DESIGN, ANALYSIS AND MANUFACTURING OF A THERMOPLASTIC UD CF-PEEK SLAT

Rüdiger Keck*, Wolfgang Machunze, Markus Kaden***
***Institute of Structures and Design, German Aerospace Center, Stuttgart, GER**
****Innovation Works, EADS Germany, Ottobrunn, GER**
Markus.Kaden@dlr.de;Wolfgang.Machunze@eads.net

Keywords: *CF-PEEK, high-velocity impact, bird strike, thermoplastic welding*

Abstract

Composite structures are increasingly being used within the aircraft industry, even for primary structures. However, the application of composites within impact endangered areas is very limited. In co-operation with DLR and EADS Innovation Works, a new advanced thermoplastic composite slat concept, based on the aerodynamic shape of an aluminium A340 outer slat, had been developed with the aim of minimizing weight and manufacturing costs.

In addition to linear static analysis using NASTRAN, dynamic high velocity impact simulations had been carried out. The objective was to calculate a bird strike impact on the composite slat, using the Smoothed Particle Hydrodynamics (SPH) option of PAMCRASH. The numerical analysis was validated with Wilbeck tests, using a gelatine bird substitute. Furthermore, the implemented composite damage model according to Ladeveze had been validated with 3 experimental impact tests. A sensitivity of the gelatine bird regarding the impact behaviour was identified.

Investigations on various existing out-of-autoclave manufacturing techniques had been performed as well as development of new techniques and integration of high-performance thermoplastic matrix materials based on unidirectional tapes. Several generic and two full scale section demonstrators were manufactured using endless fibre reinforced CF-PEEK. The critical points, concerning the casting of thick and tapered, single curved thermoplastic shells, were identified and innovative manufacturing methods were developed. Additionally, the thermoplastic welding process was improved, resulting in a low cost assembly technique as alternative to current joining methods such as riveting.

A numerical approach for high velocity bird strike impact had been shown. The results were used to specify the residual strength of a damaged slat. Furthermore, a very good compliance between the dynamic analysis and the test had been reached. Results showed that a significant weight reduction is possible by numerical optimization, even if less ductile materials as fibre reinforced composites are used for impact sensitive areas.

The verification of the impact performance for high performance thermoplastic materials had been demonstrated as well as the possibility of manufacturing complex parts consisting of the combination of short- and endless-fibre reinforced thermoplastic using out-of-autoclave manufacturing methods. Existent welding methods had been adapted to usage for endless carbon fibre reinforced thermoplastic structural components.

1 Design

Regarding the loading conditions for retractable slats, handling of the bird-strike scenario was found to be the most challenging requirement for the structural design. As all investigations had been based on the specifications for an Airbus A340-600 Aircraft, the prescribed impact scenario according to FAR/JAR 25.671 is based on a bird with a weight of 4lb (1,81kg), hitting the target structure at an just speed of approximately 170m/s (330 kts), thus resulting in an impact energy of 26 200 J.

Up to now, slats of Aircrafts are based on metallic structures with the capability of absorbing energy by plastic deformation. While recent aluminum alloys with plastic strain of 20% or even more are available, high performance composites only can afford strain of about 2-3%. For this reason, different ways of handling the impact energy had to be found

1.1 Preliminary Design Study

As a first step, various full-composite, but also hybrid, concepts for a slat structure had been developed. Some of them can be seen in Fig 1. Basing upon a detailed benefit analysis with regard to manufacturing, impact performance, weight and costs, two different design concepts were analysed in more detail: the Multi-Spar and the Multi-Rib concept (Fig 1, highlighted).

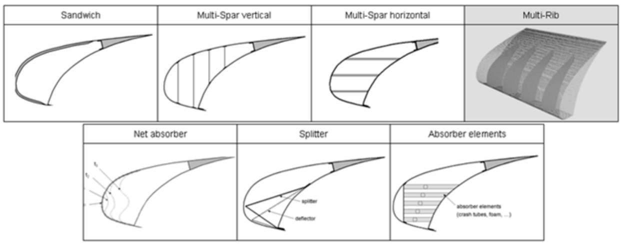

Fig 1: Various concepts for composite slat design

First impact simulations were carried out during this project stage for a better understanding of the overall impact behaviour. Because of showing best potential of energy absorption capacity, the Multi-Rib concept, based on endless carbon fibre reinforced PolyEtherEtherKetone (CF-PEEK) was selected for further investigations.

