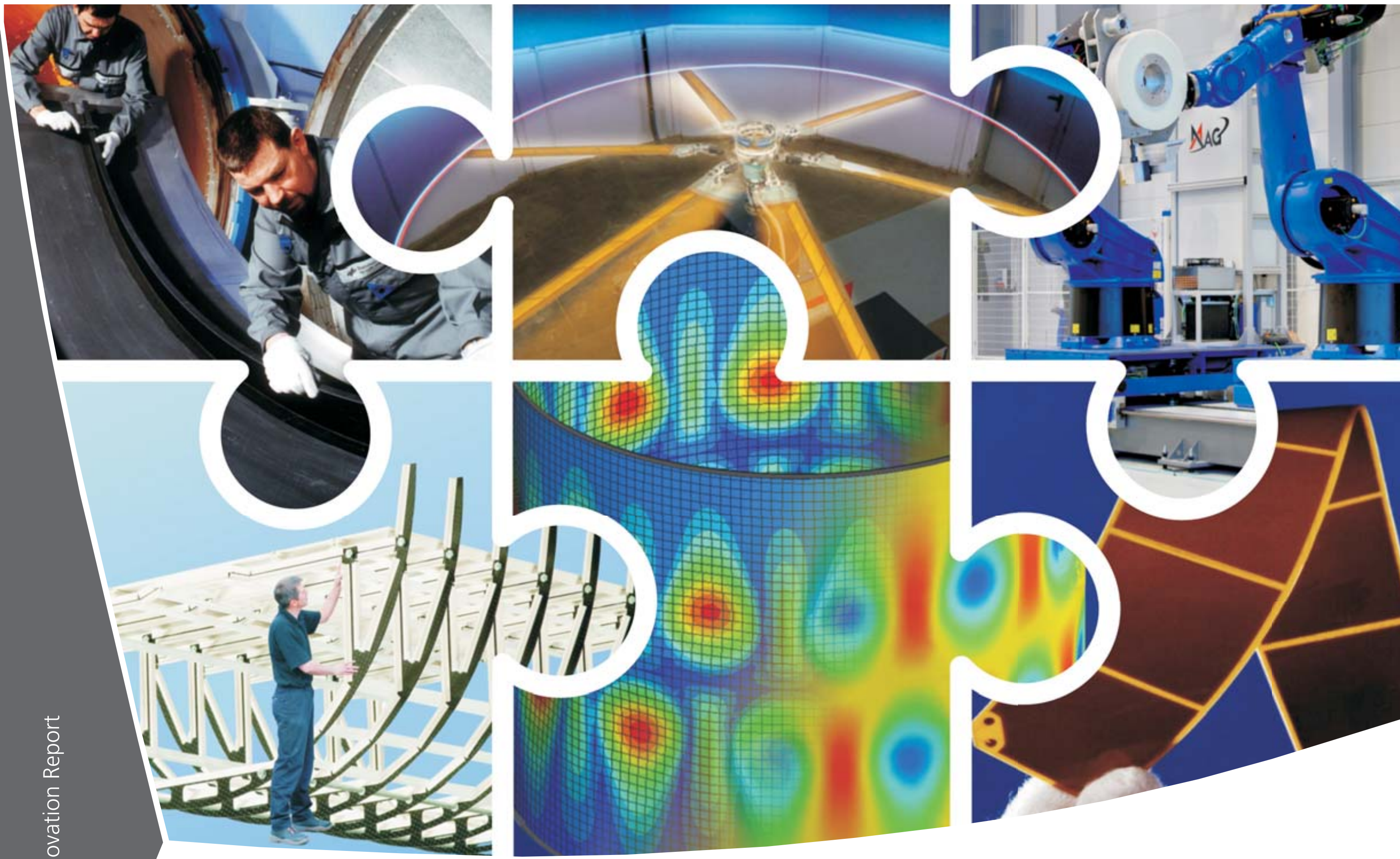


Innovation Report

Innovation Report 2011

Institute of Composite Structures and Adaptive Systems

DLR

Droop Nose.

Contents

Preface

The demand for research in Composite Structures and Adaptive Systems still increases leading to a steady growth of our institute and our research portfolio. In this seventh innovation report we provide an insight into our research by exemplary projects of the last year. Our research is focused in six fields of innovation:

- Nano – Micro – Macro
- Robust Primary Structure
- Compliant Aggregation of Functionalities
- Self-controlled Composite Processing
- Autonomous Composite Structures
- Sustainable Composites Processes

These fields of innovation reflect the entire process chain of adaptable lightweight composite structures. They are explained in detail on page 6 and serve as your guideline through this report.

The need to further extend our knowledge is reflected by the increasing number of projects with industrial partners in Germany and by an extended contribution to the European Frame Programme FP7. We have recently been invited to contribute to 6 new EU projects with our competencies in morphing structures and Structural Health Monitoring (SHM) in aeronautics and our expertise in development of ultra-lightweight space structures.

We extended our cooperation with the Technical University of Braunschweig (TU-BS) in the Campus Research Airport in various projects. We support the Collaborative Research Project 880 "Basics for Highlift Structures of Future Aircraft" with contributions on active structures. We will establish a close collaboration with the recently founded Institute for Adaptronics and Functional Structures lead by Prof. Michael Sinapius. Both Institutes, the DLR-Institute for Composite Structures and Adaptive Systems and the TU-BS Institute for Adaptronics and Functional Structures will form a new lighthouse for Adaptronics in combination with the new DLR Centre for Adaptronics and Transportation Systems being in its finalization phase.

The intention to work close to our customers and partners has motivated us to establish new sites in Hamburg and Stade. From this year on we operate an office in Hamburg close to the airport. Six researchers work there on solutions for future maintenance, repair and overhaul of CFRP aircraft and on improved lining structures. Since last year's autumn our new department for composite process technologies works with 16 researchers in DLR's Centre for Lightweight Production Technologies in Stade. Special attention paid the new research topics in the future field of sustainable composite processes within this report and in this year's Day of Science of the Institute.

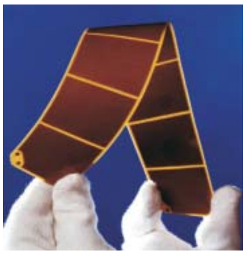
Thanks go to our research partners inspiring us with interesting requests and supporting us in development of new solutions. Special thanks go to the authors of the contributing to this report. We hope you enjoy reading this report and are looking forward to future cooperation in the field of Composite Structures and Adaptive Systems.

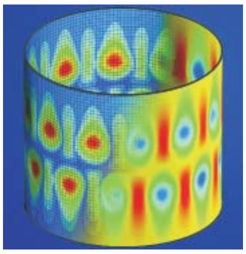
Prof. Dr.-Ing. Martin Wiedemann

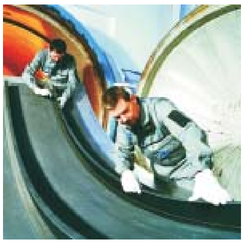
Prof. Dr.-Ing. Michael Sinapius

Institute of Composite Structures and Adaptive Systems

High-Performance Structures
Adaptable – Efficient – Tolerant







We are experts for the design and realization of innovative lightweight systems.
Our research serves the improvement of:

- weight efficiency
- cost efficiency
- functionality
- comfort
- environment protection

We bridge the gap between fundamental research and industrial application.

The expertise of the Intitute of Composite Structures and Adaptive Systems in

- multifunctional materials
- structural mechanics
- composite design
- composite technology
- adaptronics and
- composite process technologies

makes it the ideal partner for the industry, the DFG (German Research Foundation), research establishments, ministries and civil aviation authorities in all issues regarding development, design, computational prediction, manufacturing, experimental testing, and qualification of lightweight structures used in aerospace and further applications.

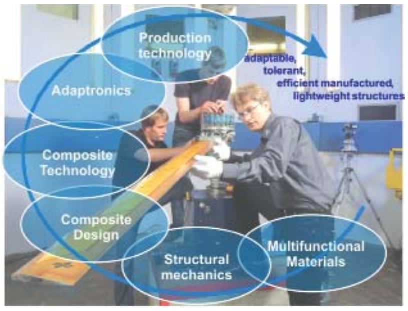
The main objectives of the research and development work on material systems and lightweight structures are

- increase of efficiency by improving stiffness, strength and durability of lightweight structures with new material systems and improved structural analysis tools
- cost reduction in the production process and by optimizing design and the fabrication procedure in order to strengthen the competitive edge
- increase of functionality of materials, structures and systems to improve their performance; the active structural shape control replaces elaborate and costly actuator systems
- increase of comfort in aerospace and on-ground transportation systems by means of actively reducing noise and vibrations
- reduction of the environmental impact (especially resulting from fuel consumption) and preservation of natural resources particularly due to reduced weight.

In order to deal with strength, stability and thermo-mechanical problems we operate unique experimental facilities like thermo-mechanical test facilities, buckling facilities with the special feature of dynamic loading. Manufacturing facilities like preforming, filament winding, liquid composite moulding or microwave curing enable us to develop novel manufacturing techniques und the realization of innovative composite structures.

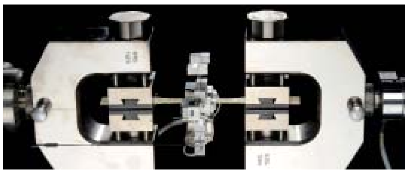
We transfer our scientific and technical expertise in the field of design and manufacture of lightweight composite structures and adaptronics as partners in an international network of research and industry.

Institute of Composite Structures and Adaptive Systems – Our Fields of Innovation



We work along the full process chain in the fields of multifunctional materials, simulation methods, lightweight functional design, production technologies, adaptronics and in the near future up to entire production processes. This consideration of the full process chain is part of our strategy, and it is our conviction that successful research in the field of functional CFRP structures is driven by collaborative work. How can research be organized in such a broad field of scientific work, and how can each scientist preserve attention for the work of the others? Innovation is the total of two steps: invention and diffusion. Invention is where we start with our ideas. Diffusion is where at the end we can present technical solutions to our customers. Innovation covers the full process chain and this is why we have decided to organize six times a year meetings with all scientists of our institute to discuss our long term strategic research topics.

Multi-phase materials like composites require the comprehensive understanding from **Nano – Micro – Macro -scale** of the components interaction. This includes the effect of nano-scaled additives to the resin as will as the effect of manufacturing defects like pores on the mechanical properties of the structure. Moreover, carbon nanotubes exhibit a significant actuation effect in an electrolytic environment. Understanding the path from Nano to Macro means thorough research for our scientists looking for new technical applications.



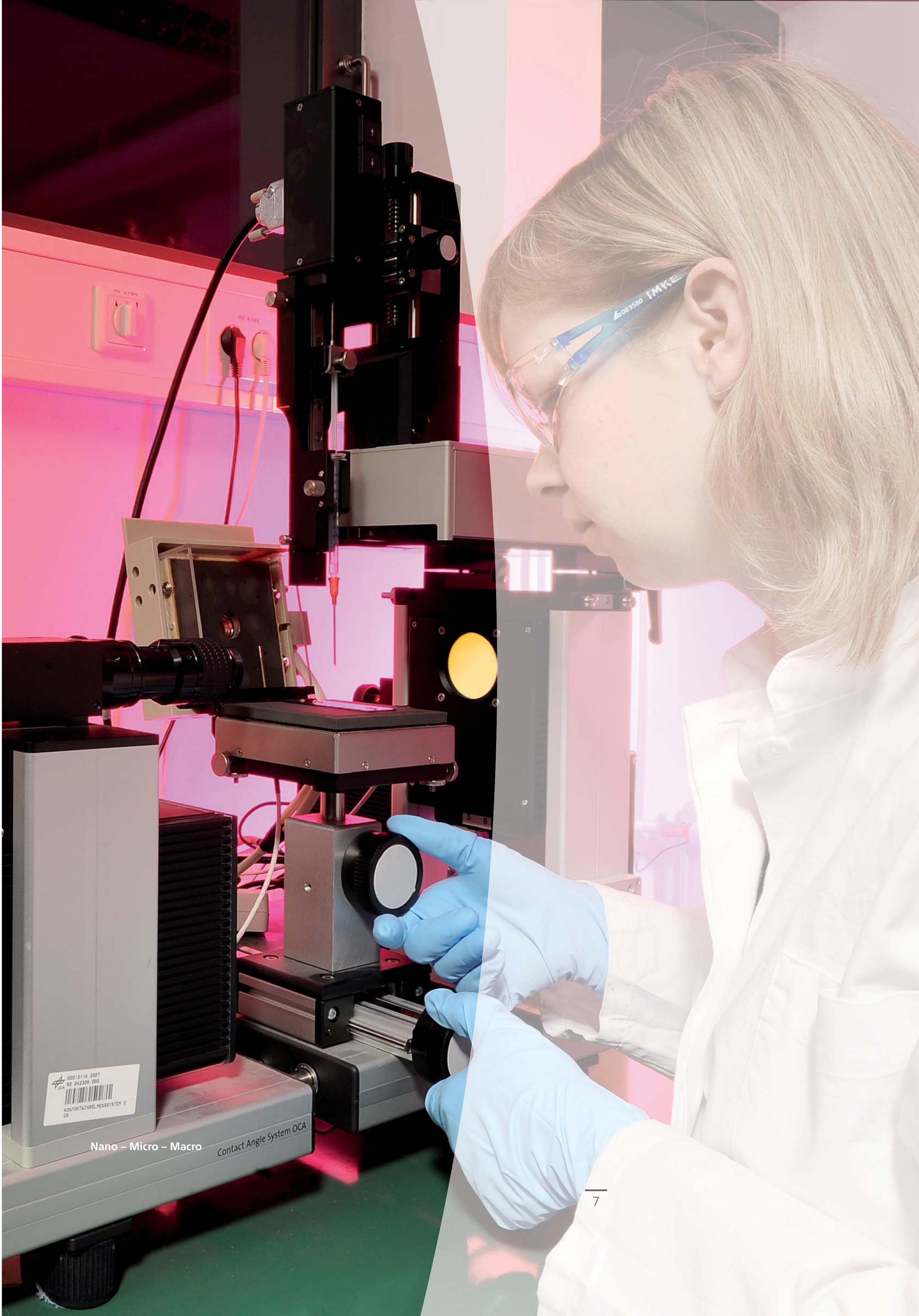
Reliable design methods for Robust Primary Structures are already mandatory, but the challenge to ensure reliability (oder robustness) by adding additional functions into the structure. We strongly believe in the potential of function integration within the composite design, but there is the need to bring all of the elements of such a structure to the same level of reliability. Our scientists keep this in mind while they are making new inventions.

Compliant Aggregation of Functionalities aims for solutions, where integration of additional functions does not degrade the original load carrying function of the structure. To reach this goal the design principles must be adapted to the additional functions. For example the active shape control of a structure may not lead to additional internal loads. Unconventional ideas from many people are required here to find the right solutions.

Self controlled CFRP Processing is one of our most promising concepts for automation in the field of production of carbon fibre reinforced polymer (CFRP) structures, but still in its infancy. With our competencies in ultrasonic NDT, process-simulation and in the field of adaptronics as well as our long lasting experience in CFRP production technologies, our scientists can build on an unique combination of knowledge.

Building **Autonomous CFRP Structures** is our vision of function integration. Any active system today requires external energy for control and actuation at least. The omission of the wiring is one of the conditions for an increasing application of function integration in structures. Our scientists know the vision and are looking for contributions to its realization.

Sustainable Composites Processes will finally become a very important topic in the future for us. Not only the lightweight and multifunctional structure itself shell support the idea of sustainability, but also the way, how this structure is produced. Our scientist know about the need for further cost reduction but very soon this will be also a demand for reduction of consumables in production and minimization of scrap. The development of precise, effective and in-line quality automation along the production processes will be a new research field for us.



Nano – Micro – Macro

A Material Kit for Aircraft Cabins

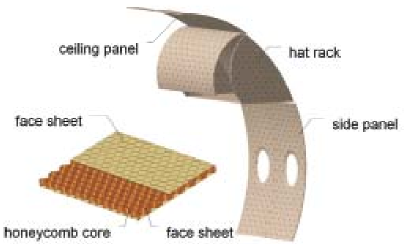


Fig. 1:
Honeycomb sandwich (left)
Cabin lining (right).

