MANUFACTURING AND REINFORCEMENT TECHNOLOGIES FOR THE NEXT GENERATION AIRCRAFT REAR END

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Abstract

Caused by increasing mobility of more and more people, the demand for reducing CO2 emissions emitted by civil aviation increases constantly. Foreseeable CO2 restrictions for future aircraft require lightweight designs, new engine concepts and likely disruptive new aircraft configurations to prevent growing ecological footprints.
Beside these ecologic requirements, the mobility increase dictates to develop technologies for low-cost, high rate production. Therefore, the Clean Sky 2 research program supports finding answers for these challenging, sometimes conflicting requirements.
Different promising aircraft concepts (hybrid electric propulsion, forward swept wings or tails) require new designs of the a/c rear end. Design drivers are the auxiliary power unit (APU) and its arrangement as well as engine integration and tail surface arrangement. Additionally, low cost manufacturing technologies for lightweight materials will be addressed in order to increase the production rate and the fuel efficiency due to mass reduction.
The German aerospace center (DLR) supports the investigations towards a future rear end with two research streams:

1.) Simulation tools for the design of lightweight and cost efficient reinforcements required at the aircraft rear end and
2.) Thermoplastic manufacturing technologies for complex and double curved rear end structures.

Meanwhile, two large high velocity impact test campaigns were conducted on a range of different materials, including a reference material. One test campaign was conducted at DLR Stuttgart and the second test campaign took place at ONERA Lille (France). A further test campaign is foreseen in the next two years. Besides the security relevant high velocity impact test, real-time damage assessment technologies are developed supporting the maintenance of aircraft and enables a flexible maintenance concept.

The first development step towards high-rate thermoplastic fiber lay-up is the approach based on the use of a xenon heating lamp. Xenon heating requires hardly any security efforts and is therefore interesting for flexible low cost manufacturing. First manufacturing trials with this technology at DLR Stade reveal the control parameters necessary to adjust the nip point temperature. Furthermore, the test samples show a good consolidation in the microsection.
The final paper will discuss the benefits and drawbacks of the investigated advanced impact materials and their effects on the initially mentioned environmental targets. Furthermore, the thermoplastic lay-up technology will be assessed with respect to the manufacturing targets of 100 a/c a month.

1. INTRODUCTION

Lowering the CO2 emissions of future a/c ensure the mobility of our modern civilization. They are required to answer the foreseeable CO2 restrictions as well as to address the ecological requirements which gain more and more attention due to e.g. the Friday for future demonstrations. Reasoned by the lifetime of modern civil a/c, disruptive and multifunctional aircraft technologies have to be developed right now in order to find their way into the market in near future. Another important aspect for the aircraft manufactures is the need for low-cost but high-rate production technologies in order to full-fill the market needs. Therefore, the Clean Sky 2 (CS2) research program supports finding answers for these challenging and sometimes conflicting requirements.
In the last research program (Clean Sky 1) and also in the frame of CS2, new a/c configurations with engines attached to the a/c rear-end (Open rotors, boundary layer ingestion) as well as new tail (stabilizer) configurations are presented. These a/c configurations together with the demand for high-rate and low-cost production require a new advanced rear-end concept. The mentioned challenges are addressed in the project “advanced rear-end” within CS2. The targeted demonstrator is shown in Figure 1.

Reasoned by the forward swept tails, the auxiliary power unit (APU) would be installed right under the horizontal tail plane in this configuration. This leads to the following risks and opportunities:

- Easy maintenance of APU
- Size of the APU could be enlarged
- Horizontal tail planes can be easily assembled
- Risk due to APU failure (impacts by APU fragments)

To mitigate the presented risk and enable the opportunities of such a configuration, the investigation of new materials to enlarge the impact resistance as well as thermoplastic manufacturing processes for complex rear-end sections are required.