1.2 Numerical Analysis

Static requirements as well as dynamic aspects need to be considered for the dimensioning process of this structure. According to FAR/JAR 25.671, a bird of a total weight of 4lb (1,81kg) impacts the structure at a speed of 170m/s (330 kts). Referring to a given Load-Manual, only a certain percentage part of the initial impact energy is allowed to remain after the penetration of the structure. In the following, this is the so called “residual energy criterion”. To measure the residual energy of the impactor, a small macro was used. Therefore, the mass and velocity of all, the whole slat penetrated SPH particles were measured so that the residual energy could be determined. The energy of penetrated fragments from front and rear skin of the slat structure was considered as well for the residual energy criterion.

Furthermore, it is mandatory for the damaged slat to endure the static load of a Get-Home load case.

In order to represent how static calculations work together with the dynamic calculations, the process is visualized below (Fig 2).

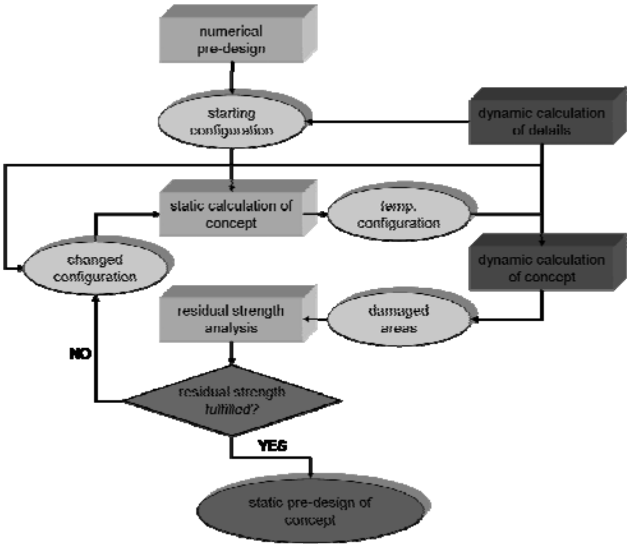

Fig 2: Methodical approach of interaction between dynamic and static analysis

The determination of the best possible weight saving concept needed several iterative design loops, whereas static as well as dynamic aspects have its particular sensitive areas within the slat structure.

1.3 Dynamic Analysis

A reliable investigation of the CF-PEEK slat impact behaviour by numerical impact simulation requires a detailed consideration of all relevant parameters. For the reproduction of the structural damage, the Ladeveze damage model [2] was used.

The Ladeveze model describes the damage behaviour of a homogenized unidirectional ply (UD) and distinguishes between matrix micro cracking under transverse tensile loading, fibre-matrix debonding due to shear loading and fibre failure for tensile and compressive loads. According to specific damage functions, the elastic stiffness properties are decreased.

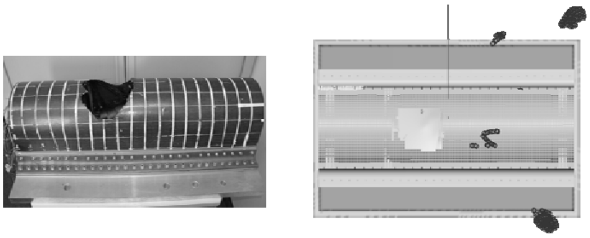

Fig 3: Wilbeck bird impact test

The discritisation of the bird impactor was done using SPH elements. The main advantage of the SPH approach is the more realistic follow of the bird matter flow compared to other known simulation methods in link with an acceptable calculation time. For instance, a possible splitting of the impactor in different parts can be reproduced using this method which is required for the event of bird impact and subsequent penetration onto a curved slat. The SPH approach uses the Lagrangian formulation for the equations of motion, but instead of a grid, kernel functions (Gauss kernel) are used to calculate an estimation of the field variables at each particle.