Fig. 2:
Exemplary sandwich specimens after 60s flammability test.

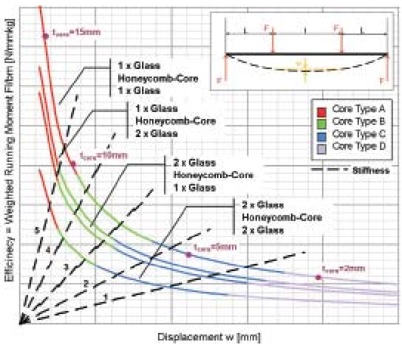


Fig. 3:
Efficiency functions of honeycomb core sandwich structures (GFRP face sheets).

In today's aircraft cabins a variety of fiber-material combinations is used. Most of the cabin interiors are sandwich structures e.g. side panels, ceiling panels and hat racks (Fig. 1). Different prepregs and core materials are combined in the construction of these parts. Due to their excellent fire behavior phenolic resins are the choice of matrix material in glass fiber prepregs and aramid honeycomb cores for many applications.

With the ambition to obtain an even more economic, efficient and at the same time more ecologic process chain, the DLR is developing a material kit for cabin interiors. This material kit consists of selected semi-finished materials for face sheets and core materials, which can be used to manufacture all common aircraft cabin parts

New Materials and Manufacturing Processes

In this context new materials and manufacturing processes are investigated with respect to their potential to substitute the nowadays commonly used phenolic resins. The yet to be identified materials have to meet the strict demands of aerospace industry concerning fire safety, smoke and toxicity. Therefore researchers at the DLR are looking into promising resin systems, analyzing their fire behavior (Fig. 2), their mechanical properties and their applicability as a matrix material in sandwich structures. As an alternative to the currently used manufacturing process the applicability of the LFI-technology (Long Fiber Injection) is investigated. The LFI-technology is an injection molding process in which long glass fibers in conjunction with polyurethane-resin are being used. Sandwich structures can be produced using this manufacturing process. By modifying the process parameters and optimizing the fiber lengths and PUR-resin properties this technology is a promising option in future manufacturing processes of aircraft cabin interiors.

Improvement of Efficiency by Demand Driven Material Selection

One of the most important problems to be solved is the development of a method that guides the engineer in the selection of the semi-finished materials from the material kit. This method under development will enable instant decision for specific materials from the kit based on the requirements, which also represent an optimum concerning weight, cost and building space. The method focuses on efficiency functions (Fig. 3) for different material combinations. To evaluate the materials from the kit – core and face sheets with different lay-ups – the weighted running bending moment is plotted over the displacement. This has been implemented by using analytical and numerical methods for strength and stability evaluation for sandwich structures. With given demands of the component, the material kit and the corresponding selection method will enable the engineer to choose the optimal material combination and lay-up of the sandwich structure for each interior application. In the next step the method will be verified by four-point-bending tests.

> **Dipl.-Ing. Imke Roese-Koerner (M.Sc.) (left), Dipl.-Ing. Jens Bold (right)**

Towards a Full Scale Active Twist Blade

Within the Green Rotorcraft research consortium of the European Joint Technology Initiative Clean Sky, DLR is aiming at the development of active rotor technologies to provide the greatest possible reduction in rotor noise, fuselage vibration and fuel consumption. A drawback of all active rotor systems that include discrete mechanical components like hinges, levers or gears is their vulnerability in a helicopter environment with high centrifugal loads and vibration levels. That's why the idea of smart materials that are directly embedded into the rotor blade structure is very attractive, since they operate as solid state actuators without any friction or wear. A promising approach is the generation of twist by the integration of piezoceramic actuators with an actuation direction of 45° into the rotor blade skin. The feasibility of this concept has been successfully demonstrated on model scale. The goal of this project is to transfer this technology to full scale. For this purpose a 2 m full scale active twist blade segment, based on a serial helicopter blade, will be designed, manufactured and tested.

Fig. 1:
Single Multilayer Composite used for characterization of active and mechanical performance.

New Actuators to Twist the Blade

The major component of an active twist blade is the piezoelectric actuation system. To provide sufficient strain it is necessary, that the actuator operates in the piezoelectric d33-mode. As the high operating voltages of state of the art d33 actuators (up to 1500 V) are not acceptable for the envisaged application, a new actuation technology based on piezoceramic multilayer technology has been developed at DLR. These new actuators are able to produce comparable active strains at operation voltages as low as 120 V. To utilize the multilayer technology for low-profile actuators, a method has been developed that allows cutting piezoceramic multilayer stacks into thin (0.2-0.3 mm) plates and to embed the fragile slices into a composite to form a robust transducer (multilayer composite). Fig. 1 depicts a single actuator that has been used for characterization purposes. Extensive material testing showed that first cracks in the piezoceramic material occur at approx. 0.2 % tensile strain. But due to the damage tolerant design of the transducer they do not result in a total failure of the actuator. In fact a first performance loss was observed at strain levels of 0.4 % and total failure occurred at even higher loads. The actuators good long term performance under dynamic loads proves the suitability for the active twist blade.

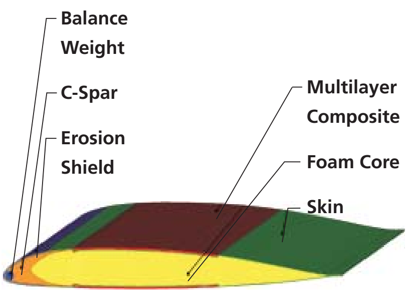


Fig. 2:
Main components of a full scale C-spar blade section.

Finding the Optimum Blade Design

Even though the reference blade is a modern helicopter blade featuring different airfoils and chord lengths, each blade section is build up by six main components (Fig. 2). To optimize the blade, a parametric FE-Model that uses up to 30 different parameters to describe the blade structure has been developed. The goal was to find a configuration, which produces a given twist rate and features certain elastic properties (esp. torsion stiffness) while having a minimum weight. According to the results of a sensitivity analysis, seven parameters were chosen for the optimization (e.g. actuator position, skin thickness). Finally the strength of the optimized blade was proven with respect to given critical load cases. The weight increase for an active twist blade, having 50 % of the torsional stiffness of the reference blade, was found to be only 12 %. Having successfully passed the preliminary design review, the next steps comprise the optimization of the 3D blade structure, the detailed design and additional characterization of the actuation system (e.g. hot wet properties). After the critical design review, scheduled in 2012, the actual full scale blade segment will be manufactured and tested.

> **Dipl.-Ing. Steffen Opitz (right), Dipl.-Ing. Daniel Schmidt (center), Dr.-Ing. Peter Wierach (left)**

Results from the Virtual Institute: "Nanotechnology in Polymer Composites"

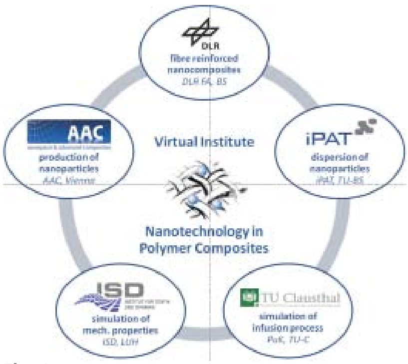


Fig. 1:
Partner and their competencies of the virtual institute.

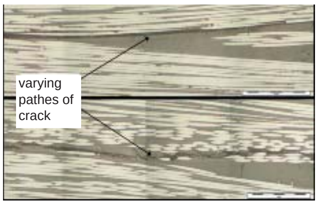


Fig. 2:
Pathes of crack in CFRP (micrograph): top: reference, below: 15 wt.-% boehmite nanoparticles.

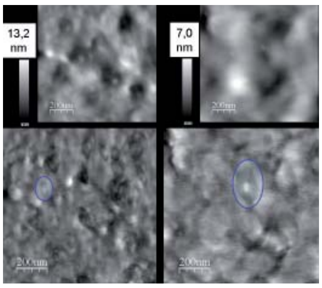


Fig. 3:
SFM: Topographies (top) and real part pictures below: left: unmodified boehmite: small „halo"; right: modified boehmite: big „halo".

The Virtual Institute (VI) „Nanotechnology in Polymer Composites" is a research network funded by the Helmholtz Association of German Research Centers (HGF). Under the guidance of the DLR Institute of Composite Structures and Adaptive Systems an interdisciplinary group of scientist (Fig. 1) investigates the influence of nanoparticles on low viscous, injectable polymer matrices and therewith the mechanical properties of the corresponding fiber composites. Typically, CFRP-structures are dimensioned via their fibers under external loading conditions. But it is well known, that laminate failure is often determined by the matrix behavior under miscellaneous loading conditions. Remaining residual stresses in the laminate after manufacturing and limited matrix properties hinder the development of these high performance materials to their full potential. Hence the idea of strengthening the matrix is not surprising.

Nanoparticles' Mode of Action in CFRP

Incorporating up to 15 wt.-% boehmite nanoparticles with a special surface modification into the polymer results in increased modulus, strength and fracture toughness of the nanoparticles reinforced polymers. Therefore, this can considerably enhance properties of CFRP. The shear strength, compression strength and their damage tolerance, which are particularly limiting parameters for highly stressed aerospace materials, can be improved by up to 25 %. Various effects are responsible:

- The enhanced resin stiffness and strength prevent fiber buckling while
- reduced initial stresses lead to decelerated crack propagation and delamination growth, and, therefore, to a higher resistance against first ply failure and
- very effective crack deflection, crack pinning and crack bridging processes lead to a disproportionately enhanced interlaminar energy release rate (differing crack paths; Fig. 2).
- Furthermore with wisely chosen particle surface molecules, the resin-particle interactions can be adjusted. Also a new network pattern can be built, which, when combined with with lower resin shrinkage, may lead to significantly higher fiber-matrix adhesion.

In summary all these attributes result in a considerably upgraded new CFRP.

Particle-Polymer Interphases

The designing of boehmite nanoparticles, in terms of their surface molecules, results in varrying dispersion stability, various particle size distribution and resin-particle interactions yielding different polymer network patterns and mechanical properties. The changed interactions can clearly be noticed through the resin viscosity and the correspondingly differing local mechanical properties. The type of surface molecules found influences and modifies the polymer stiffness surrounding the nanoparticle. The varying contrast seen in pictures taken by a scanning force microscope (SFM) in force modulation mode (FMM) (Fig. 3) illustrates these stiffness alterations.

Within the VI, we could establish the whole process chain starting from nanoparticle preparation, including surface modification and calculating nanocomposites behavior, up to producing composite parts and their testing.

> **Dr.-Ing. Christine Arlt, Dr.-Ing. Ulrich Riedel (formerly DLR)**

Image Analysis of Nano Particles in Composites

Characterization of Nano Composites

The nano particle size, shape and distance distributions in polymer composites are the main parameters of interest for the design of future nanocomposites and their properties. A typical method used to analyze the particle size distribution of polymer nanocomposites is the characterization of the liquid nanoparticles reinforced polymer before cure by the use of photon correlation spectroscopy. In order to quantify the particle size distribution of the nanocomposites after cure, a new method has to be developed. A qualified examination of scanning electron microscope (SEM) images of cured nanoparticle reinforced polymers seems to be a promising alternative procedure.

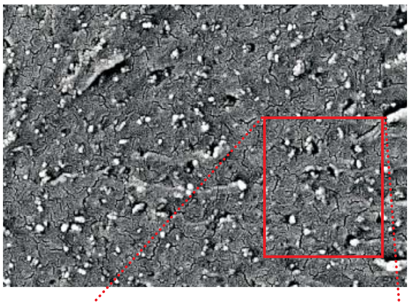


Fig. 1:
Composite with nano particles.

SEM Image Analysis

The SEM image based analysis of particle size, shape and distance distribution depends on the high contrast between particles and the polymer. Therefore an image of a nanocomposite like shown in Figure 1 must be available with a high resolution and good contrast. A high image resolution allows a detailed calculation of the particle size and an exact identification of the particle edges. High image contrast allows the fine tuning of a threshold value that is used to separate particles from the polymer. For an acceptable confidence level, several close-ups at various locations in the SEM images of a composite sample have to be analyzed.

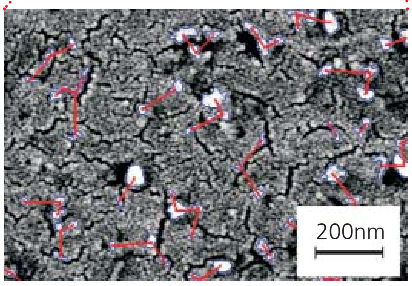


Fig. 2:
Composite section with analysis results.

In a first step an image brightness histogram is calculated with the greatest possible resolution. This allows the calculation of an applicable threshold value based on the well known OTSU's method for image binarization. This data reduction allows the application of fast image processing algorithms. Distinguishable areas in the binary image correspond to the nano particles. Their shape can be examined with an edge detection algorithm like CANNY. In a next step, all identified areas are indicated. The function delivers a vector of pixel coordinates for every area in the binary image. The vector length assigns the corresponding particle size. The average value of its coordinates represents the particle center. Knowledge of particle size allows an exclusion of unwanted results below a minimum or above a maximum accepted particle dimension.

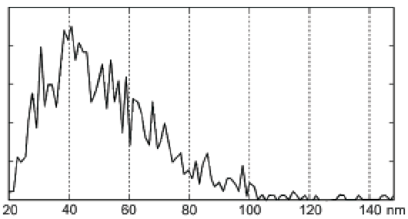


Fig. 3:
Distance histogram of nano particles in Fig. 1.

The particle distance distribution is analyzed by an assignment of every particle to his nearest neighbor. Therefore, a quadratic matrix is calculated. Every row and column corresponds to a particle index. The matrix entries are filled with the distance between both particles. The minimum value of each column indicates the sought-after neighbor. These distances are stored for statistical analysis. Fig. 2 illustrates identified particles (blue edges) and their nearest neighbors (red lines) in the selected section of Fig. 1. Fig. 3 presents as example the distance histogram of the same image.

The particle detection algorithm works in a very stable manner. A correct threshold value leads to a good particle hit rate. Nevertheless, there are some cases of unwanted hits caused by cracks or dust on the specimen surface. A possible improvement can be the consideration of criteria that exclude certain hits , e.g. on the basis of the particle shape. Furthermore, the consideration of a brightness gradient function instead of a global constant for image binarization could deliver better results.

> **Dipl.-Ing. Artur Szewieczek (Foto), Dr.-Ing. Ulrich Riedel (formerly DLR), Dr.-Ing. Christine Arlt**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Composite Tool Chain

In spite of extensive effort within several research projects, the current development process of composite structures still exhibits a mostly sequential work flow, beginning with a first feasibility and concept phase, via the more detailed definition and development phase, the production and assembly phase on prototype level up to the final phase of series production. Several different methods and software tools are applied within these development phases in order to solve particular questions. Furthermore, a heterogeneous set of tools with generally incomplete tool interfaces hinders a continuous development process with seamless interfaces. This directly affects process efficiency both short-term feasibility questions as well as comprehensive detailed design of composite structures. Therefore, great potential could be tapped by a concurrent engineering approach, which may for example arise from an early feedback of manufacturing data to the design phase (ref. Fig. 1).

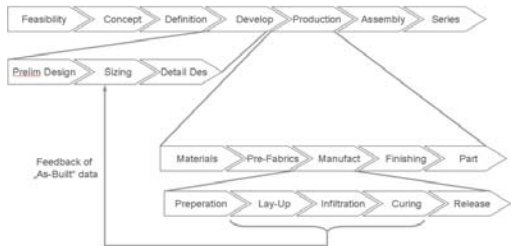


Fig. 1:
"As-Built" feedback of manufacturing data into earlier design phase.