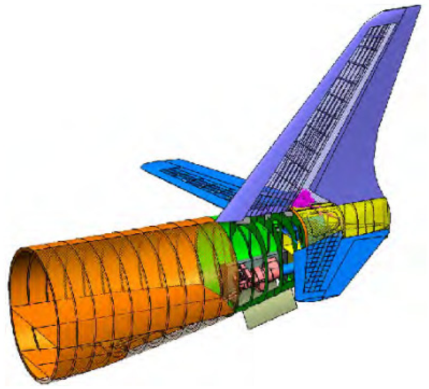


Figure 1: Advanced rear-end demonstrator

DLR and ONERA investigate the impact topic together. Furthermore, manufacturing technologies are studied at DLR Stade at the Centre of Lightweight Production.
The paper is structured as follows: First the investigations with respect to the safety relevant impacts are addressed. The main question is: which materials can prevent critical damage to the fuselage in case of an APU failure where high speed metallic fragments are released? The second major point is the development of low fidelity, high speed simulation routines which assesses the damage of low energy impacts and its application to a augmented reality workflow. The last technical part of the paper presents the thermoplastic manufacturing technologies. Mainly, xenon heating technologies and automated lightning strike protection will be presented. The paper ends with a short discussion and an outlook to the final project objectives.

2. SAFETY RELEVANT IMPACTS

In case of a critical APU failure, high speed metallic fragments can be emitted and have to be stopped by a containment or a suitable fuselage reinforcement. Therefore, DLR and ONERA have launched two test campaigns during the project so far in order to create a database for the validation of the simulation methodologies. In this chapter, the impact test set-up, the material selection as well as first test and simulation results are shortly presented. Further details can be found in [1,2]

2.1. Test set-up

During two test campaigns a heavy metallic-frame of DLR was used. The first test campaign is conducted at DLR. Then the device is transferred to ONERA for the second test campaign in order to have comparable test conditions for the high speed impact tests. The test set-up is presented in Figure 2.
The test plates are clamped between the heavy frames such that a free area of 400mm × 400 mm is realized. As projectiles, a spherical steel ball with 110g (diameter of 30mm) and a generic rigid projectile with a rectangular shape (18mm×13mm×3mm) and a mass of 5.7g are used. The steel ball is mainly used for the simulation methodology validation and the rectangular steel projectile is used as a generic representation of an APU fragment. For the tests, a Ø60mm gas gun is used at DLR and a Ø50mm gas gun at ONERA. The maximum speeds of the guns are in the range of 250m/s to 280m/s.

During the tests, the initial velocity is measured with light curtain, and the residual velocity is determined with high speed cameras. C-scans are performed prior and after each high velocity impact test to determine the delaminated area.

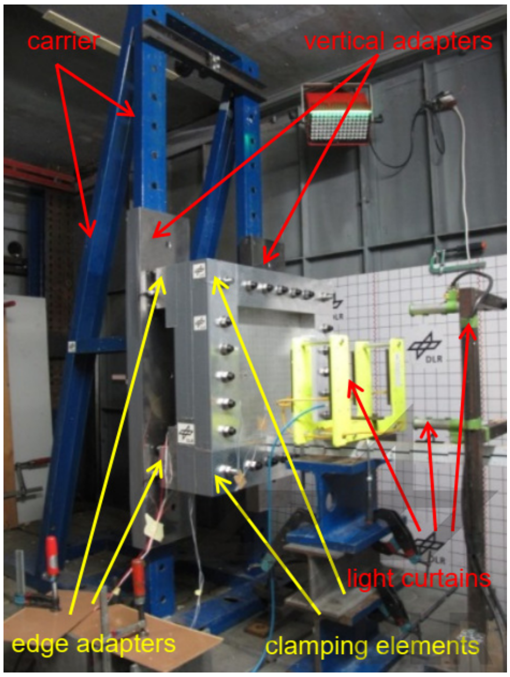


Figure 2: Test set-up of DLR for the high velocity impact tests

2.2. Material selection

In this section, the selected materials which are tested in the project are shortly described.
In order to compare the performance of new materials, it is decided to measure the impact resistance of reference materials first. The first reference material is a typical fuselage metal: the aluminum Al2024T3. As a second reference material, a carbon fiber reinforced plastic (CFRP) namely the T700/M21 prepreg is chosen. The material is chosen due to the quasi-static material properties and the current processing experiences of the partners. The T700/M21 is provided by the Hexcel Company.