A jelly bird with 10% porosity was found by Wilbeck [1] to be the best bird substitute material for impact tests. Within this test series, Wilbeck shot birds and substitutes on a rigid plate at velocities ranging from 100-300 m/s, whereby the pressures which result out of the impact on the plate were measured with pressure sensors.

To assign a physical accurate material behaviour to the model of the jelly bird, validation simulations were necessary to calibrate the parameters which are used in the elastic-plastic hydrodynamic material model (Fig 3). Furthermore, an equation of state is allocated with the material model, so that all possible pressure states within the impactor can be reproduced. Hence, the hydrodynamic behaviour of the soft body impactor is quite well represented within the numerical simulation. Next to the hydrodynamic characteristic of the impactor, like peak and duration of Hugoniot pressure and stagnation pressure, other parameters can be used to evaluate the quality of the used numeric bird model. The total impact duration, the shock period as well as the flow behaviour can be used indicator for the grad of the simulation.

The composite slat structure itself was modelled with a layered shell approach, whereas all rivets and tied contacts are considered within the model as well as a realistic bearing of the slat. For the CFRP material, regular layered Quad4-shell elements with an average dimension of 10x8mm were used. For these layered elements, one integration point for each layer was defined above the element thickness. Furthermore, solid elements were used for load introduction, short fibre reinforced rib flanges and thick metallic parts. The composite values (fibre, matrix) are defined in the ply cards and the stack-up in material card 131.

By this, the laminate properties are calculated by PAM-CRASH™ with classical laminate theory (CLT).

All together, the model had around 37000 elements / 53000 nodes, whereby under integrated elements were used to reduce CPU time. For the 8ms bird impact event, the simulation took 13 hours with SMP on a dual AMD Athlon 1800+ with 1024MB RAM. The inner edge of the rib flanges determine the critical time step for the explicit time integration, according to the Courant-Friedrichs-Levy (CFL) condition, even though the elastic modulus of the short fibre reinforced material is small in comparison to the UD CF-PEEK.

Adhesive and welded joints are modelled by the use of tied contact algorithms in connection with material type 301. This formulation has been applied to the interface between several parts which must be differentiated in master and slave segments. Rivet joints are modelled with point link (PLINK) elements in conjunction with material 302 between master and slave parts. For all connecting elements, realistic failure criterions are defined so that they can fail during the simulation.

For GSII test, a lateral fixed clamping was used. This boundary condition is modelled realistically within the numerical GSII simulation.

2 Manufacturing

First examinations had been focused on manufacturing of tapered thermoplastic laminates. This was done before the later weight optimization of the concept. With a view on manufacturing and mechanical properties of CF-PEEK, it was decided to use the out-of-autoclave Vacuum Consolidation Technique (VCT), developed at DLR, Institute of Structures and Design. All CF-PEEK laminates within this project had been manufactured using this technique.

2.1 Manufacturing of tapered shells

First steps for verification of forming shells had been realized by forming pre-consolidated flat plates of constant thickness on a single-curved positive mould with a constant bending radius. Different skins of constant thickness and a quasi-isotropic lay-up had been produced. In a second step, this technique was adopted to the production of skins with varying thickness.

Therefore, a two-step forming process was developed. After near net shape forming by mechanical pressing using an additional steel collar in the first step, the conventional vacuum forming process can be used to reach the final geometry of the skin. Regarding all procedures, a three-step manufacturing process is needed which will not be satisfying for a scheduled series production.

Due to aerodynamic needs, manufacturing in a negative mould is preferable to the method mentioned above. Therefore, a single-curved negative mould representing a non-tapered slat, based on nickel deposition in an electroforming process, was constructed and manufactured.