CompTAB Project

Within the BMWi funded project CompTAB (Composite Tool Chain "As-Built") a continuous tool chain is currently developed in alliance with partners from aerospace industry. This tool chain comprises the various interdisciplinary working phases, provides necessary connectivity for a concurrent engineering (CAD-CAE-CAM) and, thus, enables efficient iteration loops for product improvements beyond state-of-the-art. In order to capture future tool chain requirements, current process steps of design, engineering and manufacturing (-engineering) were analyzed within industrial and research environments. Hereupon, essential tool chain modules and interdependencies were derived in order to set up efficient development procedures. Aiming for sustained success within a future composite design, the following major issues could be drawn:

- early integration of manufacturing engineering
- probabilistic capturing of manufacturing tolerances and constraints
- "as-built" feedback of geometric and material composite properties

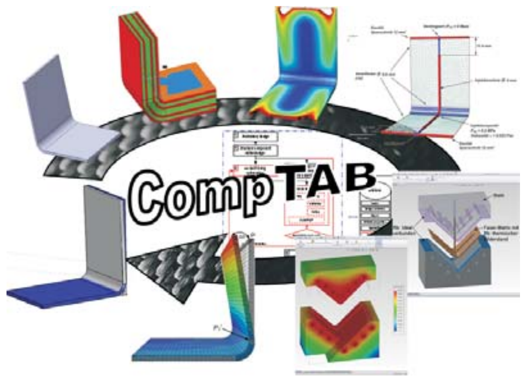


Fig. 2:
Composite tool chain "as-built".

Working Example

An extract of the composite tool chain shall exemplarily be demonstrated by the working example of an L-profile depicted in Fig. 2, finally to be applied on a frame or fuselage section. Based on an initial design, draping simulations were performed, in order to receive spatially distributed geometric composite layer properties, such as fibre orientations, fibre turns or shear angles. Depending on the applied method, even fibre volume fractions or ply thicknesses could be derived. With respect to an optimal infusion concept, CFD analyses allowed for simulations of resin flow and therefore could be used to predict flow fronts. Moreover, an optimal tooling and heating concept was achieved by performing numerical heat transfer and mechanical analyses of the tooling. Thus, thermal and mechanical boundary conditions could be provided for subsequent simulations of composite curing and shrinkage processes. The resulting distortions could be transferred to CAD drawings in order to morph part or tooling shapes from a first nominal design to an "as-built" design. Moreover, residual stress fields and distortions could be integrated as initial loadings into the structural analysis and therefore allowed for a more realistic prediction of critical areas under assembly and operational loading conditions.

> **Dr.-Ing. Tobias Wille**

Buckling Test Facility – Extension to In-Plane Shear Capabilities

Fig. 1:
Shear-compression-test-rig with curved stiffened panel.

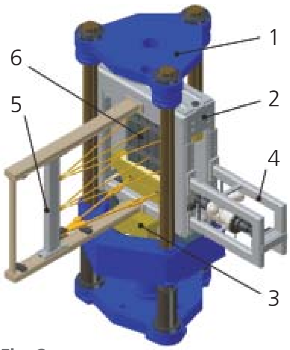


Fig. 2:
CAD-model of shear-compression test-rig mounted in buckling test facility.

Parameter	Value
max. panel radius (extended)	2300 mm (3000mm)
min. panel radius	1550 mm
max. panel length	1400 mm
max. panel width	1200 mm
max. axial force, current	380 kN
max. axial force, extended	1 MN
max. shear force, current	210 kN
max. shear force, extended	500 kN
max. shear stroke	100mm
max. axial stroke	40mm

Fig. 3:
Main parameters of shear-compression test-rig.

Scope of the Test Facility

Full advantage of composite aircraft-structures can only be achieved if the behavior of these structures under in-plane loading is very well understood. Thin walled structures under compression or shear are susceptible to buckling. The dimensioning of structures against loss of stability is still done with conservative assumptions. Developing design rules and ensuring structure's load carrying capability without stability failure requires extensive buckling tests.

In the past stability tests on thin walled cylindrical shells were performed with the buckling test facility of our Institute. Many important results were received due to matured stability tests. The ability to test cylindrical shells and curved panels under axial compression loads, partial in combination with torsion, is extended to new capabilities, now. A new test rig was developed to extend the current capabilities of the buckling test facility also to in-plane shear as well as to combined axial compression and shear loading of stiffened curved panels as representative part of a fuselage.

New Rig Designed for the Existing Facility

Before the test rig was designed, extensive investigations have been conducted to answer the question how to apply shear loads in combination with axial compression loads on a curved stiffened panel by using a device based on the existing buckling test facility. Many kinematical options have been studied and functional principles have been created and discussed to find a solution for an appropriate test rig. In addition, the concept and design phases were supported by numerical simulations with the designated curved stiffened panel and its boundary conditions. The test rig was designed to ensure well-defined boundary conditions during the test that can be modeled within a validation process. Hence it is possible to achieve the best comparability between the results of experiments and those in numerical simulations. In addition, pure axial compression tests with larger structures are still possible.

How Does it Work?

The test rig (Fig. 1, 2) is assembled to the buckling test facility (1). It consists of the shear frame (2), the cylinder bracket (4) on the right, the extension arm with guiding rods (5) and the load transmission unit (3).

The test panel (6) is cast into the clamping boxes of the load transmission unit. The shear load is applied by the horizontal hydraulic cylinder which is mounted sidewise to the lower clamping box in the cylinder bracket. The lateral edges are kept free to get constant and repeatable boundary conditions. In order to allow the panel to move according to its radius, the lower clamping box and the frames of the panel are guided through rods on a common axis mounted on the long extension arm. The axial compression load is applied by a vertical hydraulic cylinder. In addition to measure the load, displacement and strain, digital image correlation system (DIC) like ARAMIS is utilized. Damage progression can be monitored by means of thermography. The main technical parameters are given in Fig. 3.

> **Dipl.-Ing. Falk Odermann**

Multiscale Analysis – Considering Defects in Structural Analysis

Manufacturing defects in composite aircraft structures like panels or barrels can have a detrimental effect on the load bearing capacity. Fiber waviness and porosity can be frequently found in composite structures. These defects reduce the material stiffness and strength. The main reasons for porosity are entrapped air which develops during the resin infiltration process, volatile gases which occur during the curing process, or bad wettability behavior of the fibers. Especially pores that occur in the interface between two adjacent plies are critical because they could become the origin of delaminations. Fiber waviness defects on the other hand are often resulting during the manufacturing of fiber textiles or the draping of dry textiles and prepregs. The challenge is to evaluate these defects and take them into consideration within the design phase. The knowledge about their effects on the composite behaviour allows estimating the residual load bearing capacity during operation. In this context, multiscale finite element analysis is applied in order to meet this challenge.

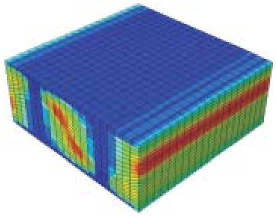


Fig. 1:
Local FE-model of a representative volume element (RVE) with fibre waviness.

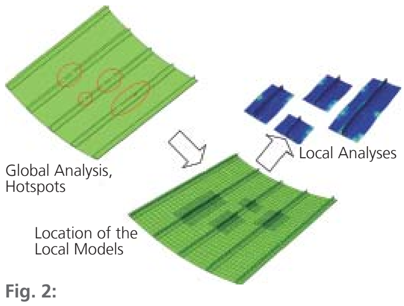


Fig. 2:
Assignment of local models to global model areas.

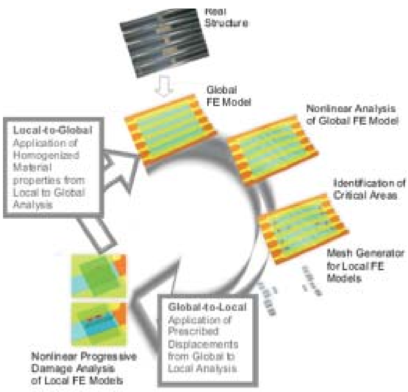


Fig. 3:
Multiscale finite element analysis scheme.

Development of a Loose Coupling Approach

Within a multiscale finite element analysis, large (global) scale and small (local) scale FE models are combined in a suitable way. The goal is to develop a numerical multiscale analysis approach in order to consider local material defects within a macroscopic description of heterogeneous composites. Global and local scale FE models in this approach shall be coupled loosely which means that they are described by different systems of equations. Local models are generated automatically such that local analyses are performed only where necessary. Failure criteria serve as so called "hotspot" indicators to determine if a local model has to be generated. Depending on the problem, a local model can be assigned to a single global integration point (a so-called representative volume element, Fig. 1) or a global model area consisting of several finite elements (Fig. 2). Once a local analysis becomes necessary, the displacements obtained from the global model need to be appropriately assigned to the boundary nodes of the local model. Having solved the local boundary value problem, homogenized stresses are written back to the respective integration points of the global FE model. By this, local effects like damage are taken into account. Since this process is carried out fully automated the user has to take care of the global model only. Damage and other local features (e.g. manufacturing defects) are automatically considered by the loose coupling procedure which is illustrated in Fig. 3 with the example of a stiffened panel under axial compression load.

Expected Benefits from the Loose Coupling Approach

By applying the presented multiscale finite element analysis approach, sufficiently accurate simulation results can be obtained at the global scale at reasonable computational cost without omitting the influence of relevant physical phenomena at a smaller scale. Moreover, the criticality of the small scale phenomena can be judged at reasonable numerical cost, which will become more and more important for weight-efficient as well as robust industrial applications.

> **Dipl.-Wirtsch.-Ing. David Chrupalla**

Payload Adapter: Struts of Hybrid Laminate

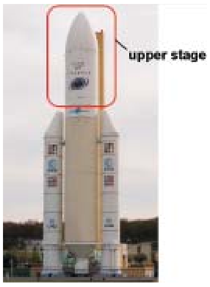


Fig. 1:
Upper stage of launch vehicle „Ariane 5".

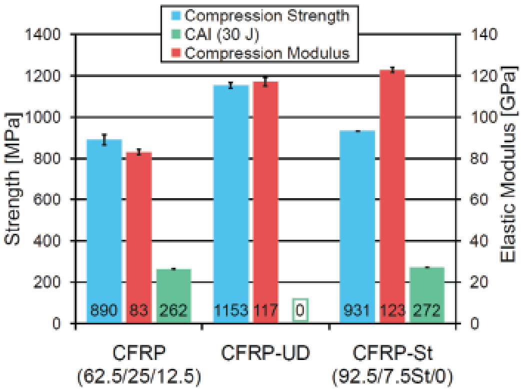


Fig. 2:
Experimental compression stiffness and compression strength properties of CFRP-St and CFRP reference configurations.

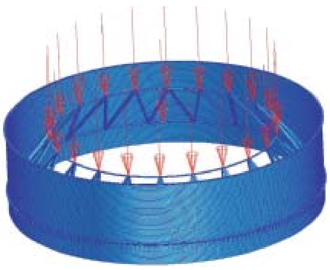


Fig. 3:
FE-model of payload adapter as framework design.

In comparison to other transport systems, launch vehicles are characterized by relatively light but extremely valuable payloads. Parts of the launcher's upper stage (Fig. 1) offer the highest weight saving potential, e.g. payload adapter and fairing. An effective weight reduction can be achieved by the combined utilization of high performance materials and adapted construction methods.

Fiber-Metal-Laminates as Structural Materials

Due to the sensitivity of unidirectional composites to impact loads, laminates of real structures are created by stacking laminae with various orientations. As a result stiffness and strength per unit weight of the laminate on a given direction are lower than the corresponding values for a unidirectional composite. Conventional CFRP-metal-laminates contain metal-layers with a thickness of 0.1 – 0.3 mm and therefore relatively high metal fractions impair the laminate's weight efficiency. To reduce these disadvantages of CFRP-metal-laminates and increase the degree of capacity utilization of the CFRP, a new laminate lay-up with metal-layers < 0.08 mm is proposed (metal volume fraction < 7 %). The metal-layers provide crack arrester layers within the laminate while replacing +/-45° and 90° fibers. Main advantage of the use of metal layers are stiffness and strength in 0°- direction, witch are not reduced in comparison to the use of variant fiber directions. Compression-After-Impact (CAI) examinations with 30 J impact were performed at CFRP-UD-laminates, CFRP-62.5/25/12.5-lamintes and CFRP-UD/steel-laminates with 7.5 % metal volume fraction using 0.05 mm steel foil. The UD-laminates showed catastrophic failure after impacting, whereas the residual strength after impact could be tested for the other lay-ups. The CFRP-UD/steel-laminates showed 4 % higher values for residual compression strength and demonstrated a 48 % higher elasticity modulus than the CFRP-62.5/25/12.5 reference laminate (Fig. 2).

Payload Adapter as Framework

The most critical value for light-weightdesign is the buckling stress. Higher elastic modulus allows for higher buckling stresses. The damage tolerant CFRP-UD/steel-laminates with an extremely high elastic modulus are therefore ideal for unidirectionally loaded parts like struts of adapters carried out as framework design (Fig. 3). Struts with circular and square cross-sections made of CFRP-UD-titanium and CFRP-UD-steel-laminates were analyzed and the following weight savings are gained for low metal volume fractions (1.43 – 7 %):

- up to 23 % compared to struts with circular cross-sections made of CFRP with high unidirectional fiber fraction (75/25/0)
- up to 74 % compared to the CFRP-cones as sandwich structure for the 'Ariane 5' reference structure
- up to 37 % compared to the CFRP-cones as sandwich structure with additional frames to bear the local concentrated loads of the struts

Further experimental investigations on the mechanical behavior and processablility are planned to assess the suitability and feasibility of the new hybrid material.

> **Dr.-Ing. Boris Kolesnikov, Dipl.-Ing. (FH) Johannes Wölper, Dipl.-Ing. Daniel Stefaniak**

Anisogrid Structures

The word anisogrid describes designs, where the mechanical properties in all directions are different (AN-ISOtropic). The structure has a GRID-wise shape. In the case of composite anisogrid structures, the fibers are arranged in the direction of the grid struts. As fibers have the highest mechanical performance in the fiber direction, and consequently also in the strut direction, therefore very high tension and compression loads can be transferred. Struts are also arranged in the diagonal (shear) direction; therefore this fiber critical load case is nearly eliminated. Anisogrid structures have the potential to be highly efficient as high cost- and weight reduction is expected.

Fig. 1:
Anisogrid structure.

Fields of Research

The lightweight potential of anisogrid for space applications has already been demonstrated by numerous rocket components (e.g. on Proton). The DLR is working on adapting these excellent results to other components in other branches, as well as advancing the good results to further space applications.

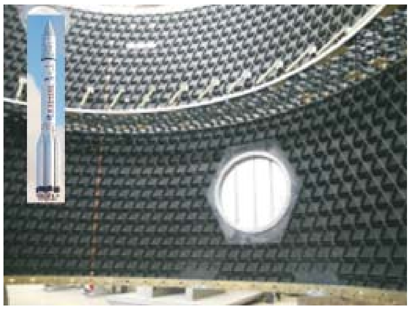


Fig. 2:
Interstage Proton-M,
space-launch vehicle [Vasiliev].

In the aviation industry there is still a high demand for structural weight reduction of the next generation of aircraft. A demonstrator of a single-aisle fuselage segment built with anisogrid composite structure has already been realized in 2001 in cooperation with a Russian partner (CRISM). The general feasibility, as well as the potential for light-weight undisturbed structures has already been shown. Nowadays, the research is focused on achieving an appropriate technology readiness level. Actual fields of research are therefore: durability, reparability, joining, large cut-outs, as well as local load introduction. These issues are currently investigated in a variety of national projects (DLR CFRP fuselage 3rd Gen, TENOR-GRUND, ALF) as well as international projects (ALaSCA, MAAXIMUS).

In the branch of ground transportation the anisogrid design is being adapted to express trains, called "next generation train". While the afore named air and ground transportation products have comparable dimensions and tubular shapes, anisogrid structures are also used in differently shaped structures such as an active stabilizer for large vessels in the naval industry.

Fig. 3
ALaSCA anisogrid configuration.