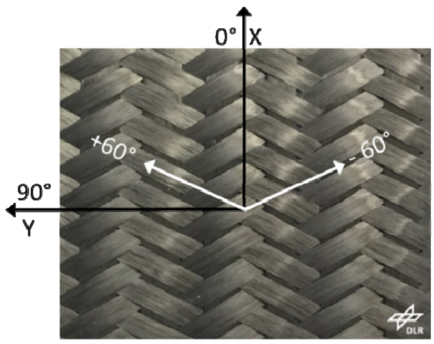


Figure 3: Tri-axially braided CFRP

As a first advanced material a tri-axially braided carbon fiber material in combination with a toughened resin is selected (see in Figure 3). This is reasoned by the following thoughts which as to be proven by simulation and test: Due to the tri-axially braided carbon fiber architecture (A&P Tech. QISO-L-A-52) combined with the highly toughened epoxy matrix (Hexcel HexPly M36 Resin Film) the proposed material system meets all conditions to offer superior impact properties. In fact, this holds true for both low velocity impact as well as high velocity impact behavior. Besides the potential of the toughness modification, energy dissipation is linked to the high number of fiber crossings. Further improvements of high velocity impact capabilities can be achieved by using relatively thin (low areal weight) fabrics. By increasing the number of plies and interfaces, additional energy can be dissipated through multi-layered delamination formation.

Due to the high speed and low weight of the metallic fragment considered for the APU failure, ballistic fibers are also taken into account. This is reasoned by the performance of ballistic fibers in the field of structural and personal armor protection.
In order to combine the characteristics of the ballistic fibers (Zylon AS) with the tri-axially braided architecture, a special braid is ordered. The ballistic tri-axially braided material is combined with a CYCOM 890 resin which has a very high tensile elongation (6,3%).

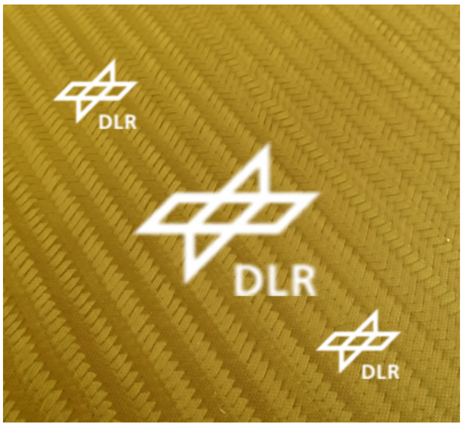


Figure 4: Tri-axially braided Zylon AS ballistic fiber

Up to now, the manufacturing process is developed at DLR. According to this manufacturing methodology, plates will be produced to perform further high velocity impact tests.
The third impact test campaign with the plates made out of the ballistic braid is scheduled in early 2020 in DLR.

2.3. Achievements in simulation & material performance

First of all, the impact simulation for the carbon fibre reinforced reference material (T700/M21) is compared to the experimental tests. At DLR the simulations are conducted with ABAQUS and at ONERA with the EUROPLEXUS code.
The material card in ABAQUS and EUROPLEXUS are developed w.r.t available material characterization test results that are performed previously at ONERA.
For the carbon fiber reference material the simulation tool shows a very good estimation of the experimental results.
Figure 5 shows that the ballistic limit is slightly underestimated in most of the simulations. The different simulations (mesh 1 to 4) with are conducted in order to test the computation time in order to estimate which mesh can be used for further simulations with larger scale. Mesh 1 has the smallest element size and mesh 4 the largest element size. Mesh 4 reduces the simulation time to approximately 17 % of the computation time needed with Mesh 1. The mesh study is conducted in order to prove that the simulation is also applicable for larger scale specimens like sub-components of the rear-end.

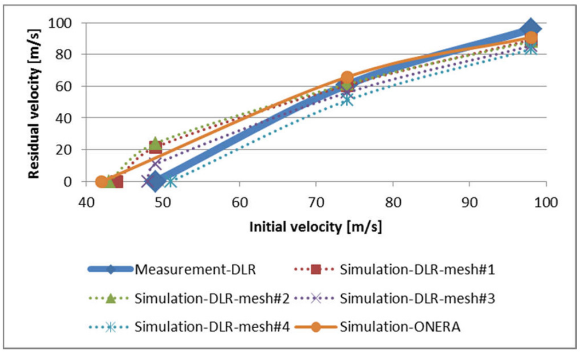


Figure 5: Comparison between simulation and experiment for the T700/M21 reference material

Comparable results are achieved for the more complex tri-axially braided material. The simulated ballistic limits underestimate the experiments slightly. Therefore, the utilization of those simulation methodologies will lead to conservative structural designs for the high velocity relevant aspects.