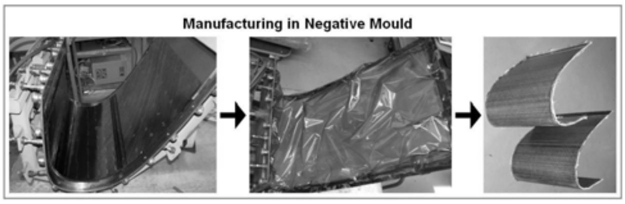

Fig 4: Front skin manufacturing in negative mould

With the needs of a weight optimized slat design, the manufacturing of UD prepreg skins with optimized lay-up, several thickness variations and offsets had been examined. Also the implementation of a lightning protection layer on top of the skin had been realized.

As can be seen in Fig 4, lay-up and quality of skins is comparable to conventional CF-Epoxy prepreg manufacturing, but can be realized within only one single manufacturing step without using any additional pre-consolidation steps. No additional pressure pads or anything comparable had to be used. The consolidation of the skin itself was realized inside a conventional convective oven.

2.2 Manufacturing of bended laminates

Due to the geometry of the rear skin of the slat, manufacturing methods had to be modified for this complex part, including optimized thickness variations in both, span wise and chord wise direction. As the cross section of the laminate is more like a single-curved shell with an angled tip on the lower end, manufacturing had to be divided into two steps.

First manufacturing step is identical to manufacturing of the front skin onto a curved mould with constant radius, thus forming a near net shape panel, including the joggle for the trailing edge at the upper end.

Within the second step, the angled tip was realized using the Vacuum Forming Technique (VFT). Therefore, the tip had been formed by vacuum after heating up to forming temperature. The length of the tip was approximately 50mm at an angle of about 95°. No additional pressure pads had been used during forming process inside a convective oven.

2.3 Manufacturing of ribs

The final design of the ribs had been based on a nearly conventional rib design with T-L shaped rib flanges (Fig 5). Therefore, various manufacturing techniques had been examined. Investigations using vacuum forming techniques showed that the quality of the ribs manufactured within this technique was not acceptable for series production.

As a result, manufacturing had to be switched to a well-known and established press forming technique. Due to the complex T-L shaped design and the need for different types of ribs for the demonstrator, a multi-functional tooling had to be designed to achieve the possibility of manufacturing each part needed for the slat demonstrator within one single tooling.

The innovative construction of the tooling allows the manufacturing of C-, Z-, L-, TT- and TL-shaped ribs, using only one tool, consisting of 22 different parts. After forming simple C- or L-shaped geometries, different rib bodies can be combined within the tool using the press welding technique (Fig 5).

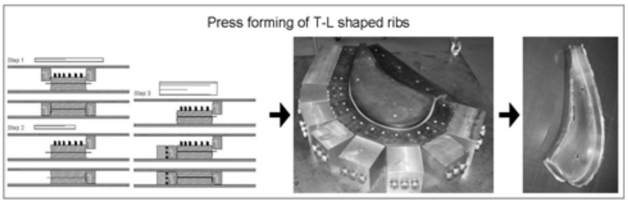

Fig 5: Manufacturing technique for T-L shaped ribs

2.4 Manufacturing of trailing edge

When starting the project, an overall CF-PEEK design of the slat was preferred. During the construction phase, the design of the trailing edge had to be switched from a monolithic approach to a conventional sandwich design using a foam core instead of a honeycomb core. Front spar and end ribs had been realized by using powder-coated CF-PEEK fabrics in a press forming process, the shells using unidirectional CF-PEEK tapes using the VCT.

Assembly of all parts was realized by adhesive bonding, using a conventional film adhesive. As it was decided that this configuration was not suitable for series production, a well-known CF-Epoxy sandwich design was investigated, using unidirectional CF-Epoxy tapes for all parts.

Assembly was realized by using the same materials and processes as in the thermoplastic version.final design of the ribs had been based on a nearly conventional rib design with T-L shaped

3 Resistance welding

The development of a welding technique for connecting carbon fibre reinforced thermoplastic structures was one of the focal points within this project. Due to previous investigations at DLR, Institute of Structures and Design [6], resistance implant welding was chosen to be investigated.