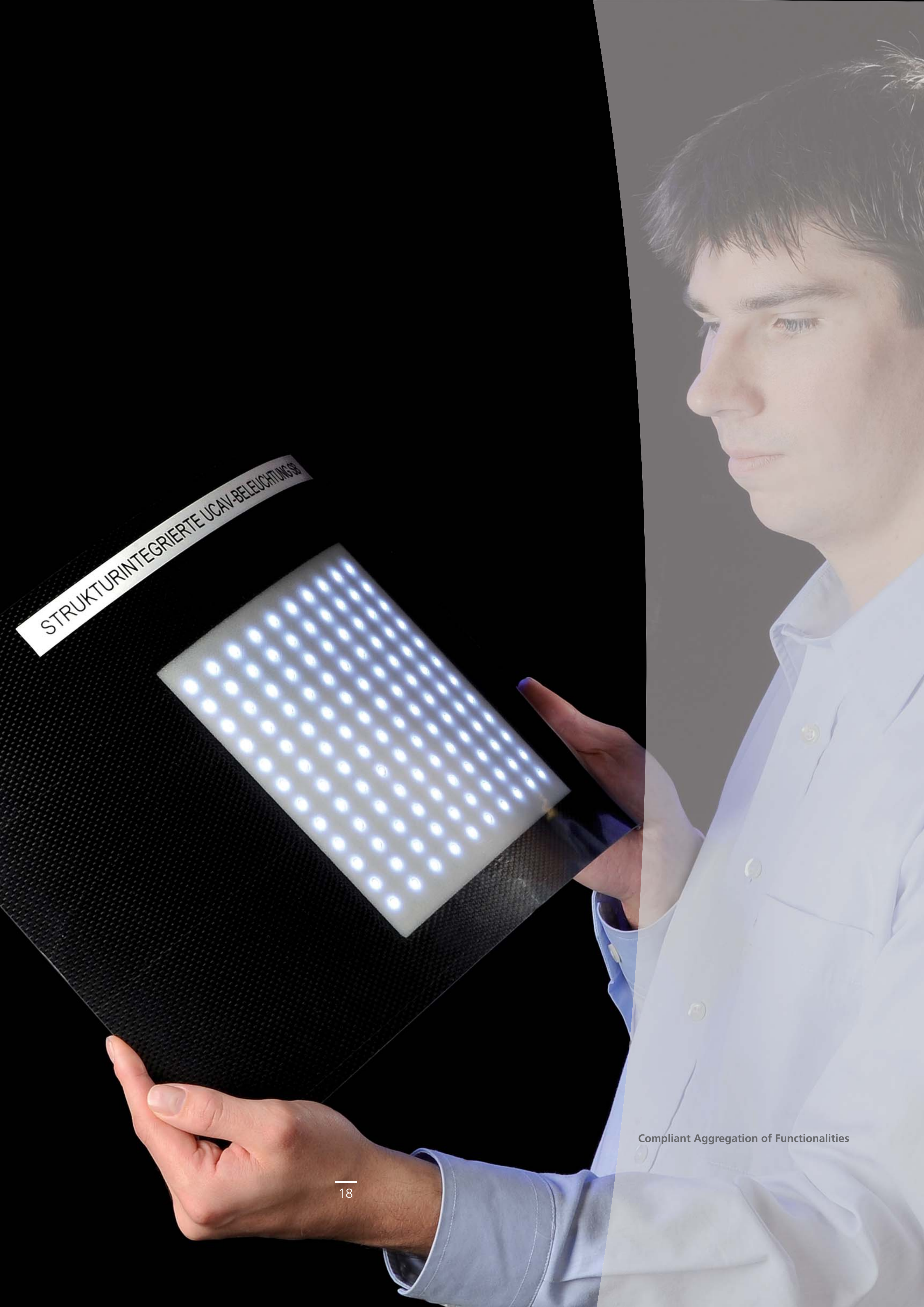
Future Challenges

Although the anisogrid concept has been proven in the space industry, a lot remains to be researched in order to apply it to other areas. The load cases for the mentioned applications differ substantially from those for the well-known space applications. Experience about the durability of these types of structures is missing. The stress and stability criteria for monolithic structures cannot be used, as the behaviour of these new structures is totally different. In the last two years, the Institute has invested in appropriate laboratory equipment, to carry out such studies in parallel to the development of new design concepts, as well as the adaptation of production machinery.

The anisogrid design has the potential to revolutionize the classic lightweight architecture, provided all disciplines are working together towards one solution. The Institute is well placed to fulfil needed future research due to its present knowledge, its current research and laboratory investment, as well as its active multidisciplinary approach to projects.



> **Dipl.-Ing. Tobias Ströhlein, M.S.E. Heike Lohse-Busch,**
M. Sc. Steffen Niemann



Compliant Aggregation of Functionalities

Ground Test of a Full-Scale Morphing Leading Edge High Lift System

Pioneering Technology for Natural Laminar Flow

In the framework of the fourth German national research program in aeronautics a morphing leading edge high lift system was developed by the partners Airbus, EADS-IW, CASSIDIAN Air Systems and the DLR. In order to reduce the airframe noise during landing and the drag in cruise flight, a gap and step less high lift system at the leading edge of an aircraft's wing is the only alternative to conventional high lift devices like slats. Due to the extremely high requirements with regard to surface quality a gap and step less high lift device at the leading edge can be seen as pioneering technology for natural laminar flow application at the wing and further drag reduction in the future.

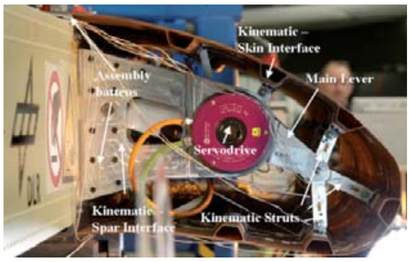


Fig. 1:
Kinematics with actuators in the smart leading edge structure in deformed state.

How to Provide Maximum Flexibility and Maximum Stiffness at the Same Time?

But how can a system be developed which has to be flexible and stiff at the same time? The developed concept consists of an especially tailored glass fiber reinforced skin for maximum flexibility in the desired deformation mode and on the other hand maximum stiffness to carry the aerodynamic forces during cruise flight and landing. Inside the skin a customized kinematic mechanism is developed by EADS-IW which is closely attuned to the skin's deformation mode for the actuation of the system. The aerodynamic loads and actuation forces are transferred by longitudinal stiffeners in span direction which feature the well-proven design of omega shaped stiffeners.

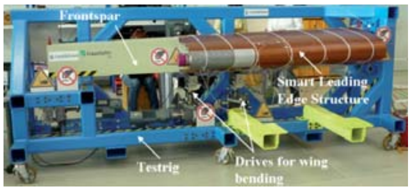


Fig. 2:
Test setup with test-rig, test (front) spar and smart leading edge structure.

Demonstrating the Functionality under Wing Bending

In order to test and to demonstrate the functionality of the developed system a full-scale segment of an A320-like wing was manufactured and successfully tested under wing bending in a ground test at CASSIDIAN Air Systems. The tests were especially focused on the measurements of the deformation behavior and the strain in the flexible skin structure. Both, the deformations and strains, are found to be in good agreement with the simulation results. However, the functionality and performance of the developed concept as well as the tools for the structural design could be demonstrated successfully.

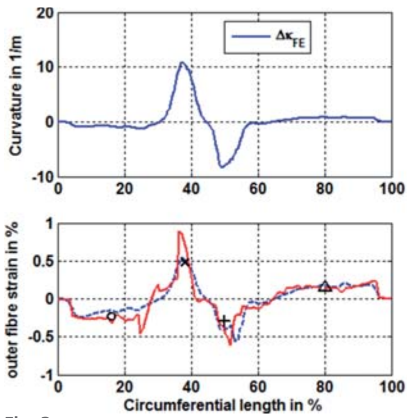


Fig. 3:
Measured curvature and strain in comparison with simulation results.

Aiming for Wind Tunnel Tests

The next step will be the wind tunnel test of a follow-up concept which is developed in the European project SADE. At the end of 2011 a full-scale demonstrator of 5 m span will be tested under realistic aerodynamic loading in the wind tunnel test facilities of TsAGI, the T-101, one of the biggest wind tunnels in the world.

> **Dipl.-Ing. Markus Kintscher**

Addressing Adaptive Structure Technology to Reduce the Airframe Noise

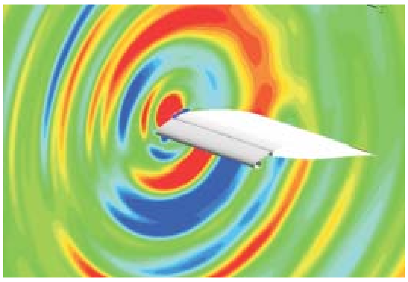


Fig. 1:
Leading edge slat as a dominant noise source.

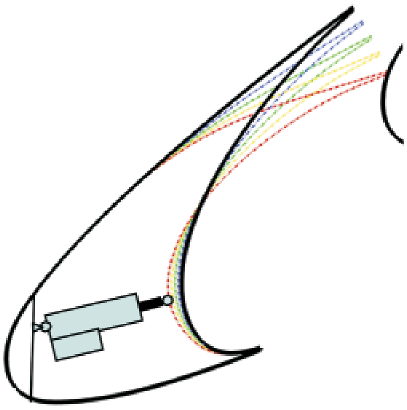


Fig. 2:
Adaptive slat mechanism.

Today's high lift configurations benefit from open slots, required to improve the maximum lift for start and landing. However, slotted high lift devices and especially the leading edge slat represent a dominant noise source as illustrated in Fig. 1. That issue is to be managed on the road to a greener commercial aircraft and is the scope of the SLED and OPENAIR projects with DLR participation..

Adaptive Slat: Providing a Tailored Low Noise Solution

A slot between the leading edge slat and a main wing provides additional energy to the boundary layer and helps to prevent a wing from stall at high angles of attack. However, flight operations at such angles are an exceptional case for commercial aircrafts. This means, that a slotted slat can be sealed to reduce the noise emission for regular operations.

Conventional slot sealing systems did not achieve the desired success due to the use of relatively complex mechanisms to move or rotate the complete slat body. Compared to such developments, a new approach is being investigated within the projects OPENAIR and SLED. The scope of these projects is the development of a system comprising a flexible slat trailing edge and an appropriate actuating mechanism, as illustrated in Fig. 2. The idea is to develop a structure that is flexible enough to enable the required deformations and strong enough to sustain the applied aerodynamic and the actuator forces. Furthermore, the structure has to meet tough requirements concerning the geometric fidelity of the airfoil in cruise flight conditions, in order to minimize the drag impact.

An additional benefit of the considered approach is the integrated passive releasing mechanism: the initial tension of the slat trailing edge restores the original slat shape in case of inactive system or if required by the flying conditions. Thus, an adaptive slat provides a tailored solution with desired noise reduction for normal operations and full high lift performance, if needed.

Validation and Integration

An iterative multidisciplinary design process, defined by a combination of structural (FE), aerodynamic (CFD) and aeroacoustic (CAA) computations provides the required structural topology. The next stages will be a series of tests in the Aeroacoustic Wind Tunnel Brunswick (AWB) to validate the aeroacoustic computations for various optimization parameters. More detailed investigations concerning the system integration of the adaptive slat mechanism will be performed as well, to increase the technological readiness of the system.

> **Dipl.-Ing. Anton Rudenko**

ULD – Light and Robust Structures

Freight gets carried and protected by Unit Load Devices (ULDs), which contains air-freight pallets with nets as well as airfreight containers. The different existing types of ULDs are related to the aircraft type and their location inside the airplane. They differ in size and contour. Common ULD-types have a base area of three to six square meters, while the contour adapts to the fuselage cross section of the airplane. The cargo load is between one and a half and six tons.

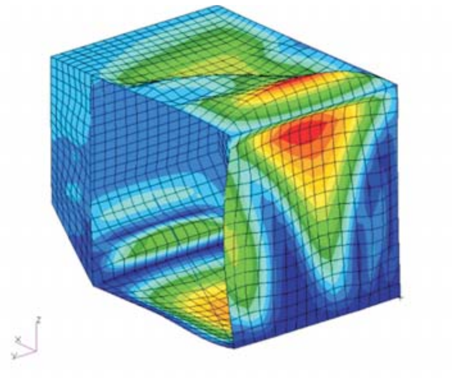


Fig. 1:
Simulation of Racking Test for container of type AKE.

Stringent Conditions

In addition to the certification specifications and the already mentioned requirements, ULDs have to withstand harsh conditions. On a daily basis, they are pushed along roller beds and ball tracks and, while being used and stored in the open air, they are exposed to wind and changing weather. They are prone to damage while being moved by forklift trucks.

More Efficiency in Air Freight Transport

Air freight transport is the fastest and safest but also most expensive category of transportation. To make it more environmentally friendly and cost efficient, the weight of these Unit Load Devices needs to be minimized and, at the same time, they need to become more robust. By minimization of the tare weight, either more freight can be transported, or fuel can be saved. In all cases the environment can be protected by minimizing of CO^2 emissions. Also life cycle costs can be reduced by enhancing the robustness, which results in less repairs. Hence a replacement of damaged containers or sending them to specialized repair companies can be avoided.

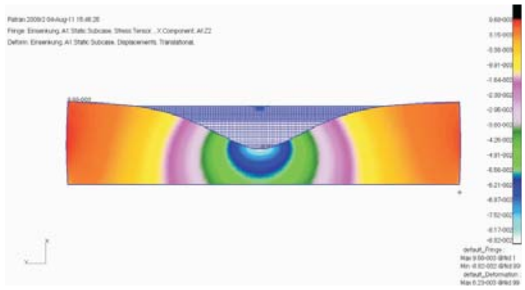


Fig. 2:
Simulation of Ball Test for airfreight pallet.

Input for the Logistics Branch

Since 2009 the Institute of Composite Structures and Adaptive Systems works on the topic of lightweight airfreight containers. To save cost and weight, leading companies of the logistic branch have already sought our Institute's expertise. Moreover, in the field of composite materials research, future concepts for innovative ULDs were developed by our Institute along with other partners ranging from research facilities over material suppliers to manufacturers and ULD-users. The Institute also conducted technology evaluations and feasibility studies to develop sophisticated concepts in order to meet the challenging specifications of the customers. Possible combinations of materials were identified, which result in a reduction of weight and increase of functionality like simplified and quick repair or compatibility to RFID-technology. Solutions address all components of a ULD, such as base, side panels or frame. First results predict a weight reduction between twelve and thirty per cent depending on the type of container. With the help of FE-Models simulations of necessary tests required by the IATA ULD Technical Manual for pallets and containers were carried out. Fig. 1 shows a simulated Racking Test of an airfreight container of type AKE and Fig. 2 shows a simulation of a Ball Test on a pallet. The simulations help to derive the required mechanical properties of the materials. Real Roller and Ball Tests were carried out in the Institute. The assembly of the Ball Test is shown in Fig. 3. The next step will be the development of a test rig for full-scale ULDs. The Institute develops its expertise in every area, from the concepts through the materials to the full scale test.

> **Dipl. Ing.-Ivonne Bartsch**

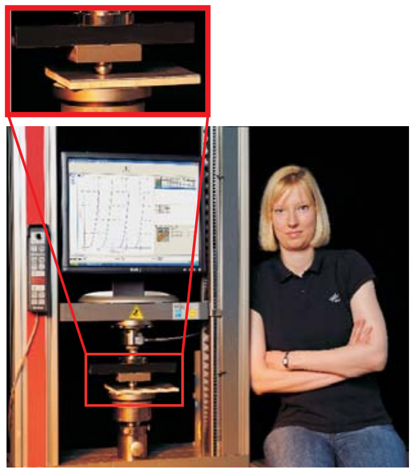


Fig. 3:
Test assembly Ball Test with author Ivonne Bartsch.

LamAiR – Tailoring Composite Wing for Next Generation Single Aisle Aircraft

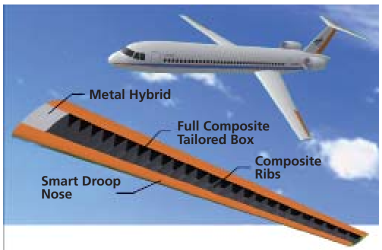


Fig. 1:
LamAiR configuration.

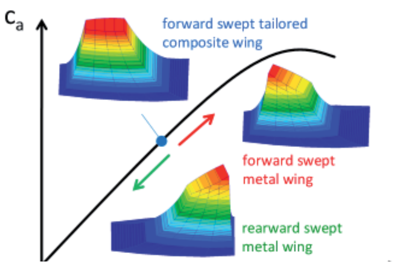


Fig. 2:
Tailored wing concept.

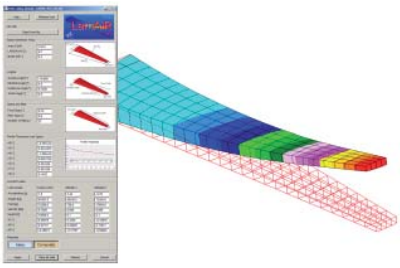


Fig. 3:
Parameterized finite element model.