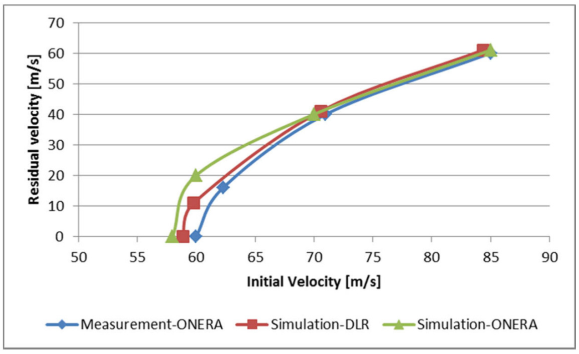


Figure 6: Comparison between simulation and experiment for the tri-axially braided carbon fibre

In order to compare the material performance, the different ballistic limits and areal weights are shown in Table 1.

Table 1: Ballistic limits of the different materials for the steel ball impactor under normal impact conditions

Property	**AL2024 T3**	**AL20243 T3**	**T700/M21**	**AS4C/M36**
Thickness	3mm	6mm	~3.2mm	~3.9mm
Ballistic limit	98 m/s	154 m/s	49 m/s	60 m/s
Areal density	8.5 kg/m²	16.9 kg/m²	4.9 kg/m²	5.63 kg/m²

Compared to the CFRP reference material, the tri-axially braided carbon fiber has better shielding properties. Therefore, the tri-axially braided architecture is kept for the use with ballistic fiber.
The impact investigations clearly show that the simulation tools are able to predict the ballistic limits for the chosen materials and can be therefore used to design and size necessary reinforcements at the rear end.

For DLR, the next step is the validation of the simulation tool for the ballistic fibers. Afterwards, the validated simulation will be used to estimate the weight impact for a proper APU reinforcement to ensure a/c safety.
At ONERA, different concepts with shape memory alloys and other additional layers to reinforce structures will be conducted.

3. HIGH SPEED ASSESSMENT OF LOW ENERGY IMPACTS

A disadvantage of composite aircraft structures is their vulnerability to impact damage caused by e.g. hail or ice shedding during operation or accidental tool-drop during maintenance. These impacts can lead to so-called BVIDs (Barely Visible Impact Damage). As a result, the damage may remain undetected in the structure and accumulates over time.

3.1. Modelling approach

Because of inherent uncertainties underlying such impact events and the natural scatter of composite material properties, several simulation loops are necessary to capture the resulting possibility space. Conventional high-fidelity finite element models are not feasible due to their high computational cost. Consequently, alternative approaches have to be provided.
A simulation approach using semi-analytical contact expressions to derive the resulting time-variant pressure distribution acting on the aircraft structure during impact has been developed. The methodology either derives its required input from the impactor and target material properties and the initial impact conditions [3] or uses time-variant data provided by SHM (Structural Health Monitoring) systems [4]. The damage morphology extracted from these simulations is subsequently used to obtain a measure for the severity of the damage and thus, if the structure is in need for repair.

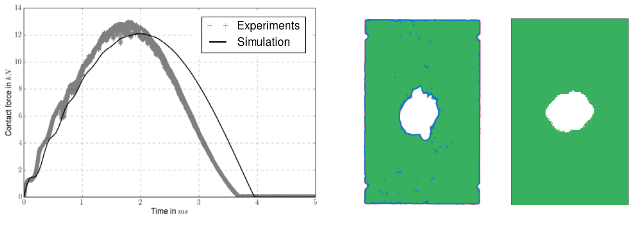
3.2. Validation by means of drop-tower test

The implementation was verified using literature values [3] and validated by comparing the simulation results with experimental data from conventional CAI (Compression After Impact) tests conducted with a drop-tower. The quality with respect to contact force history and damage morphology is acceptable for both cross-ply and quasi-isotropic layups (Fig. 7) [3]. Furthermore, the simulated damage morphology is used as input in a subsequent damage assessment analysis. Again, the results are in good agreement with experimental data, although accuracy has been reduced in favor of lower computational effort (Fig. 8).

3.3. Selected application

A demonstrator developed by DLR comprises SHM based on Lamb waves and the aforementioned low-fidelity simulation framework. An augmented reality system is used to highlight future capabilities in on-site decision making on the serviceability of a composite aircraft structure (Fig. 9). The system is currently employed in a double-curved composite shell and was presented at the JEC Composites 2019 in Paris.

It is planned to realize the combination of damage assessment and SHM system on a stiffened and curved shell segment (pre-loaded) inside the project.



(a) (b)

Figure 7: Experimental results of a 30 *J* impact on a specimen with quasi-isotropic layup compared to the simulation [3]. (a) Contact force history (b) Projected delamination area from D-scans (*left*) and simulation (*right*).