The Resistance Implant Welding technique for welding carbon fibre reinforced thermoplastic structures using a stainless steel mesh is similar to the technology used by STORK-FOKKER for manufacturing the J-Nose of the A380 in present series production, which is made of glass fibre reinforced PolyPhenyleneSulfide (GF-PPS).

Based on the results of Kempe and Krauss [6], first investigation had been done using carbon fibre heater elements. During examinations, current leakage (a short circuit due to electrically conductive carbon fibres) was found to be one of the main critical aspects when dealing with greater welding length. It was discovered that current leakage does not appear at smaller welding length. When going to full-scale manufacturing, welding length of up to 750mm had to be realized in order to connect the ribs to the front skin [8].

Various electrical insulations between laminate and heating element had been examined. It was found, that insufficient insulation may cause local overheating, which easily can be proven by investigating polished specimen.

Further examinations of local overheated areas showed, that not only electrical insulation can be responsible for this effect. A close relationship of heating element mesh type, welding parameters and electrical insulation could be found. It was observed, that optimization of only one of these points is not sufficient for improving welding strength.

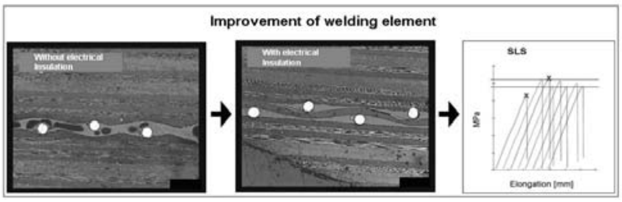

Fig 6: Improvement of stainless steel heater elements

Performing an extensive testing program with more than 600 test specimens according to Airbus Industry Test Method QVA-Z10-46-09, an optimized layout for a heating element with the ability of increasing the welding length could be found (Fig 6). This heating element, consisting of one single ply of stainless steel mesh covered with woven glass fibres on each side, can be pre-produced within a VCT or press process in advance. The thickness of this lay-up after consolidation is about 0,5mm at an aerial weight of less than 1kg/m².

For this specific type of welding element, a processing window was defined based on the results on the testing program mentioned above. As can be seen (Fig 7), the power level needed for welding is dependent on welding time and welding area. Welding time itself is dependent on thickness and lay-up of the parts that have to be joined and has to be verified by specimen testing. A detailed report dealing with this issue will be presented at a later time.

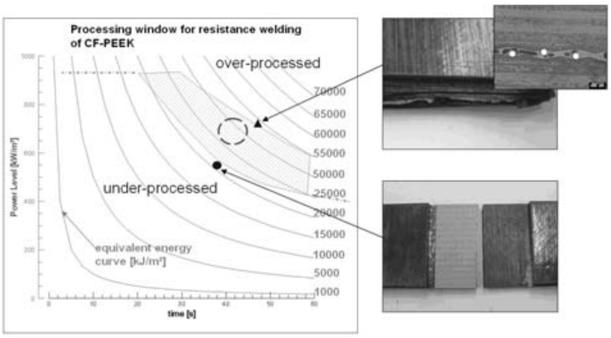

Fig 7: Process window for welding of CF-PEEK

4 Testing

During the last years, a lot of investigations had been done on all-thermoset or all-thermoplastic structures [3, 4, 5] at DLR, Institute of Structures and Design. Based on this expertise, pre-selection of manufacturing techniques was done.

4.1 Static testing

As unidirectional CF-PEEK had been selected to be first choice for the main structure, a small test program for verification of the mechanical properties of adhesive bonding had been conducted and compared to [6, 7]. It is obvious, that adhesive bonding could not be chosen for a real structure, but it was found to be sufficient for the first generic structures.

4.2 Dynamic testing

Complementary to the static testing, an amount of impact tests on flat test plates using different impactors had been conducted. Therefore, UD CF-PEEK laminates with a quasi-isotropic lay-up had been used. All of the tests had been performed using the 60mm calibre gas-gun at DLR, Institute of Structures and Design.