Fig. 4:
Ary Zipfel, Lars Heinrich, Jens Bold, Christian Ückert with ATOS test equipment (missing: Thomas Wurl and Matthias Grote).

In the DLR project Laminar Aircraft Research (LamAiR) a full composite forward swept wing (Fig. 1) is designed and dimensioned in an interdisciplinary approach between Aerodynamics, Aeroelasticity and our Institute. Based on the global evaluations for a new single aisle aircraft done with PrADO at the Institute of Aerodynamics, we have the task to tailor the wing to the aerodynamic and aeroelastic needs.

Bending-Torsion Coupling as Baseline

Today's rearward swept wings act uncritical to increasing loads by spanwise alleviating the angle of attack from a streamwise perspective. A forward swept wing under load inverts this behaviour – loading naturally behaves self-energizing (Fig. 2). This effect can be compensated by turning the primary stiffness direction out of the geometrically predetermined main load direction. Full advantage of composite anisotropy can be exploited by tailoring the wing to the proper behavior.

Non Linear Response Optimization

First investigations were made using the full potential of MSC Patran for modelling parameterized finite element models and automate the calculation (Fig. 3). For the system solution and optimization the new ESLNRO method in MD Nastran was applied. Many parameters have been varied to find the best compromise between all disciplines. These included geometrical parameters like wing area, profile thickness, taper and aspect ratio, but also structural parameters as position of spars and number of ribs. The aerodynamic lift and induced moments were formalized and typical load cases have been used for the optimization.

Computational Fluid-Structure Coupling

Based on the global finite element model, a fine mesh was used to directly couple the aerodynamic loads calculated with TAU at the aerodynamic department and the structure calculation done with MD Nastran in our Institute. This iterative coupling takes into account the changes of loads coming from the changes in the elastic behaviour of the wing.

Tailored Manufacturing

Aerodynamic loads on stiffened panels lead to local displacements in the skin. These displacements can be compensated by beneficial use of the manufacturing effects spring-in and warpage, which act in the opposite direction. New approaches will make these effects become predictable. Together with high precision calculation of the local displacements, superposition will lead to a more laminar wing. The system ATOS of the Braunschweig based company GOM was used to determine the small displacements generated by these effects.

> **Dipl.-Ing. Lars Heinrich, Dipl.-Ing. Jens Bold**

Composite B-Rib for a Next Generation Car

Composite Rib as Essential Component of the DLR Rib and Space-Frame Design

The project „Novel Vehicle Structures“ aims at improvements in weight reduction, safety and modularization strategies of future cars. An essential component of the DLR Rib and Space-Frame is the B-Rib, which uses a novel mechanical principle to meet the side impact crash requirements.

While the rib in the vicinity of the roof beam acts as a deformable joint, the area between the roof beam and the rocker panel is designed to be extremely stiff for optimal passenger head and shoulder protection. The resulting rotation around the deformable joint transfers the crash energy to the crash elements in the floor region between the rocker panel and the continuous side member. The lightweight potential of the B-Rib is shown through a weight reduction of up to 35 % with significantly increased safety and overall performance compared to the steel reference structure of a compact class vehicle.

Fig. 1:
Carbon fibre composite B-rib demonstrator for a next generation car design.

Challenges in Design and Manufacture

The development of the composite B-Rib covers the entire process chain. Herein are included conceptual and detailed design, static and dynamic calculation, sizing, and simulation to lay-up design. Manufacturing aspects such as design of prototypical autoclave manufacturing concepts and manufacture of prototypes are also addressed. Validation tests are ongoing.

Fig. 2:
Side-view (left) and cross-section (right) of composite B-rib.

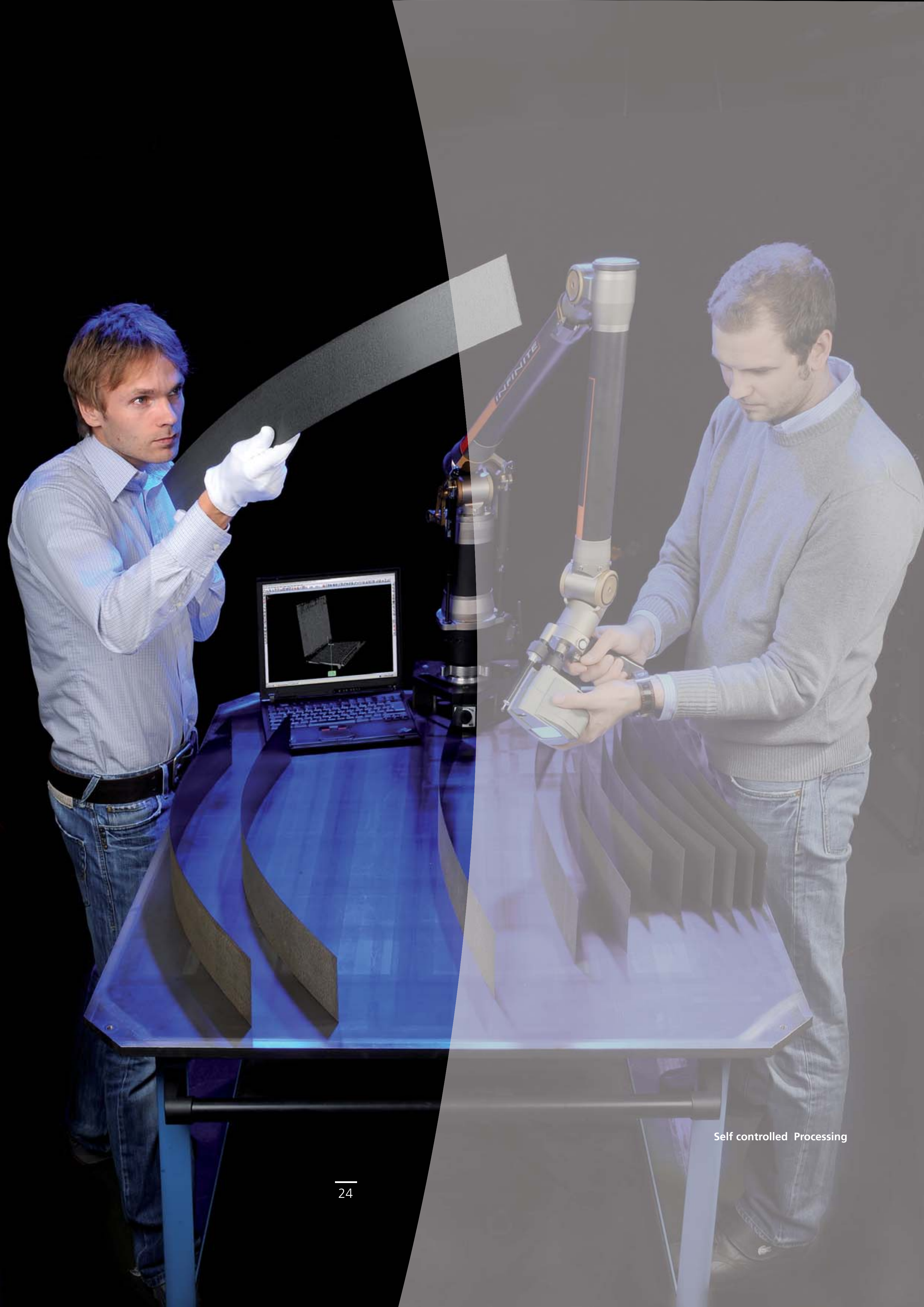
Many processes are available to manufacture CFRP components. Infusion technologies involving modern preform processes offer an attractive, automatable and low-cost manufacturing method for complex components such as frames. In contrast to prepreg processes with resin-impregnated fiber layers, infusion processes involve injecting dry semi-finished fiber products with a low-viscosity resin system. These allow complex geometries to be achieved through cost-reducing textile technologies such as sewing and draping.

For the manufacture of prototypes, SLI (Single-Line-Injection) is suitable for the frames considered here. This only requires a solid, tool half (“open mold”) which gives the shape. The other mold half is replaced by an air-tight membrane. The required consolidation pressure is applied by an autoclave. The pressurized injection allows even low-permeability preforms to be soaked with resin and large flow paths to be achieved without flow promoters. Not using flow-promoting manufacturing aids allows a very high surface quality even on the membrane side by applying caul plates.

Fig. 3:
Autoclave tool concept for manufacture of prototypes.

Experiences reveal the inherent potentials and interferences between a pro-composite component design and cost-efficient and cost-effective manufacturing technologies. Examples are Resin Transfer Molding (RTM) and their variants, which will have to be further exploited for an optimum solution in terms of weight and cost to get ready for mass production.

> **Dipl.-Ing. Jörg Nickel**



Self controlled Processing

Thermally Optimized Closed Molds

The Advantage of Temperature Control

Current mold design and heating systems are not able to correctly fulfill the cure cycles prescribed by the resin manufacturers. Due to time delay, local and global variations in temperature control and exothermic reactions, parts cannot be cured under identical conditions in order to achieve homogeneous laminate quality.

Applicable production technologies are required to produce the targeted high quantity of CFRP parts in a low processing time and with the desired material properties. The resin transfer molding technology (RTM-process) provides advantages like higher productivity, repeatability and two-sided finish within a fully automated process chain. But the advantages assume that the RTM-process is properly designed and efficient. Therefore, when designing a tool for the RTM-process, specific attention has to be paid to the type and design of the heating system. It has to be compatible with the requirements and needs of the CFRP-production, such as temperature range and tolerance, heating and cooling and the thermal gradient. Additionally to the temperature requirements, the integration of heating systems into the mold and the adjustment according to the geometry of the part have to be realized.

Furthermore, the method and the position of the mold temperature measurement have to be chosen carefully. Temperature control of the part is the key factor for optimized (short, flexible and efficient) production.

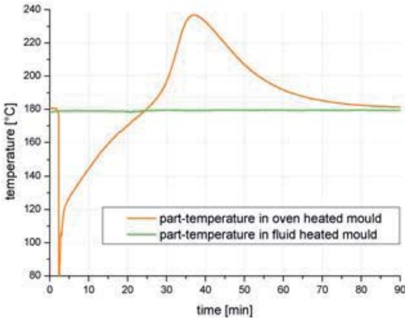


Fig. 1:
Comparison of the part-temperature during isothermic cure (180 °C) with thermal controlled and non-controlled molds.

Part-Adjusted Variothermic Molds

The temperature control system has to allow for an active and continuous heat flow between the mold and the part during the curing process. The mold temperature can be maintained by a circulating fluid (usually water), thus creating a fluid driven temperature control. The external heat supply not only activates the chemical reaction and maintains a constant temperature, but it also dissipates build-up exothermic energy. While the resin state is directly measured, the process can be dynamically adapted to the ideal curing curve. For this purpose, however, it is necessary to precisely know the correct resin-behavior during curing.

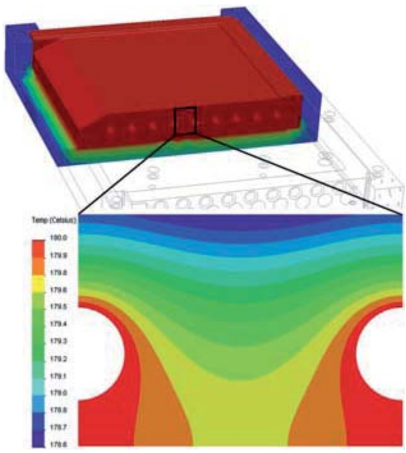


Fig. 2:
Temperature field on a thermally optimised mold.

On the other hand, molds have to be modified to achieve a homogeneous temperature distribution throughout the part independently of its complexity (e.g. geometry, thickness, insert, core material). This can be accomplished by minimizing the static thermal mass (heat sink) of the mold and by shifting the energy input only to the circulating fluid. Furthermore, significant improvements can be achieved by attaching an insulating layer that conforms to the contour of the part. This reduces the heat loss to the surroundings and produces a robust process that can be well controlled. Using the support of simulation tools, a thermally optimized RTM-tool can be designed without experimental trials and with acceptable effort.

First results show that lowering the tool weight decreases the energy consumption by about 30 %. By increasing the effective area for heat flow, it is possible to speed up the process by 50 %.

> **Dipl.-Ing. Mark Opitz (right)**

CFRP Structure Optimization and Quality Control by High Accuray 3D-Digitizing

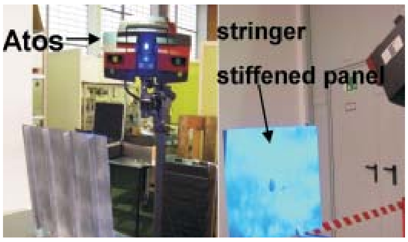


Fig. 1:
Optical 3D digitizing.

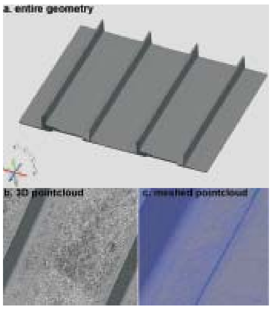


Fig. 2:
Measuring data.

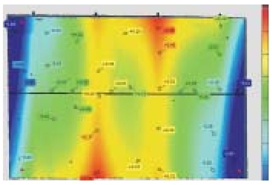
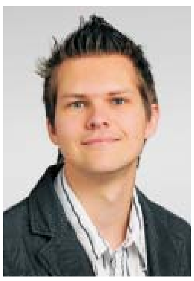


Fig. 3:
Contour color plot.

Fig. 4:
Section view.



In the scope of producing high quality CFRP- structures, a comprehensive quality control is necessary. Due to rising production rates and stringent tolerance requirements, this need will increase in the future.

A main task of quality assurance is to examine the part geometry. Especially for the production of CFRP structures with effects such as SpringIn or Warpage, an entire coverage of the component's geometry is essential.

The manual measurement of parts is costly and inappropriate to measure complex structures. Even tactile measurement systems are not able to capture the entire geometry in an effective manner.

The disadvantages of the classical measuring methods spurred the development of the optical 3D Digitizing. The cost effective high resolution capturing of entire geometry data is the strength of this new method.

As an example of the optical 3D Digitizing, the development of an upper wing cover with high surface quality, which is supporting natural laminar flow, is presented.

Development of an Upper Wing Cover for Natural Laminar Flow

The projects LamAir and LaWiPro investigate the feasibility of laminar wing structures.

To achieve natural laminar flow, an increased evenness compared to current wing structures is necessary. Surface deviation coming from manufacturing or load has to be kept in a much smaller tolerance band than in current aircrafts.

To study the surface waviness of stringer stiffened CFRP- structures, various stringer stiffened panels have been produced and their entire geometry has been captured using the optical 3D scanner gom Atos3 (Fig.1). The Atos3 delivers high resolution 3D pointclouds as shown in Fig. 2b.

This raw data needs to be processed using different software systems, e.g., gom Inspect or Matlab, to extract the surface waviness. An example for the deviation between a manufactured part (3D pointcloud) and a calculated plane is shown in Fig. 3. The figure shows a contour color plot wherein a significant waviness is recognized. The section view is shown in Fig. 4 (scaled 30:1). The peak to peak amplitude is about 0.18 mm and the wavelength corresponds to the stringer distance (160 mm).

Based on the 3D digitizing, major influence factors were identified and an optimization process was started.

In a next step, the captured data will be transferred to a Computational Fluid Dynamics (CFD) analysis to examine the effects of surface waviness on the laminar flow.

> **Dipl.-Ing. Matthias Grote**

Preforming of Frames – Process Prediction by Simulation and Fiber Orientation Measurement

Draping Simulation is currently used for qualitative checks mostly. Critical areas of fiber deformation or deviation can be determined, but real and reliable fiber orientations cannot be simulated due to missing validation methods.

Draping Simulation is a key to cost effective design and dimensioning of composite parts built of non-crimp fabric (NCF). By using simulated fiber orientations instead of idealistic values, results that are more realistic can be achieved in the dimensioning of composite parts. To gain reliable results a validation of draping simulation is essential. In cooperation with the WZL of RWTH Aachen, an optical measurement system was used to analyse fiber orientations in the draped NCF material during the preforming process (Fig. 1).

Fig. 1:
Measurement system.