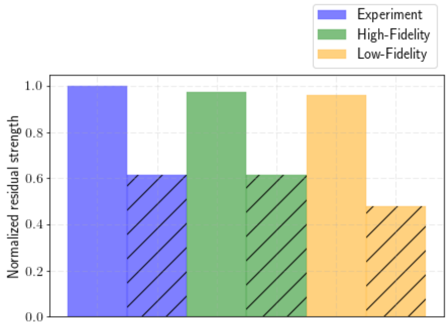


Figure 8: Normalized residual compressive strength of a pristine (*blank*) and impacted (*dashed*) composite specimen.

Figure 9: Maintenance demonstrator combining SHM with on-site damage classification and 3D visualization using an augmented reality system.

4. THERMOPLASTIC MANUFACTURING TECHNOLOGIES

4.1. Xenon heating technology for the Automated Fiber Placement of carbon fibre reinforced thermoplastics

Over the past decade, production technologies such as Automated Tape Laying (ATL) and Automated Fibre Placement (AFP) in combination with pre-impregnated unidirectional fibers, were established as the standard in serial production of large scale CFRP shells [5, 6]. With

AFP a number of separate small width tows are automatically laid onto a mold for manufacturing complex geometries or small structures. Depending on the processing temperature of the laid material different heating technologies were used. For the layup of thermoplastics in commercial production scenarios, heating methods like gas torch heating, laser heating and infrared heating were mainly used [7, 8, 9]. Hot gas heating is very effective at achieving high temperatures but waste a lot of energy by trying to heat convectively. This method is also relatively slow and complicated to control [10]. Infrared heating for welding of thermoplastics was described by Nejahad et al and Yousefpour et al [11] and have shown that this noncontact heating method is capable of rapidly and consistently producing 40% of the strength of compression molded composite parts and can reduce residual stresses while still maintaining dimensional stability [11]. However the heat control of an IR heating device for high temperature process is difficult because the lamp itself is acting slow [12]. Laser heating for processing thermoplastics has been investigated by Beyeler at al. in the mid-1980s and is today the most used method for the layup of high quality thermoplastic laminates [13]. The disadvantage is that lasers are expensive, need a large installation space and creates some health and safety issues. Especially for the manufacturing of larger parts on robot or gantry based layup platform a cost intensive enclosure is required.

Compared to the State of the Art the Xenon heating technology offers the potential to layup thermoplastics without any safety issues and lower investments especially compared to laser heating systems. Therefore the DLR Center for Lightweight Production Technologies (ZLP) in Stade investigates this technology for the layup of complex curved and thick laminates out of carbon fibre reinforced PEKK and LM-PAEK (CF-PEKK & CF-LM-PAEK) with aimed processing temperatures between 325°C and 420°C. In a first step a Xenon heating system developed and provided by Heraeus Noblelight Ltd. Cambridge is installed on an existing 16*1/4” AFP machine. With an electrical input of 6kW the system is able to generate roughly 3kW heating power. Because the system is designed for smaller AFP machines, the layup width is limited to 8 tows with ¼ inch. The heating unit with their function principle is shown in Figure 7.

After installation and testing, layup trials at different power levels were performed to determine the achievable layup speed for CF-PEKK and CF-LM-PAEK. Due to the limited heating power and high melting temperatures of the processed thermoplastics, layup speeds up to 4m/min where investigated. The chosen setup with an incidence angle of ~30° and a nip point distance of ~ 10 mm demonstrated an acceptable laminate quality between 0.8 m/min and 2.7 m/min. For CF-PEKK the reached crystallinity depending on layup speed and heating parameters varies between 16.3% and 23.4%. Exemplarily the resulted laminate quality and crystallinity of two unidirectional CF-PEKK specimens with 6 plies laid at 0.8 m/min and 1.5 m/min are shown in Figure 8.

By use of the same heating power, trials with a heated mold were performed. For mold temperatures between 21°C and 40°C no nip point temperature increase were investigated. As follows no potential for a layup speed increase was seen. An increase of the mold temperature from 40°C, 60°C to 80°C relates in a nip point temperature increase. As follows the layup speed could be increased by 15% to 21%. A raise of mold temperature to 100°C causes a potential layup speed increase of 39%.