4.3 Generic slat

For the verification of the numerical impact simulation approach as well as for the development of the thermoplastic manufacturing technologies, two different generic slat structures with a different level of detail had been designed and tested, called Generic Slat 1 (GSI) and Generic Slat 2 (GSII). The test setup and a soft body impactor made of gelatine are shown below (Fig 8).

Due to a better reproducibility of bird strike testing using an gelatine bird, this project uses no real birds for the testing as well as for the simulation. Furthermore, the simulation approach for bird strike testing should be improved within this project. Only for the authorization of a new developed slat structure, a test with a real bird need to be done.

For the validation of the numerical gelatine bird, the results of Wilbeck were used. Therefore, the Hugoniot and Flow pressure were compared between Wilbeck tests and simulation. Wilbeck shot real birds against a rigid wall where pressure transducers were applied. Afterwards, he tested different material to reproduce the real bird pressure curves and found that 10% porous gelatine has quite similar characteristics. Furthermore, the flow behaviour (viscosity) and total impact duration as well as the shock period were used as indicator of the impactor performance.

As the 200mm calibre gas-gun was not available at DLR already, impact testing had been performed at Natural Impacts Ltd., Farnborough, Great Britain.

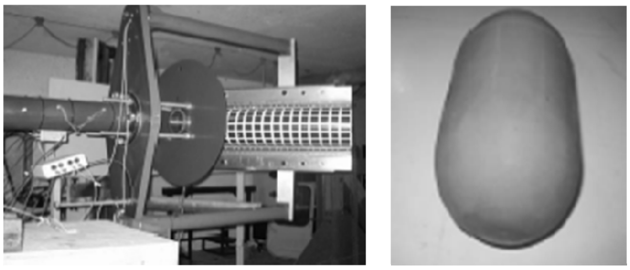

Fig 8: Test setup of GSI (left) and a 4lb soft body impactor

All GSI structures had a CF-PEEK front skin of constant thickness and bonded ribs. To achieve a high comparability to the real slat structure, the front radius of the specimen was geometrically equal to the real slat, as the front skin is mainly responsible for the impact performance.

For the determination of the remaining kinetic impactor energy, the back side of the closed box was made of aluminium. Pre-test simulations were made in order to prepare the experimental bird strike tests on the generic slat specimen at Natural Impacts laboratory and to give assistance for the test specification.

To get as many information as possible from this test set-up, different skin thickness and impact scenarios had been tested, whereby the penetration of the impactor was promised.

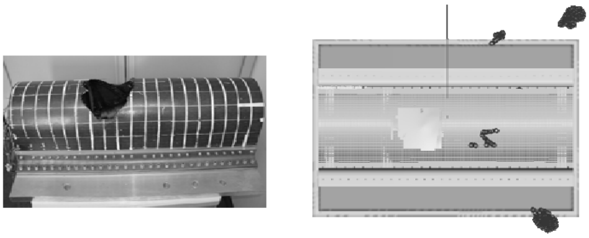

Fig 9: Impact testing on GSI, impact between two ribs

Like shown above (Fig 9), the impactor penetrates the skin in case of an impact scenario between two ribs for test and simulation. Furthermore, the structural damage of the inner structure could be reproduced in a good agreement with the test results (Fig 10).

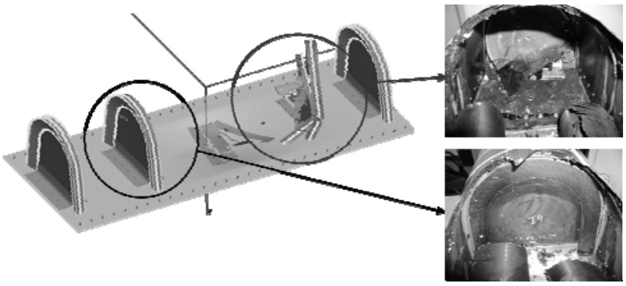

Fig 10: Comparison of computational (left) and real (right) structural damage within GSI in case of impact between two ribs

Besides the reproduction of the structural damage, a very good compliance between simulation and test concerning the residual kinetic energy of the impactor was found, measuring the plastic deformation of the aluminium rear skin.