Draping Simulation and Fiber Orientation Measurement

Accurate draping of highly complex 3D preforms from flat fabrics is a challenging task. Draping simulation software (Fig. 2) can be used to simulate the draping process and the fabric shear behaviour of NCF or woven textiles and to determine the fiber angle deviation.

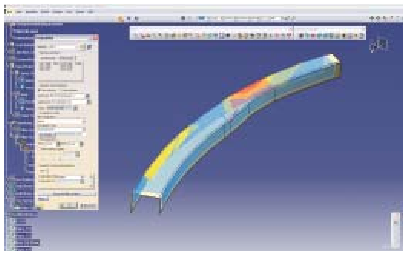


Fig. 2:
Draping simulation of a C-frame.

During the lay up the textiles are draped on a tool surface resulting in strongly deformed flat patterns. The draping simulation predicts the fiber angles. For the calculation of these fiber angles within the simulation, the software creates a mesh with nodes and elements in-between. The used draping simulation software is based on a kinematic algorithm. Characterizing this algorithm, the shear in the fabric is the only deformation mode that is considered during the simulation. Input parameters like the seed curve, seed point, mesh size and first stage region have strong effects on the quality of the simulation result. Due to the complex geometry of aircraft frames with multiple radii around several axes, it is important to understand the impact of each input parameter and its effect on the simulation result. Therefore, a parameter study was conducted with the input parameters being varied. At defined measurement stations, fiber angles from the resulting draping simulations were derived.

To detect the fiber deviation in the 3D preform an optical measurement system is used at DLR in cooperation with WZL. The visualization system is based on gray scale value analysis. Orientations with a line of the same gray scale represent the direction of a fiber. The direction is measured for all fibers in predefined measurement fields and is statistically evaluated. Outputs of the measurement are angles between a specific reference direction and the measured fiber orientation in selected measurement stations.

Validation of Draping Simulation

For each measurement station, results from the various simulations and optical measurement are compared. By analyzing the differences between both values, the most accurate simulation method can be identified.

After having proved the universal validity of the simulation strategy, the designer will be able to predict the result of a preforming process in the design phase and to transfer the accurate fiber angles to FEM.

> **Dipl.-Ing. Henrik Borgwardt (left), Dipl.-Ing. Arne Stahl (right)**

Compensating Spring-In and Warpage – A straightforward Approach

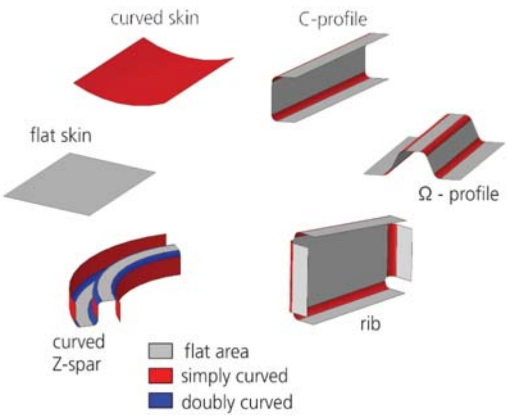


Fig. 1:
Complex geometries can be traced back to simple regular geometries.

One key challenge in composite manufacturing is to get the part within narrow dimensional tolerances. Orthotropic thermal and chemical material properties in combination with production parameters, such as high curing temperatures and elevated pressure, are detrimental to achieve this goal. Due to the complex nature of CFRP structures, current simulation strategies account for a variety of phenomena such as resin cure, chemical shrinkage and heat generation. However, a physically reliable simulation of those effects demands complex and often transient modeling within FEA. High computational and modeling efforts, utilizing solid elements, make such micro-level simulation strategies hardly applicable in an industrial environment.

There is a lack of easy to use, target-oriented simulation strategies, which focus exclusively on production caused distortions, and that can be applied at the part level. Consequentially, extensive experimental investigations have been conducted to determine the main drivers of manufacturing induced deformations. It was concluded that the two substantial contributors, which are responsible for the occurring distortions, are both caused by the anisotropic material properties. First, inhomogeneous material behavior occurs, which leads to spring-in. Secondly, the residual stresses induced by tool-part interaction result in what is often referred to as warpage. The magnitude of each effect depends on the part geometry. Typical aerospace parts, such as spars and stringers, consist of flat and curved areas (Fig. 1). Spring-in deformations could be attributed to curved areas of a part, whereas warpage occurs mainly in flat panels.

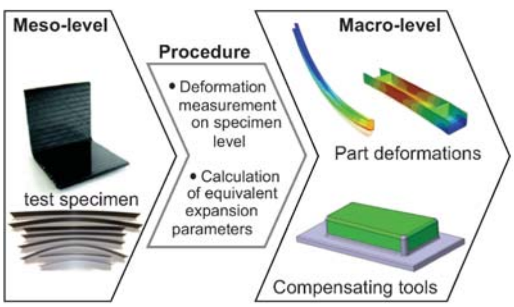
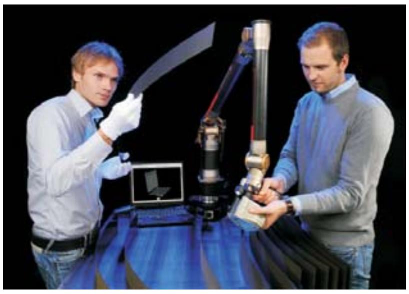


Fig. 2:
Part deformations and compensating tooling geometries on macro-scale are simulated based on meso-scale test specimen.

Semi-Analytical Simulation Procedure

Assuming that the distortion of a complex part can be traced back to simple regular geometries, the developed approach utilizes simple and easily produced test specimens in order to test for the characteristic distortion-properties of the material at hand (Fig. 2). A meso-to-macro approach is applied in the transfer of measured distortions from the test specimen level to part deformations on the macro level. Striving for an applicable procedure that allows the handling of large structures, the developed approach is designed for the use of shell elements. Spring-in of curved sections and warping of flat sections can be regarded as a change in curvature. Thus, one fundamental mathematical model, based on the CLT, is utilized in order to transfer measurement results into corresponding simulation parameters.

Being able to predict manufacturing shape changes allows to design tool geometries that already compensate for the undesired change in curvature. First tests of the developed approach reveal a significant reduction of the spring-in angle of over 95 % for an extruded C-profile.



Benefit of the Developed Strategy

The developed approach represents a structured procedure to counteract production caused distortions. This leads to a significant cost reduction within the tool-design process due to the saving of cost intensive experience based rework steps. Further efforts are planned to confirm and extend first promising results of the presented strategy.

> **Dipl.-Ing. Erik Kappel (left), Dipl.-Ing. Daniel Stefaniak (right)**

Preforming of Next Generation Toughened NCF Materials

In recent years, lightweight structures made from carbon fiber reinforced plastics (CFRP) have gained in importance due to their outstanding strength-to-weight ratio. Currently, entire CFRP primary structures for civil aircrafts are realized. However, the production of CFPR parts causes intense process and material costs. Novel toughened non-crimp-fabric (NCF) and innovative preforming methods have the potential to replace the expensive state-of-the-art prepreg materials and processes. The understanding of the NCF draping behavior provides the basis for a high degree of automation in the production of complex shaped fiber preforms. In addition, the incorporation of reliable toughening techniques will provide superior mechanical properties compared to standard prepreg materials.

Fig. 1:
Draping the rectangular 2D cut out into the shape of a C-frame.

Interlaminar Toughening

Low viscosity and brittle resins are necessary to impregnate dry fiber preforms in Liquid-Resin-Infusion (LRI) processes. In the past, low damage resistance and damage tolerance properties of LRI-laminates prevented the LRI-technology from being used in primary structures. The improvement of the bulk matrix fracture toughness, in most cases, leads to a significant increase of the viscosity. This effect considerably limits the ability of the resin for preform impregnation. The use of interlaminar non woven tougheners made of solvable thermoplastics intends to chronologically separate the impregnation and the resin toughening processes. In fact, simultaneous impregnation of the fiber layer and dissolving of the interleave thermoplastic is hardly avoidable. This can lead to an unpredictable distribution of the thermoplastic matrix content and a poor reproducibility of the impregnation quality.

Fig. 2:
Finished Preform of a generic frame.

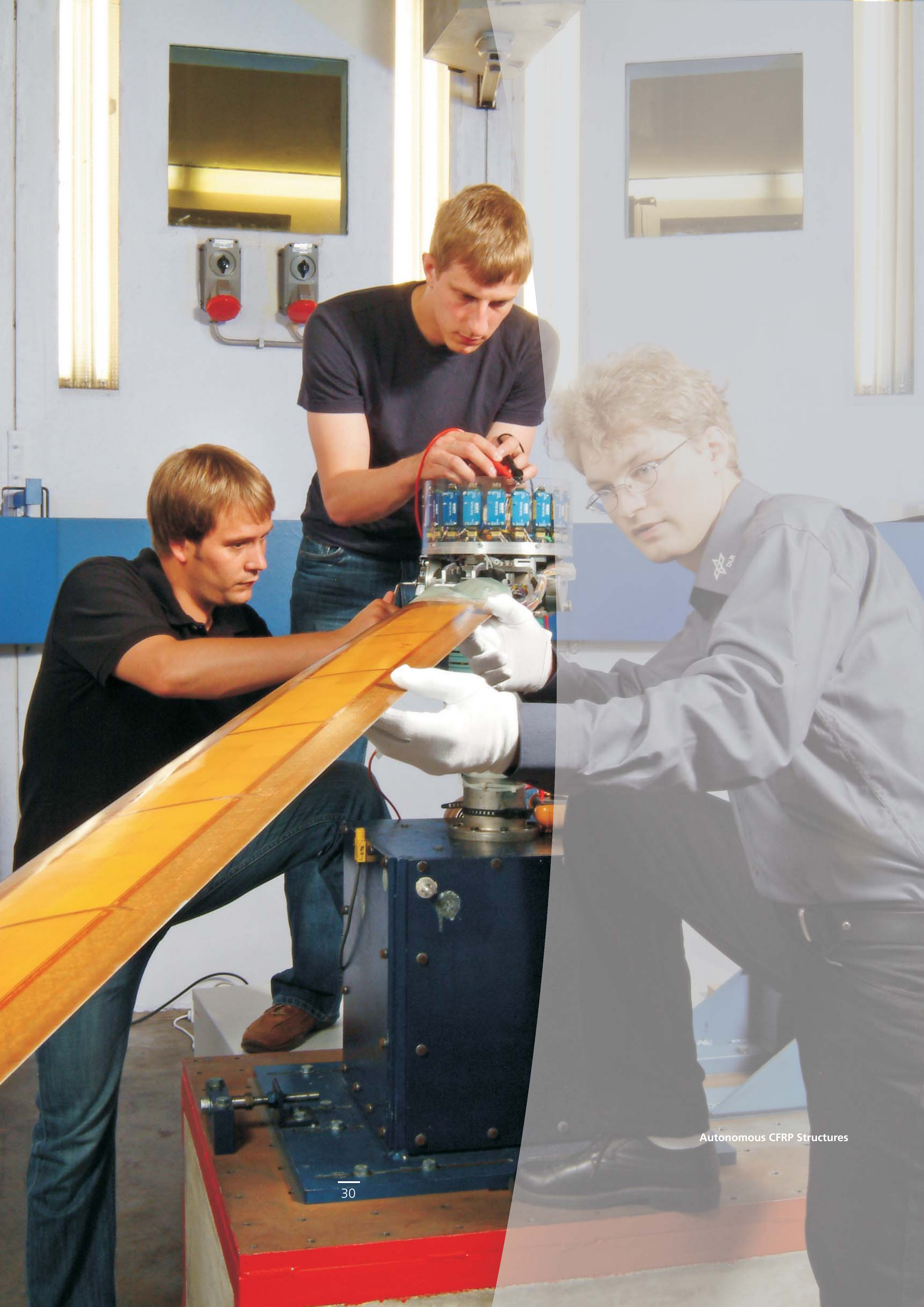
The latest generation of toughened NCF materials incorporates non woven thermoplastic interleave layers between each NCF-layer. The thermoplastic interleave has a melting point above the processing temperature of the resin and is not solvable by the resin. The interleave layers can suppress or delay the occurrence of interlaminar delaminations as well as limit their propagation. Both effects increase the impact tolerance of a multiangle laminate.

Preforming of Complex Frames

Various preforming methods have been tested to understand the preform process of interleave toughened NCF Materials on a macroscopic scale. Preforming of 3D shaped geometries implies a double curvature deformation. This inevitably leads to in-plane sheering of semi-finished material. This shearing has to be controlled during the whole draping process in order to minimize the deviation from the optimal fiber orientation.

Fig. 1 shows the draping process of a fiber layer from toughened triaxial NCF into the shape of a C-spar. In order to achieve maximum performance and reduce scrap material, one piece of a nearly rectangular 2D cut out was used as base material. Constant profiles as well as changing section geometries in longitudinal spar direction were realize with this technique (Fig. 2). The theoretical analysis of our preforming tests will now lead to improved forming devices with reduced fiber degradation, as well as minimization of the processing time and enhancement of the capability to handle multiple fiber stacks.

> **Dr.-Ing. Robert Kaps, Dipl.-Wirtsch.-Ing. Jan Philip Ringert**



Autonomous CFRP Structures

Ultra-Low Power Excitation of Lamb Waves

Guided Waves for Health Monitoring

Lamb waves exist in plate like structures; they can penetrate large areas with small attenuation and interact with defects. Therefore this kind of waves are interesting for Structural Health Monitoring (SHM). A network of glued piezoelectric elements, which is permanently attached on the structure, delivers an excellent performance for a signal excitation and -receiving. A wave interaction (reflection, mode conversion) with a defect influences the received signal in comparison with a baseline, so that damage detection without time consuming scanning is possible.

The number of generated Lamb wave modes is dependant on the product of component frequency and thickness (f*t). For low values of f*t two Lamb wave modes are generated, a symmetric (S0) and an unsymmetrical (A0) one. Higher frequencies generate additional modes like S1, S2,…, and A1, A2,… . Therefore a narrow band excitation signal is required. Usually the excitation is carried out with a 5 cycle tone burst enclosed in a Hamming window. The modulated sinus signal can be controlled by the frequency of the carrier signal and the bandwidth by the number of burst (pulse length). In order to drive the capacity of a piezo element, a linear amplifier is required. Such kind of excitation unit requires a power consumption of several 100mW up to few Watts. For an embedded SHM system the power consumption is important, especially for systems based on energy harvesting.

New Method for Lamb Wave Excitation

The requirements of a pulser module are low cost, simple construction and narrow band excitation in order to generate only one symmetric and one anti symmetric mode. In the communications engineering switched mode amplifiers are used. The efficiency factor is larger than 90 % in contrast to 70 % for linear amplifiers. Power amplifiers of radio transmitters with hundreds of kilowatts are built in this way. Because of the square signal, output harmonics are produced, so that a low pass filter is necessary at the output. The CD4049UBC hex buffers are monolithic complementary MOS (CMOS) integrated circuits, constructed with N- and P-channel enhancement mode transistors. These buffers have no quiescent current, which means that there is only a current flow when they are switching over. A wide supply voltage range from 3 V to 15 V is possible. An operating voltage of 3 V for a low power has been chosen. A parallel connection of two or more buffers increases the output current. It is not useful to connect a piezoelectric element directly to the output of the buffer because of its relative high capacity (8 nF) which gives a reactance. This reactance can be compensated by inductivity. Both elements form a serial resonant circuit. Its frequency should be the optimal frequency for the Lamb wave excitation. For the 2.5 m long CFRP demonstrator with a thickness of 3.4 mm the excitation frequency has been optimized to 34 kHz. A coil of 2.7 mH delivers the desired resonance. Fig. 1 shows the principle of the circuit diagram. The excitation signal with peak amplitude of 9 Vss is displayed in Fig. 2. The received signal in a distance of 2.5 m indicates Fig. 3. The differences between the red and black displayed amplitudes is caused by an artificially defect. The power consumption of the pulser is only 30 µW (3 V, 10 µA). It should be noted that the other buffers of the CD 4049 can be used for the generation of the pulse repetition frequency (100 Hz), so that only one chip is necessary.

