Characteristic Volume
GF: Glass Fiber
GHG: GreenHouse Gas
ICAO: International Civil Aviation Organization
ILSS: Inter Laminar Shear Strength
ILTS: Inter Laminar Tensile Strength
MFFD: Multi-Functional Fuselage Demonstrator
OEE: Overall Equipment Effectiveness
OoA: Out of Autoclave
PAEK: Poly Aryl Ether Ketone
PEEK: Poly Ether Ether Ketone
PEI: Poly Ether Imide
PoA: Percentage of Aperture
R: Stress Ratio ($R = \sigma_{min}/\sigma_{max}$)
REACH: Registration, Evaluation and Authorisation of Chemicals
RT: Room Temperature
RTD: Room Temperature in Dry Conditions
RTW: Room Temperature in Wet Conditions
SPC: Statistical Process Control
SRIA: Strategic Research and Innovation Agenda
TCT: Transverse Crack Tension
Tg: Glass Transition Temperature
TP: Thermoplastics
TS: Thermosets
UD: Unidirectional
wt%: Weight Percent
WA: Wet Ageing
XWB: Extra Wide Body

9. Contact Author Email Address

M. HERMAN melanie.herman@airbus.com
E. DUPUY eric.dupuy@airbus.com
C. PARIS Christophe.c.paris@airbus.com
E. PETIOT emilie.petiot@airbus.com
J.-P. CABANAC Jean-Pierre.Cabanac@airbus.com
C. FUALDES Chantal.fualdes@airbus.com
G. MASSE guillaume.masse@airbus.com
M.-A. CELLI marc-antoine.celli@airbus.com

10. Copyright Statement

11. References

[1] Herman M., Besson J.-M, Hochard C., Charles J.-P., Lahellec N., "Development of Techniques for Composite Parts Failure Analysis in Static and Fatigue Mode - Application on Thermoset and Thermoplastic Materials for Rotorcraft Main Rotor Hub Analysis", AHS International 74th Annual Forum & Technology Display, Phoenix, Arizona, USA, 2018.

[2] Besson J.-M., Celli M.-A., Capelle N., "H160 Helicopter : development of a carbon thermoplastic hub", ERF, Lille, France, 2016

[3] Besson J.-M., Marino Y., "The Starflex® flying all over the world and always in evolution", 37th European Rotorcraft Forum, Vergiate and Gallarate, Italy, 2011.

[4] Zambelis G., Da Silva Botelho T., Klinkova O., Tawfiq I., Lanouette C., "Evaluation of the energy release rate in mode I of asymmetrical bonded composite/metal assembly", *Engineering Fracture Mechanics*, Vol. 190, 2018, pp. 175-185

[5] Aymerich F., Found M., "Response of notched carbon/PEEK and carbon/epoxy laminates subjected to tension fatigue loading," *Fatigue and Fracture of Engineering Materials and Structures*, Vol. 23(8), 2000, pp. 675–683.

[6] AC29.573: §29.573 (Amendment 29-55) in AC29-2C Change 4, Jan 2014

[7] DIAO X, YE L and MAI Y-W (1997), Fatigue behaviour of CF/PEEK composite laminates made from commingled prepreg – Part I and Part II, Composites, 28A, 739–755.

[8] Harris B., "Fatigue in composites - Science and technology of the fatigue response of fiber- reinforced plastics", Woodhead Publishing, 2003.

[9] Hojo, Tanaka, Gustafson, "Effect of water environment on propagation of delamination fatigue cracks in CFRP", ICCM6-ECCM2 Vol. 4

[10] Stumpff P., "Failure analysis", *ASM Handbook Volume 21 Composites*, ASM International, 2001, pp. 947–1002.

[11]Selzer R., Friedrich K., "Mechanical properties and failure behaviour of carbon fibre reinforced polymer composites under the influence of moisture", *Composites Part A*, Vol. 28 (6), 1997, pp. 595–604

[12]Ma C.-c. M., Yur S.-w., "Environmental effects on the water absorption and mechanical properties of carbon fiber reinforced PPS and PEEK composites", Part II., *Polymer Engineering and Science*, Vol. 31(1), 1991.

[13] Hojo, Tanaka, Gutsafson, "Effect of water environment on propagation of delamination fatigue cracks in CF/PEEK""

[14] Stumpff P., "Failure analysis", *ASM Handbook Volume 21 Composites*, ASM International, 2001, pp. 947–1002.

[15] Assadi M, Electroimpact Inc. "High Speed AFP Processing of Thermoplastics", SAE, AeroTech Digital Summit, 2021-01-0043, 2021.

[16] https://www.airborne.com/automation-solutions-advanced-composites/

[17] Guillon, D.; Lemasçon, A.; Callens, C. QSP®: An innovative process based on tailored preforms for low cost and fast production of optimized thermoplastic composite parts. In Proceedings of the ECCM 2016—Proceeding of the 17th European Conference on Composite Materials, Munich, Germany, 26–30 June 2016

[18] Periodic Reporting for period 1 - KEELBEMAN (Keel beam manufacturing oriented solution) | Report Summary | KEELBEMAN | H2020 | CORDIS | European Commission, 2019 https://cordis.europa.eu/project/id/785435/reporting

[19] https://www.xelis.de/technology/x-ccmr.html

[20] Curved thermoplastic pultrusion, Curved profiles | CQFD Composites (cqfd-composites.com)

[21] This project has received funding from the Clean Sky 2 Joint Undertaking under the European Union's Horizon 2020 research and innovation programme under grant agreement No CS2-LPA-GAM-2018-2019

[22] Wang Q., Springer G. S., "Moisture absorption and fracture toughness of PEEK polymer and graphite fiber reinforced PEEK". *Journal of Composite Materials*, Vol. 23(5), 1989, pp. 434–447

[23] International Civil Aviation Organization ICAO - Aircraft Noise to the Convention on International Civil Aviation. Environmental Protection, Volume I, Annex 16.

[24] ICAO - Guidance on the Balanced Approach to Aircraft Noise Management. Doc 9829.

[25] Kempton A., "Acoustic liners for modern aero-engines", Rolls-Royce, University of Southampton, 2011

[26] Batard H. «The zero splice engine intake liner : an efficient way of reducing aircraft noise without any weight or aerodynamic penalty », 24th ICAS, Yokohama Japan, 2004

[27] Argerich Martín C., Carazo Méndez A., Sainges O., Petiot E., Barasinski A., Piana M., Ratier L. and Chinesta F. «Empowering Design Based on Hybrid Twin™: Application to Acoustic Resonators», *Designs*, MDPI, Vol. 4, No 4, pp 1-14, 2020.

[28] Leylekian L., Lebrun M., Lempereur P., "An overview of aircraft noise reduction technologies", AerospaceLab, pp 1-15, 2014.

[29] Dupuy E., "Airframe Composite Structures: Consideration of manufacturing capability in the composite design", JEC Conference – Paris, 2017.

[30] https://www.airbus.com/newsroom/press-releases/en/2019/06/ctos-cooperate-to-drive-the-sustainability-of-aviation.html