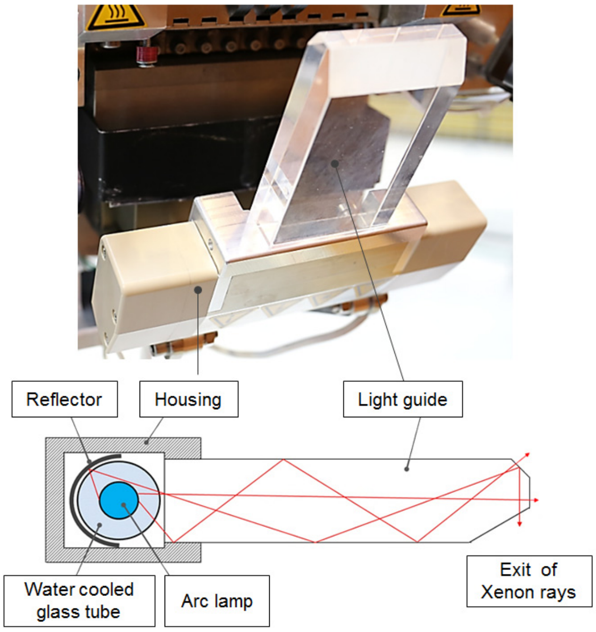


Figure 7: Design configuration of the Xenon flashlamp head unit and their function principle

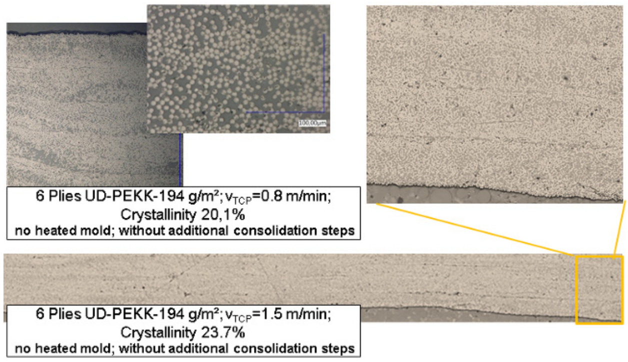


Figure 8: Resulted laminate quality of CF-PEKK specimen

The major result of these fundamental trials is the process window for CF-PEKK and CF-LM-PAEK by use of a Xenon heating source for AFP processes. In a next step several 12 ply LM-PAEK laminates with a size of 2.8 m by 2 m were manufactured to investigate the reliability of the test setup, equipment and chosen process parameters on a larger scale (Figure 9).

The results showed a high level of temperature control in the aimed temperature range of 325°C to 420°C and the suitability of the Xenon heating technology for the layup of high performance thermoplastics in an industrial production environment. In collaboration between DLR in Stade and Heraeus Noblelight Ltd, a new unique system for higher layup speeds and wider layup widths is developed. This new Xenon heating system provides an electrical power up to 32kW and allows the layup of 16 ¼” tows in parallel. Future activities are focused on an increase of the layup speed under consideration of the resulting laminate quality. The layup of more complex parts with double curvature, ramps and high laminate thicknesses will be investigated as well. As one main task the results will be transferred to a simulation environment to determine the heating parameters with minimized layup trials. As final demonstration of the manufacturing process, the heating technology and the simulation model, a double curved stiffened panel will be manufactured.