> **Dr.-Ing. Wolfgang Hillger**

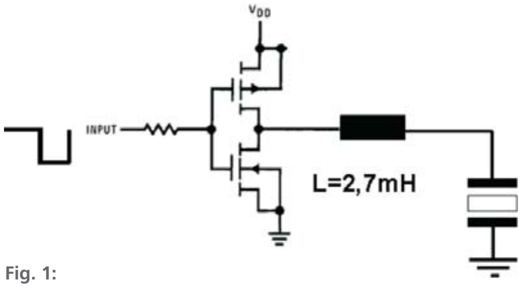


Fig. 1:
Principle of low power excitation.

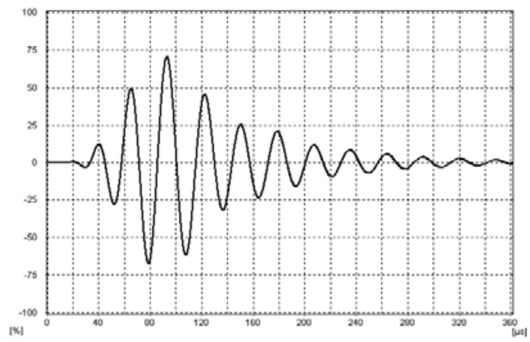


Fig. 2:
Excitation signal measured at the piezoelement.

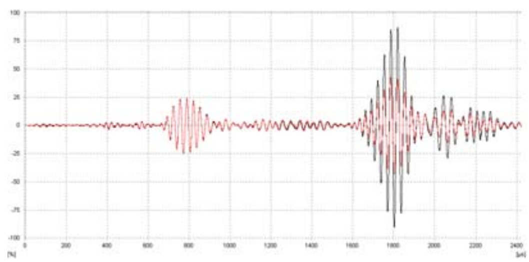


Fig. 3:
Receiver signal in a distance of 2.5 m.

Adaptive Control of a Prosthetic Socket and Adaptation of Running Blade Characteristic

Fig. 1:
Active socket system with piezoelectric patches and amplifier unit.

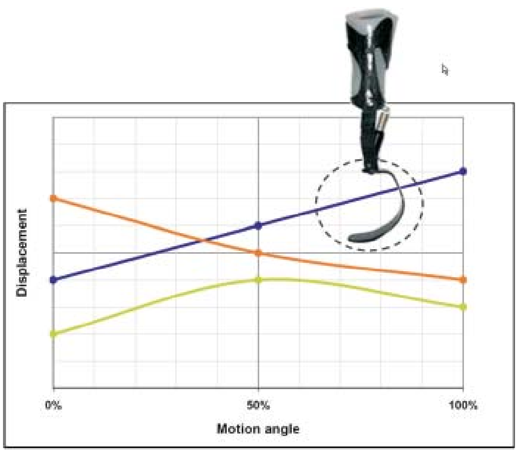


Fig. 2:
Diagram with different exemplary spring characteristics and exemplary blade. (displacement over motion angle).

The first prosthetic systems are reported from the Egyptians, who successfully created toes made from wood and leather. Until the 20th century the used materials were nearly unchanged and prostheses were merely rigid devices. This changed with the availability of new materials, as high performance aluminum, titanium and carbon fiber-reinforced plastics (CFRP), which offer more opportunities for flexible and lightweight structures allowing movements closer to the natural pattern.

Due to the complexity of walking sequence, it is still a challenge to design optimal prosthetic parts. At DLR, two prosthetic parts are investigated, first the socket, which connects the prosthesis with the stump and second a high-tech prosthetic foot has been designed as spring for use in sports.

Adaptive Prosthetic Socket

While flexible mechanic or even active joints are already available, the prosthetic socket is still an inflexible structure. In this respect, this is a disadvantage, because the limb is not as static as the socket structure. While walking, the muscles are moving and changing their geometry and position. These induced misfits usually lead to pressure and friction in the skin, so that the socket always will be a compromise between stability and comfort. To compensate for this, an active socket system is designed and built, that adapts the supporting structure for an improved fit. It consists of two parts, the adaptive socket system including myoelectric sensors and piezoelectric actuators and an electronic unit with controller and actuator amplifier.

For best performance, the socket was modeled with Finite Elements to derive a setup of the CFRP layers capable of carrying the loads from walking and in parallel allowing a good performance of active contour change. A prototype is displayed in Fig. 1.

Adaptation of Blade Characteristic

Today's needs of performance of lower leg prostheses increase not only in the field of competitive sports, but also for a high grade of mobility. Different kinds of foot prostheses are developed for different sport activities. Typical prosthesis foots for running are C-shaped blade foots, which are working like a spring. The performance of so-called running blades depends on parameters like geometry and used materials.

At DLR, the characterization of such running blades gets analyzed and developed. It has been shown, that a motion angle-displacement relation is suitable for that (Fig. 2). The diagram shows the displacement of the blade respectively spring during motion with given load. The distribution of the motion angle-displacement relation has to be adapted individually to the patient and application activity respectively.

For design of future spring protheses, the mentioned motion angle-displacement diagram can be used as direct target function for an optimization algorithm.

> **Dipl.-Ing. Martin Pohl (left), M. Sc. Steffen Niemann (right)**

Robust Bonded CFRP-Repairs by Automated Scarfing

The steady increase of CFRP-Structures in modern aircrafts will reach a new dimension by entry into service of the Boeing 787 Dreamliner. Because of an excellent corrosion and fatigue behavior of CFRP, a decrease of maintenance costs for the overall aircraft is expected. A repair technique for damaged aerospace structure components is the so-called bonded composite scarf repair. Nowadays it is a manually process requiring well trained and experienced craftsmen. The strength of a damaged part is recovered by bonding a composite patch onto its surface. Therefore a continuously decreasing circular contour needs to be grinded out. The time needed for this so called scarfing depends on the chosen scarf ratio (1:30-1:40) and the geometric complexity of the part. Especially double curved and single curved surfaces with stacking changes are time consuming and the process needs four or five times as long as a regular scarf. In order to reduce the time required for a bonded scarf repair and to reduce human impact on repair performance, an automation of the scarfing process is developed.

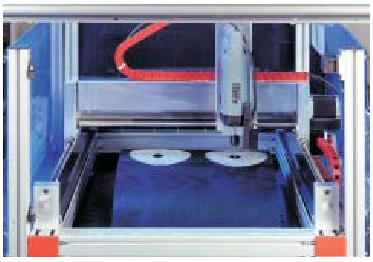


Fig. 1:
Repair scarf machined by CNC controlled milling.

Machining Concept

The proposed machining concept replaces the manual grinding by a CNC-controlled milling of the scarf. The milling is performed by a transportable 720 mm x 400 mm triaxial mill, which is mounted on the repair surface via suction cups. The programming of the machine needs a detailed CAD-model of the repair and especially of the repair surface. Therefore the latter is digitized by a laser sensor, which is coupled to the axis of the machine. The generated data is transformed by an automated surface reconstruction algorithm into a NURBS-surface, which is commonly used by CAD-software. Based on the reconstructed surface and user input on the specific repair geometry, a virtual repair is designed. The model is subsequently used for an automated generation of the machining data. The surface reconstruction can also be used to validate the repair contour by rescanning the machined surface.

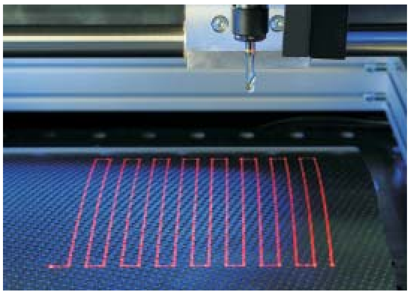


Fig. 2:
Laserscan of surface.

Within a DLR project a commercially available triaxial milling machine is modified and a software environment is developed for the repair worker. The main focus of the work is an easy handling in order to keep the repair process simple. This requires a full automation of the described process. Within the self developed windows based software, the user input is kept to a minimum and is restricted to regular repair parameters like repair size and scarf ratio. The machines interfaces have been modified to make it transportable and quick to reinstall. The usage of a triaxial machine restricts the repair contours to continuous scarf repairs (in contrast to stepped repairs), but the automation concept may also be applied to machines with five or seven axes.

Fig. 3:
CAD-model of DLR's automated scarfing machine.

New Possibilities

The automation of the scarfing process will not only reduce maintenance times for damaged complex parts, but will also allow new scarf contours and shapes. Especially load optimized repairs with varying scarf angles are easy to produce with the machining concept. The chosen design of a simple machining and software concept allows the usage of low cost components. This allows an easy integration into aerospace repair shops.

> **Dipl.-Ing. Dirk Holzhüter (right), Dipl.-Ing. Daniel Schmidt (left)**

A Structure for the DLR-Satellite Asteroid Finder

Fig. 1:
Asteroid Finder in orbit.

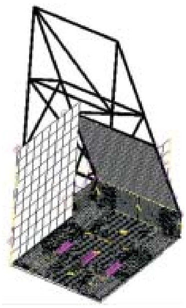


Fig. 2:
Structural model of Asteroid Finder in launch configuration.

Fig. 3:
Thermal and structural test model (hardware).

By now, more than 500,000 asteroids are known in the solar system. Telescopes scan the night sky looking for moving light dots in order to discover the asteroids. Knowing about their existence and their orbit is of great interest to science. It allows to learn more about the formation of the solar system, to test simulating models and to predict and ultimately prevent an asteroids impact on the earth.

Even though most of the asteroids have been discovered during the last two decades, only ten objects are known to stay within the earths orbit around the sun at all times. Their number is so small due to the inability to observe them against the bright sky during daylight. To find an asteroid closer to the centre of our solar system one must leave the lower atmosphere.

After launch in 2014, the DLR-Satellite "Asteroid Finder" will repeatedly take images of the sky close to the sun. Moving objects can be identified by comparing images of the same sky section taken at different times. Whether or not objects are found, the results will greatly help to calibrate simulation models of the asteroid distribution in the solar system and increase our safety on earth accordingly.

Though in orbit the problem of the glaring sky is solved, the image taking equipment (telescope and computers) must be of high quality to find the small and dark asteroids. This leads to several demands on the satellite structure. First it has to carry and protect the fragile instruments at high loads during launch. Then it has to conduct heat from the power consuming image processing computers to the outer surfaces, where the heat is radiated into space. Finally it has to shield the optics from direct sun light, hence it needs a huge cover. At the same time the satellite and mainly its structure has to be light and agile to be able to slew in a short time and take pictures from many different sections of the sky.

A quick slewing, which in this case means 10° in less than a minute, requires a low moment of inertia. This enforces low masses, combined with a high mass concentration close to the centre of gravity. This is solved by combining all electronic equipment in an aluminum box directly beneath the telescope. Although it is heavy, the aluminum is necessary to conduct heat to the outer surfaces of the satellite.

The telescope is surrounded by a framework of very light carbon fiber struts that support an envelope of insulating kapton foil layers. This protects the telescope's structure from the heat of the sun as well as the optics from direct sun and stray light. Furthermore the framework carries the solar panels and communication antennas.

The concentration of the masses, the sophisticated framework and the use of high modulus fiber composites keep the satellite light and agile, being stiff and rigid enough at the same time to withstand the launch accelerations and vibrations.

Currently a smaller sized test model is build to calibrate the thermal simulations and to test different bonding methods. It also serves as a demonstrator for the solar panel deployment hinges.

> **Dipl.-Ing. Olaf Mierheim**

Sustainable Composites Processes

Advanced Automated Fiber Placement Research Platform for Large Composite Structures

Fig. 1:
GroFi – simultaneous operation of two heads on one tool.

With the GroFi-AFP-platform, a production technology for large composite aircraft structures in a combined Automated Fiber Placement (AFP) and Automated Tape Laying (ATL) process will be developed by mid of 2013. The targets of GroFi are

- 150 kg/h fiber mass throughput with only one GroFi-platform
- production of aircraft certified structures
- simultaneous coordinated operation of 8 robot units on a multimould tool
- online path control, online correction, online quality control
- automated vacuum bagging and debagging

Robots are Working Simultaneously While Moving on the Rail System

Fig. 2:
GroFi – stage of completion.

Several tests of the GroFi-platform have been performed already. They proved the full movement capability of the robots on one straight rail, especially in continuous operation mode. The coordinated movement facilities of two robot units have been demonstrated by painting the DLR logo with a pen on a whiteboard. Pen and whiteboard have been mounted on different units for this test. The logo has been painted by the units first with fixed whiteboard and moving pen and then with fixed pen and moving whiteboard. This proves the capability for basic coordinated operations within one NC-file. Currently the system is mechanically set up with its rails and rotary stations. Strategies for different operation tasks have also been developed and validated. Theses tasks include rail switching of robot units, passing of rotary stations and drive system management during the unit movement operations. In addition, basic tests for sensor-based correction of NC-files and the robot trajectories have been done. Future tests will target the simultaneous and automatic movement of 4 robot units within the whole GroFi-platform and its rotary stations.

Clarifying and Resolving Technology Constraints

Fig. 3:
GroFi - team: top row (left to right): Dirk Röstermundt, Christian Ückert, Sebastian Rosskamp, Marcus Perner, bottom row (left to right): Matthias Bock, Chinh Duy Nguyen, Christian Krombholz.

A comprehensive understanding of the behavior of whole systems is required to develop future technology. Besides the process itself, it is necessary to model and control the dynamic transactions between plant components during their movement. This knowledge is subsequently used for optimization of almost every aspect beginning in construction up to path programming.

Acceleration sensors, mounted on a GroFi robot unit, are used to aquire measurements of the dynamic behavior of the system and its components. First measurements have been recorded and assembled already. The ongoing process of data acquisition will be assisted by an autonomous data logger, which will be integrated into a special GroFi travel unit version to track vibrations during defined movement scenarios. Its performance in combination with the used sensors have been confirmed by initial measurements at the test bed wind-up unit in Braunschweig. Additional measurements in Stade already showed the need for suitable vibration isolation and damping concepts. It is planned to use these concepts and the required additional actuators to reach or even increase the aircraft specified laminate quality.

> **Dipl.-Ing. Dirk Röstermundt, Dipl.-Ing. Christian Krombholz**

Dynamic Autoclave Process Control Based on Real-Time Process Simulation

In the project OnQA (Online Quality Assurance in Autoclave Processes) a modern autoclave control system is being developed aiming at higher productivity and part quality at low process cost. It is based on online quality assurance using modern sensor technologies and a real-time autoclave process simulation performed simultaneously during the running production process. All obtained information by sensors and simulation is needed for an open loop control, for process optimization, quality assurance and scrap part prevention. The relevant information to the product quality is acquired during the whole production process by modern sensor technologies installed in the autoclave or mould. The data is gathered in the so-called MASTERBOX and is used to take decisions for updating the process course like skipping to the next process phase or to prevent overheating during curing by adding a cooling phase. The decisions are also based on a real-time Virtual Autoclave simulation, which is currently in development. The simulation is performed in parallel to the real autoclave process and delivers process predictions for different control strategies. The simulation results are evaluated in the MASTERBOX for optimal control strategy selection. Especially the high thermal inertia, the complex convectional heat transfer and resin cure process show the necessity of numerical prediction tools. Furthermore the simulation predicts quality parameters which cannot be measured directly, like residual stress, three-dimensional distribution of temperature and cure degree, chemical shrinkage and warpage.

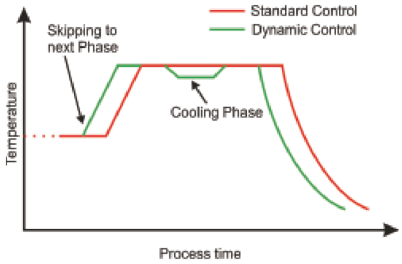


Fig. 1:
Standard and dynamic autoclave control.

Sensors for Process Transparency

Sensors play a fundamental role in quality-assured production. Their objective is gathering the quality related information including relevant process parameters as well as to gain more profound comprehension of the physical and chemical processes inside the autoclave. Special attention is paid to sensors giving preferably direct information about part quality and property. The sensors must be designed for operation under harsh conditions: The autoclave processes take place at pressures at up to 10 bar and temperatures of up to 250 °C . The sensors being developed and tested are amongst others thermal cameras to measure temperature distribution, ultrasonic and dielectric sensors for cure monitoring and pressure sensors to obtain the actually applied vacuum on the composite part.


Fig. 2:
MASTERBOX with data acquisition systems.