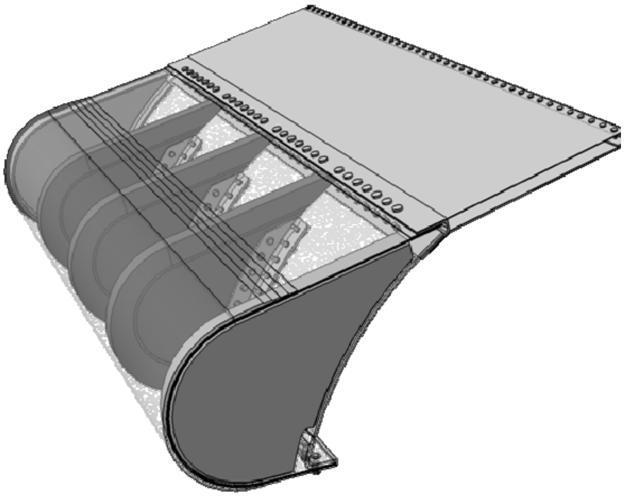

Fig 11: CAD model of generic slat GSII

The GSII test structure (Fig 11) was of more realistic shape, fitted with a skin of optimized thickness variation, welded rib connection and a CF-PEEK back skin of realistic shape.

The tests compared to the original slat showed, that test conditions, especially the distance between the end of the gun barrel and the test specimen, are very sensitive regarding the behaviour as predicted. This was caused by distortions and decomposition waves within the gelatine impactor, which results out of the impactor redemption from the sabot in interaction with a too long free flying phase.

By considering these deviations within the impact simulation concerning the distorted shape, the test result could be reproduced (Fig 12).

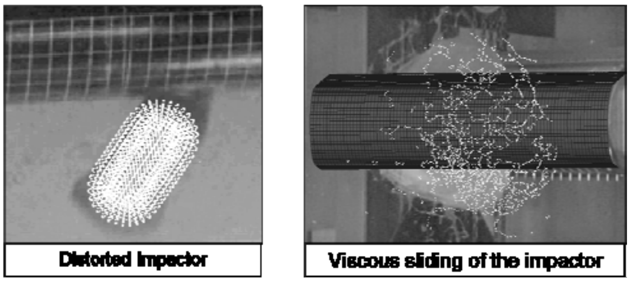

Fig 12: Comparison of results of GSII impact test

The comparison of the real soft impactor (grey) and the theoretical SPH impactor (white dots, left side) on the left side shows the distortion of the impactor clearly. On the right side of the picture, the flow of the gelatine (grey) and the SPH model (white dots, right side) show very good compliance.

5 Full-scale demonstrator

All final demonstrators built within this project represent a Full-Slat Cross Section, using the geometry of an Airbus A340-600 slat No.4 (Fig 13).

The design was based on a fully optimized CF-PEEK slat design performed by EADS, Innovation Works, including skins of optimized thickness variations, resistance welded T-L shaped CF-PEEK ribs and a conventional foam core sandwich trailing edge device. Except for load introduction ribs, all required features had been implemented within these demonstrators.

Fig 13: Full-scale-section demonstrator No.2

6 Repair concept

To accomplish general acceptance for the OEMs, it has to be shown, that repair is possible to the points of failures or defective areas without big expenses, and without any significant reduction of mechanical strength. With regard to the material properties such as processing temperature and process ability, the DLR, Institute of Structures and Design is currently working on two new processing techniques to enable a load path conforming, reproducible and effective repair.

One of the most challenging problems of conventional repair techniques is to generate a precise removal of the defected plies. In general, a hand-held router is used to treat the damaged area. A feasible possibility to replace this imprecision tool is the use of a laser system. The investigations have shown that an UV-laser-system offers a Ply-by-Ply removal and can generate precise stepped-lap repair geometry[9, 10].

Another challenge to process high performance thermoplastics is the high processing temperature. For realization of thermoplastic repair, the patch up to the interface zone has to be heated up to consolidation temperature. In a conventional repair for thermosets, heat blankets are used.