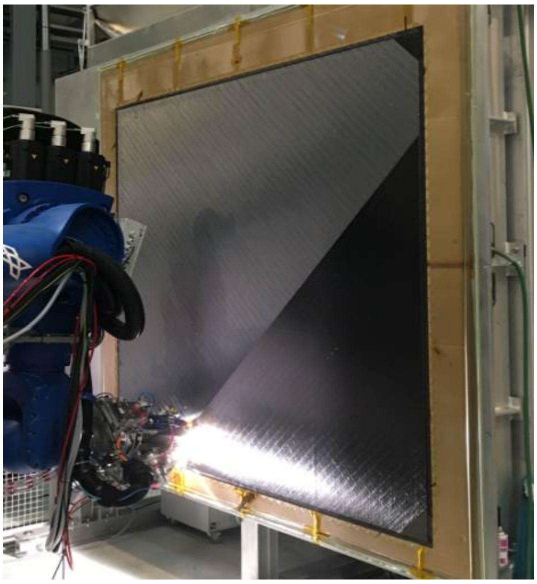


Figure 9: 2.8m by 2m CF-LM-PAEK laminate during vertical AFP layup process

4.2. Integration of LSP to a thermoplastic composite structure by using an Automated Fibre Placement process

Besides the layup of carbon fibre thermoplastic tape, a layer for lightning strike protection (LSP) has to be laid on the outer surface of the thermoplastic composite part. In thermoset processes this layer consists out of an expanded or perforated copper foil with a veil on top, surrounded by a resin layer. In serial production of large scale aircraft parts these layers where applied by hand or automated layup. Since 2016 Airbus uses an Automated Tape Laying (ATL) machine for the deposition of the copper mesh in their A350 wing [14]. A method for an automated incorporation of lightning strike protection layers into a composite structure is described in [15] and [16] showed the automated layup onto a thermoplastic structure. Sources, which deal with the application of LSP with ATL or AFP technology, could not be found. Additional information, for example detailed arc testing results or integration of LSP on a double curved structure with AFP could also not be found. One reason might be that no off the shelf materials for LSP integration onto a thermoplastic structure are available today. Major benefits using an AFP technology for the integration of LSP are an increase in the degree of automation, higher reliability of the process, lower investments, because of existing production equipment and the possibility to use this technology in part areas with high curvature.
In a first step, the thermoset material layout known from previous projects is applied to the thermoplastic material. Therefore, fundamental manufacturing trials for the production of LSP material that fulfills the requirements of an AFP process are performed by DLR. The specimens consist of different material stacking based on thermoplastic films and a single copper layer. Expanded (ECF) as well as perforated (PCF) copper foil were used.

Exemplarily some stackings are shown in Figure 10. With configuration B, a good quality regarding homogeneity and embedding of the copper foil within the thermoplastic film could be achieved.
After successful production this compound was placed by hand onto 2 mm laminates and consolidated together by an autoclave cycle. Different concepts of overlap were chosen to ensure contact between each LSP layer.

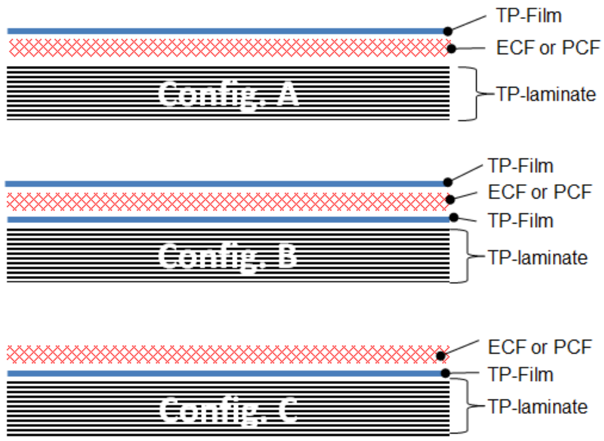


Figure 10: Different material stacking of LSP layer

The specimens demonstrate a single overlap which can be used for tape laying or hand layup processes. Feasible configurations for an automated layup by use of a fiber placement head are a cross layup and parallel layup with tow to tow overlaps or a parallel layup without overlaps.

Figure 11: Single overlap for hand layup or ATL processes

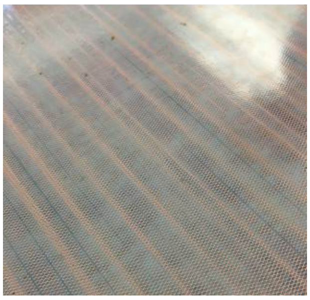


Figure 12: Parallel layup with multiple overlaps to assure contact between each tow

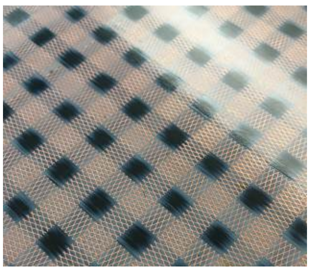


Figure 13: Cross layup

The described test specimens are shown in Figure 11, 12 & 13. Some of these configurations can be created by modification of the existing fiber placement head. Following arc test with described LSP layup concepts will help to determine an appropriate one.
Parallel to the hand layup trials, automated layup trials of LSP with AFP technology were performed. The Xenon heating technology described in the previous chapter was used to heat up the LSP material and to place it onto the mold or a laminate. Depending on a male or female layup process the LSP layer has to be laid directly onto the mold as the first ply, or the final composite laminate. No modification on the fiber placement head was performed. As one result of the trials it was seen that the fibre placement head has less feeding problems with the stiffer and more stable PCF compound. In difference to that, the layup trials with ECF showed feeding problems. Due to the tow tension the material stretches to a smaller material width (Figure 14)