Industrial Scale Autoclave Research Platform

To gain a fundamental understanding of industrial processes an industrial scale was considered. The autoclave's usable loading room has an inner diameter of 5.8 meters and a length of 20 meters. It is designed with a high adaptability, modularity and equipped with a high number of interfaces like windows for the application of optical sensors, vacuum and pressure junctions and cable implementation. The autoclave will be operational in the ZLP (Center for Lightweight-Production-Technology) laboratory facilities in Stade in November 2011. This new approach for autoclave process control allows short, flexible and efficient production cycles at a high level of automation, leading to low cost and significant reduction of scrap parts, which is an important step towards complete automated high volume production of composite parts.

> **Dipl.-Ing. Nico Liebers, Dipl.-Ing. Michael Kühn,**
> **Dipl.-Ing. Jens Bölke, Dipl.-Ing. Hakan Ucan**


Fig. 3:
Industrial scale autoclave research platform and OnQA-team.

RTM Processing for Net Shaped Parts in High Quantities

Fig. 1:
Automized Preforming Area.

To introduce CFRP for broader application, reliable processes showing high productivity and quality have to be developed. The combination between resin transfer molding and the automation of accompanying process steps seems to be promising for efficient manufacturing technology. First trials in this technology have already been successfully applied, hence, the scientific challenge is to develop the technology for complex 3D shaped parts and make the process capable for the production of 100.000 parts per year. As automation should help to achieve those goals, new procedures in process controls have to be found. They should assure the quality of the part at each process step. An inline quality assurance is necessary to fulfill the requirement of automation on the one hand and on the other to gain a fundamental process understanding.

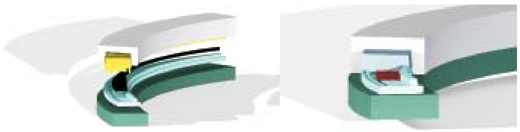


Fig. 2:
Variable Tooling Concept.

RTM Processing with High Production Rates

The quantity of 100.000 parts per year requires a productivity of 20 parts per hour. State-of-the-art RTM-resins in aerospace industry are hot curing single component epoxy-systems with cycle times of 90 minutes and more. A reduced cycle time with standard components requires an optimization of the heat treatment. The approach is an isothermal processing with a downstream tempering process by splitting the curing time between the heated mould and an oven. For this and the purpose of automation, two component resin systems provide better handling qualities compared with single component systems. Hence, the development of a robust process by controlling the process parameters is one of the project's scientific goals.

Fig. 3:
Laser Cut Preform.

Near Net Shape Preforming

To achieve a robust and reproducible RTM-process, it is necessary to retain constant initial parameters. Besides rheological and thermo-mechanical properties of the resin, the preform's quality is of relevance referring to geometry and permeability. This will be obtained using near net shape preforming. Further advantages of this technique are significant reduction of post-processing, such as milling and edge-sealing. A variation of net shape trimming methods is examined and evaluated by focusing on the possibility of industrialization, efficiency and quality.

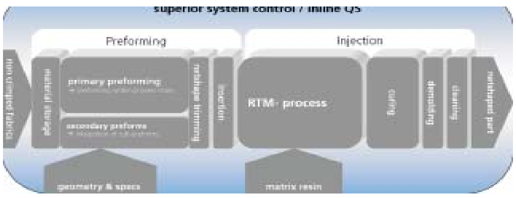


Fig. 4:
EVo-Process Chain.

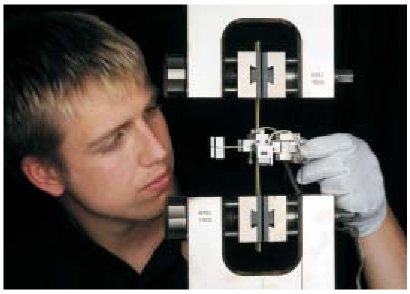
System Control

A benchmark of a process chain in terms of robustness, economy and quality does not only need to consider a partial view on single process steps. Furthermore, the process data of single steps as well as sensor data from the inline quality assurance have to be gathered within a superior system control unit to create a digital life data sheet. The influence between the segmental parameters themselves along the whole process chain has to be implemented by quality, productivity and cost. For the first time a research platform is build to scientifically analyze a complete RTM process for high production rates regarding robustness and productivity and the applicability of various fiber and matrix materials. This platform will provide robust solutions for high rate complex 3D-parts RTM production in an industrial environment.

> **Dipl.-Ing. Sven Torstrick**

Multifunctional Materials

Mission



From materials to intelligent composites!

The department of Multifunctional Materials is doing research on the development, characterization and qualification of advanced fibre composite materials. New materials with superior properties are a prerequisite for technological innovations. Especially the integration of new functionalities is the key to further enhance the competitiveness and application range of composite materials. The collaborative research on composite materials within interdisciplinary and international teams is focused on the following areas:

- integration of new functionalities
- improvement of properties
- advancement of processability
- provision of reliable material data
- qualification of new structural concepts

Based on our knowledge and experience in composite materials we explore new possibilities to enhance the properties and functionality of composites in many aspects. By adding nano-scaled particles the mechanical properties, processibility and fire resistance of composite materials are drastically enhanced. New bio-composite are developed and characterized to offer sustainable and environmentally friendly material solutions. Beyond that, new functional materials with sensing and actuation capabilities as components for adaptive structures are investigated. Sensor and actuator networks are embedded in materials to allow a continuous monitoring of fibre composite structures during production and operation.

Competences

The department of Multifunctional Materials operates facilities for static and dynamic testing of materials and structures. In combination with a well equipped thermo- analysis lab and a long experience in non destructive testing with ultrasound, new material systems from coupon level and beyond can be evaluated. Our competence profile comprises:

- evaluation of new textile semi finished products
- nano-technology in fibre composite materials (nano composites)
- development and characterisation of bio composites
- exploration of smart materials for adaptive structures
- design and characterization of piezocomposites
- development of structural health monitoring (SHM) systems
- non destructive testing with ultrasound (NDT)
- static and dynamic testing of materials and structures)
- thermo-analysis and microscopy

\> **Dr.-Ing. Peter Wierach**

Structural Mechanics

Mission

From the phenomenon via modelling to simulation!

In order to fully exploit the high potentials of composite materials, efficient and qualified structural mechanical methods and tools are increasingly demanded. To cope with this we develop, verify and validate computational and experimental methods integrated in robust development processes from the preliminary design up to the detailed design phase. Within the scope of aerospace, aeronautical, automotive and railway transportation applications our focus is laid upon:

- fast and accurate design, simulation methods and tools
- virtual testing for the entire life cycle
- innovative experimental methods and test facility concepts

Competences

Supported by a highly qualified staff of scientific and technical employees, we bring structural mechanical methods and tools to application for our customers within concurrent/integrated engineering concepts in the following areas:

- strength analysis (e.g. 3D reinforced composites, extended 2D methods)
- structural stability (e.g. postbuckling, imperfection, dynamic buckling, robust design)
- damage tolerance (e.g. failure criteria, impact, residual strength, degradation)
- "Effects of Defects" (EoD) (e.g. fibre waviness and porosity)
- "As Build/Manufactured"-analysis (e.g. AFP feedback loop to account for manufacturing deviations)
- thermo-mechanics (e.g. extended 2D methods, models for fibre metal laminates)
- multi-scale analysis (e.g. global-local or submodelling concepts)
- multidisciplinary simulation (e.g. resin curing, spring-in, piezo-electric-thermal coupling)
- tool integration (e.g. fast, seamless and robust tool-chains for structural analysis and life cycle assessment)
- methods and tools for global aircraft analyis
- test facilities (e.g. strength, thermo-mechanics, structural stability)

An example is our contribution to the European large scale project MAAXIMUS (More Affordable Aircraft structure through eXtended, Integrated, and Mature nUmerical Sizing), where we hold the lead for the sub-project "Design" and give scientific contributions on the topics Effects of Defects (EoD), postbuckling and "As Build"-analysis of advanced fibre placement methods development.

> **Dr.-Ing. Alexander Kling**

Composite Design

Mission

Our design for your structures!

The department Composite Design offers a closed development chain from the first sketch of composite structures, their sizing up to a design for an efficient production:

- preliminary design: Herein, design concepts, an adequate selection of materials, hybridisation, and further aspects specific to fibre composites are being addressed.
- sizing: design concepts are optimized and assessed by using low and high fidelity simulation tools, which also take into account probabilistically distributed material and manufacturing parameters.
- detailed design: In the end the detailed design is realized under consideration of tolerance management, quality assurance and appropriate tool concepts.

Particular emphasis is placed on the design of multi-functional structures, which contain additional features like electrical conductivity, acoustic noise absorption, information transmission etc. besides their required structural mechanical properties.

Competences

From requirements via concepts to multi-functional structures

The department Composite Design proves itself as a strong link between research and industrial application in the following topics:

- door surround structures in future aircraft
- composite-driven design of airframe structures
- CFRP-metal hybrid structures in aerospace applications
- design considering relevant manufacturing aspects, e.g. spring-in effects
- tools and facilities for efficient and economic CFRP-production
- deployable structures in ultra-lightweight space applications
- design of multi-functional lightweight terrestrial vehicles

The closed development chain and the design of multi-functional structures are subject of continuous common research work with our partners.

> **Dr.-Ing. Christian Hühne**

Composite Technology

Mission

The experts for the composite process chain!

To fully exploit the potential of lightweight composite structures it is necessary to have a detailed understanding of all physical and chemical parameters that have an impact on the final component quality. Most of these parameters have to be adjusted during the manufacturing procedure which means that there is a high potential for process optimisation. On the other hand there is a significant risk because inaccurate process parameters will inevitably lead to inacceptable results. To solve this problem our approach is to directly control all crucial production parameters in a way that the outcome of the production process is highly reproducible on the highest possible level. In order to do this different sensors and adequate control strategies for geometrical parameters like e.g. local fibre volume fractions and for structural parameters like e.g. residual stresses are under development to realise smart and mature manufacturing concepts.

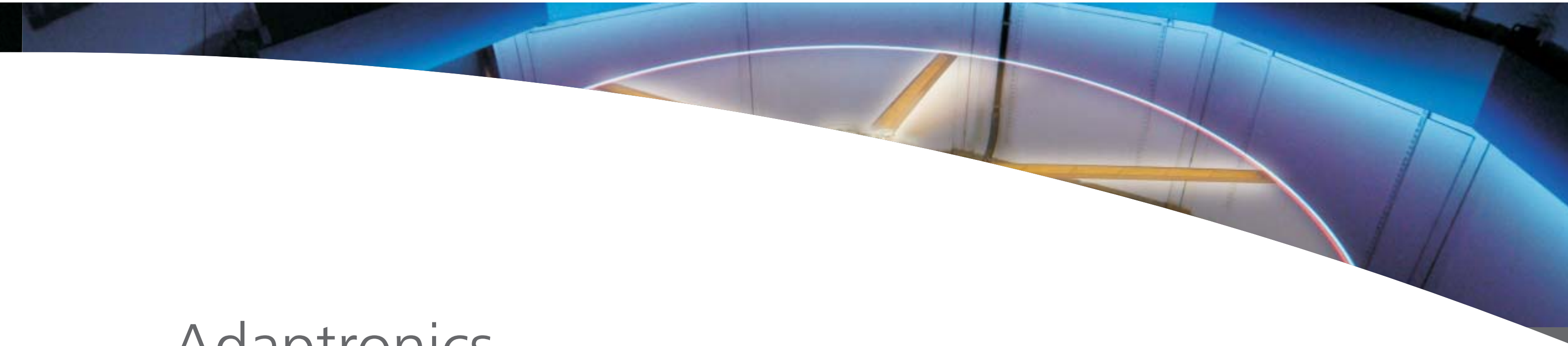
Competences

- development of quality assured process chains for specific production scenarios
- development of production optimised mould concepts
- development of production optimised manufacturing equipment
- manufacturing of demonstrators and test components
- evaluation of innovative fibre and matrix products under processing conditions
- realisation of highly integrated multi-functional components
- cost analyses and trouble shooting for production processes

Even though creating composite components simply means to embed load bearing fibres in a polymer matrix the variety of technical approaches is nearly as multifarious as the field of applications itself. Within the last 30 years all baseline manufacturing processes like filament winding, prepreg lay-up, Liquid Resin Infusion and RTM processing have been considered and further developed in order to meet the demands of the various research and development projects.

To ensure the highest possible productivity in terms of cycle times and reproducibility at acceptable costs the actual focus is on the utilisation of industrial automation equipment for composite manufacturing strategies.

> **Dr.-Ing. Markus Kleineberg**



Adaptronics

Mission

The adaptronics pioneers in Europe!

Since 1989 the department of Adaptronics works as one of the first European research groups on solutions in the field of smart-structures technology. With their experience adaptive systems comprising structural material, distributed actuators and sensors, control strategies and power conditioning electronics across all lines of business can be realised. Applications range from space systems to fixed-wing and rotary-wing aircraft, automotive, optical systems, machine tools, medical systems and infrastructure.

An adaptive system has the capability to respond to changing environmental and operational conditions (such as vibrations and shape change). Microprocessors analyse the responses of the sensors and use integrated control algorithms to command the actuators to apply localized strains/displacements/damping to alter the elasto-mechanical system response.

Within national and international interdisciplinary teams the department of Adaptronics focuses the research on the following areas:

- active attenuation of vibrations (e.g. for parallel robots, antennas)
- active structural acoustic control (e.g. for CFRP fuselages, magnetic resonance tomography)
- morphing structures (e.g. for high lift devices, rotor blades)
- stand-alone systems (e.g. energy harvesting, shunted systems)

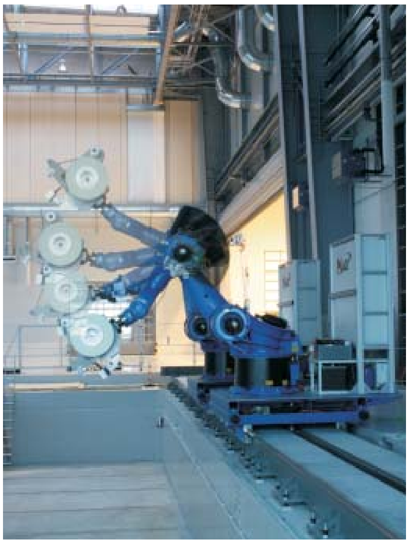
Competences

The department of Adatronics offers its competences to customers and project partners starting from consulting and system analysis up to the design of adaptive systems:

- experimental methods for structural dynamical and vibro-acoustical system analysis
- experimental deformation analysis of large structures
- development of actuator and sensor systems
- modelling and numerical simulation of complex adaptive systems
- controller development and implementation
- system integration and validation
- demonstration of adaptive systems and their components

> **Dr.-Ing. Hans Peter Monner**

Composite Process Technologies



Mission

Research on an industrial scale!

Research on CFRP sustainable and resource efficient production processes is DLR's new approach within the Center of Lightweight-Production-Technology (ZLP) in Stade. It offers opportunities in doing projects by considering industrial requirements in terms of scenarios and scale. By testing and simulation of processes in a full scale dimension, effects can be explored which otherwise could have shown up at later utilization of technology. Hence, the complete process chain could be examined before the industrial realization.

The department of Composite Process Technologies takes part in the ZLP. It provides the scientific backbone of the center in Stade. By doing fundamental research work in the field of advanced fiber placement, automated RTM processes and autoclave technology, production technologies will be developed and tested for application. An interdisciplinary approach between manufacturing engineering, design specialists and machine manufacturers will help to build up competences in the assessment of production chains. The major aim is to find the optimum in production technologies with respect to efficiency, energy and resource consumption, quality and cost and to give a feedback to design, as well as to materials and processes.

Competences

The core competences of the department reflect the application of large scale research facilities:

- first integrated advanced fiber placement and automated tape laying machine
- first fully automated RTM production line
- world's biggest research autoclave
- development and simulation methods to improve the reliability of production processes
- process integrated data logging and data analyzing systems

As CFRP will become more and more important, research has to provide solutions for production, otherwise the breakthrough of this material could not be guaranteed. By obeying needs from various end users, the composite process technologies enhance the interdisciplinary approach to introduce CFRP for a broader application.

> **Dr.-Ing. Matthias Meyer**

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German Aerospace Center

Institute of Composite Structures and Adaptive Systems

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