For these matrix systems, normally the processing temperature is not above 250°C. The material used in these studies, has a melting temperature over 300°C and a processing temperature of up to 400°C. Due to the material of heat blankets, made from fiberglass reinforced silicone rubber, temperatures are only permitted up to 260°C.

A different concept to generate the compacting energy is the heating of a metallic-sheet by induction. During the first test series, the general suitability of this procedure was proven [11]. A controlled heat generation is essential to achieve a high quality connection through the parental laminate with integrated load patch. It has been shown that a homogeneous heating up can be realized.

Both concepts, the use of a laser and the inductive heating technique, are promising a high potential. The focus for the next investigations will be to determine the mechanical parameters of specimens, repaired with these techniques. The main objective of this project is to develop different tools, which can simplify the repair as well as to shorten the whole repair process.

7 Conclusions

It has been shown, that numerical simulation of a bird impact can predict the structural damage as well as the residual energy. So, simulation can be used for preliminary development of impact endangered composite structures.

Furthermore, a manufacturing concept for the thermoplastic CF-PEEK slat structure with innovative manufacturing techniques had been developed based on out-of-autoclave manufacturing techniques and resistance implant welding of carbon fibre reinforced thermoplastic structures.

All main targets of the project, weight and cost reduction concerning the manufacturing as well as the feasibility of simulation of impact endangered composite structures had been shown within this project.

Next steps performed at DLR, Institute of Structures and Design, will be focused on the improvement of manufacturing techniques due to aspects of series production and the investigation on alternative joining solutions for thermoplastics as well as hybrid joining of thermoset and thermoplastic substructures. This will be essential for the next milestone, the development of a hybrid slat, based on thermoset skins and thermoplastic inner structures.

Next to these aspects, further system based issues needed to be considered within the development of a CFRP slat. Compared to a conventional aluminium version which uses a bleed air system, new ice protection systems as well as an optimized lightning protection system for composite structures had to be developed and integrated into the slat structure. All these issues will be presented at a later time.accomplish general acceptance for the

References

[1] Wilbeck, J.S., *Impact Behaviour of Low Strength Projectiles*, Technical Report AFML-TR-77-124, Air Force Materials Laboratory, 1977

[2] Ladeveze, P.; Le Dantec, E. *Damage Modelling of the Elementary Ply for Laminated Composites* Composites Science and Technology Volume 43, 1992, pp. 257 – 267 (Elsevier Science Publishers Ltd.)

[3] Feiler, M.; Häberle, L.; Hetzel, Th.; Steinheber, R. *Kosteneffiziente Herstellung eines Seitenruders aus faserverstärktem Thermoplast*, Presentation, DGLR 2002

[4] Kocian, F.; Kempe, G.; Keck, R.; Dudenhausen, W. *Application of alternative thermoplastic technologies in aircraft structures*, Presentation, SAMPE 2006

[5] Keck, R. *Cost effective manufacturing techniques for fibre reinforced thermoplastic materials*, Presentation, Airtec 2007

[6] Kempe, G.; Krauss, H. *Moulding and Joining of Continuous Fibre Reinforced PolyEtherEtherKetone (Cf-PEEK)*, Presentation, ICAS 1988:

[7] Kempe, G.; Krauss, H. *Adhesion Bonding Techniques for highly loaded parts of continuous carbon-fibre reinforced PolyEtherEtherKetone (Cf-PEEK)*, Presentation, ICAS 1992:

[8] Freist, C.; Keck, R. *Resistance implant welding of thermoplastic carbon fibre reinforced structures*, Presentation, Airtec 2007

[9] F. Fischer, R. Keck, M. Kaden, *Laser as an innovative tool for laminates repair*, Sampe Europe 2010, Paris, April 2010

[10] F. Fischer, L. Romoli, R. Kling, *Laser-based repair of carbon fiber reinforced plastics*, CIRP, Pisa, August 2010

[11] M. Kaden, R. Keck, H. Voggenreiter, *Developing a repair concept, using the advantages of carbon fiber reinforced thermoplastic*, Sampe 2011, Long Beach, Mai 2011