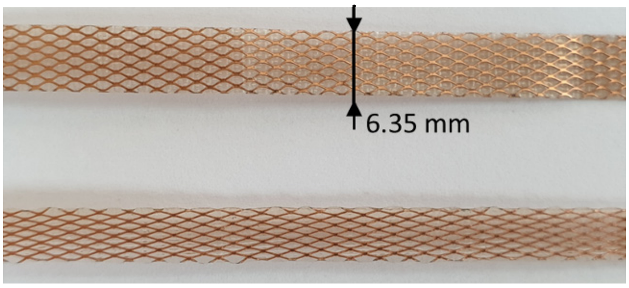


Figure 14: Stretching of LSP material during the layup

To create are more stable ECF material, which can withstand some tow tension, one additional layer of a material with higher modulus was added to the LSP. Following trials showed that with this modification of the LSP the problem could be solved.

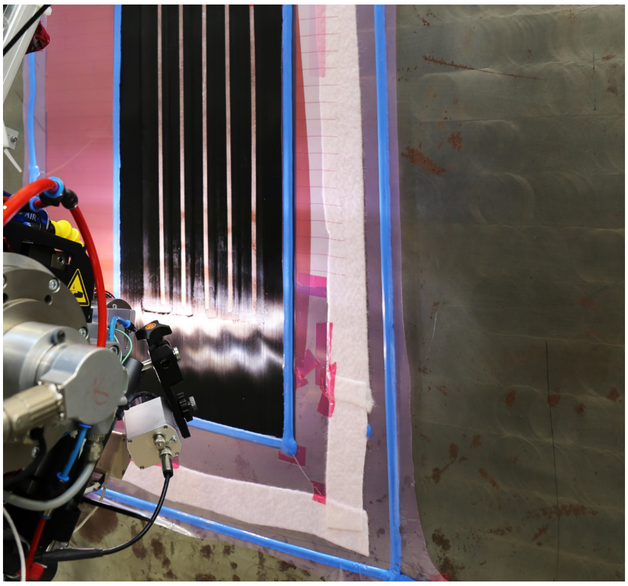


Figure 15: Automated layup of single thermoplastic LSP tapes onto the thermoplastic material for fundamental manufacturing trials

The layup of the LSP on the final composite laminate was tested. In this case the LSP has to be laid up onto the thermoplastic prepreg material. With a layup speed of up to 2 m/min the LSP could be applied successfully (Figure 15). Processing the material within the layup head like cutting or feeding did not show any problems. In a following step, the layup of the LSP onto the mold surface as the first ply will be tested as well.

Figure 16: ¼“ LSP applied on thermoplastic prepreg

The presented results demonstrated a successful integration of a LSP layer onto a thermoplastic laminate from manufacturing view. The paper also presents several configurations and layup strategies for automated integration of LSP. It could be presented that the automated layup of a LSP material for thermoplastic composite structures is feasible with an AFP technology. Future activities focus on the further investigation of the layup process for a better understanding and steering capability of the material. Especially for high curvature areas of a rear-end fuselage, this property is one of the keys to a successful and high quality LSP application. Beyond the fundamental layup trials and the manufacturing of test samples, the arc testing of the automated placed test specimens will be performed.

5. CONCLUSIONS & OUTLOOK

In this paper an overview about the activities of DLR and ONERA in the “Advanced rear-end” project are presented. The developments are related to impact studies and manufacturing of thermoplastic a/c structures. In the field of impact simulation, several advanced reinforcement materials are tested and the simulation tools are validated. Therefore, they are ready to use for assessing and designing reinforcement areas in the rear-end. Beside the safety relevant simulation methodologies, simulation tools are developed which are very fast in order to support a/c maintenance with augmented reality. They can be combined to the well-known structural health monitoring systems and can enrich the analysis with assessment criteria’s and in future with maintenance advises. Furthermore, thermoplastic manufacturing technologies are presented which enable high rate production with low-cost. The development of these technologies is rather new in the project, but first promising manufacturing trials are presented.
In the next phase of the project, reinforcements will be designed which will withstand the given threat scenarios at the rear end and the additional weight can be evaluated. These weight values can be fit into several trade of studies which will be done for the next generation a/c rear-end. The manufacturing with Xenon heating technology could be an enabler for future high rate production and will be investigated further for the special requirements of an a/c rear-end in the project. Also the automated lay-up of a lightning strike protection could be an enabler for the high

rate production of fiber reinforced plastic.

6. ACKNOWLEDGEMENT

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