1. General Introduction

This paper focuses on innovative application of composites in primary aircraft structures. Current developments indicate a significant weight saving potential by using composite materials for primary structures. The aim is to reduce the weight by using composite material and to reduce costs with highly integrated design solutions combined with innovative and low cost manufacturing methods. Over the past years a few new innovative composite designs for complex primary aircraft structures have been developed by EADS Innovation Works. The work has been conducted in a multidisciplinary environment, involving numerous experts from design/stress, manufacturing and testing. As an example, the development of a composite flap rib (1) and a composite landing gear fitting are shown (2). Load introduction and load allocation are particularly critical design aspects for composites; both can trigger undesired matrix driven failure initiated by transverse stresses. In terms of material properties and analysis methods, little is known about the load bearing capacity of thick composite structures. These are investigated in detail and different analysis approaches are presented.

In order to maintain design flexibility during the development process and in order to reduce development costs, the open mold Vacuum Assisted Process (VAP) has been chosen. All parts are manufactured with this process and afterwards validated in full scale fatigue and damage tolerant components tests.

It is shown that complex primary aircraft structures can be designed for composite materials. The new designs even provide certain weight and cost benefits.

2. Analysis of Composite Fittings

Conventionally the classical laminate theory (CLT) is used to analyze laminated structures. The CLT however does not incorporate the influence of transverse shear and normal deformations. First- and higher order shear deformation theories have been proposed to improve the determination of transverse stresses, see Chang et. al (3) and Jing et.al. (4). Initial finite element investigations are conducted with 2D shells, in order to evaluate the behavior of composite fitting and joints. Different software packages provide a variety of elements with composite material options. For the analysis of compact composite components subjected to high loads it quickly becomes obvious that a 3D analysis is required in order to achieve satisfactory results, especially if significant transverse stresses are expected. Of special interest for the conducted calculations is the isoparametric 3D composite brick element provided by several software packages, such as Abaqus and MSC Marc/Mentat. For each layer different material properties can be applied. It has been previously shown by Kuhlmann and Rolffes (5) that this type of stacked brick element provides reasonable result for transverse normal stresses. Transverse shear stresses and however contradict the exact solution on a ply level since the step like
displacement distribution over the thickness of the composite element cannot be reproduced, see also Figure 1.

Figure 1The accuracy of the calculated shear stresses can however be increased by using higher order shape functions. That is, elements with more nodal points through thickness, as suggested by Chang et. al. (3). A reasonable transverse shear stress distribution over the thickness of the structure can also be achieved with a discretization that features multiple elements over thickness, an approach chosen for the analysis of UTL. Hence this type of element presents an efficient way to model ultra-thick laminates that feature a large amount of layers since a layer wise discretization can be avoided.

Figure 1: Deformation of composite brick element.

In addition to the used 3D approach, methods have been presented in the literature to use 2D shell elements to obtain transverse stresses using the equilibrium equations, see Rohwer and Rolfes (5). The approach is implemented by Kuhlmann and Rolfes into the software package TRAVEST. 2D FE models offer far greater flexibility to design changes and usually require less computational resources. The 2D approach can be regarded as suitable for many structures where the thickness of the component is relatively small but where transverse stresses still are expected. Even for first assessments and the concept phase of thicker structures this approach can deliver good results with little effort. For more progressed design steps of UTL a full 3D analysis is however advised in order to accurately calculate 3D stresses.

In addition to brick elements, continuum shell elements can be used. These provide all stress components with an enhanced formulation for the transversal shear stresses. Since delamination is a common type of failure for composite load introduction, the transversal shear and peel stresses are of high interest

3. Composite Load Introduction Rib (LIR)

The flap is part of the wings high lift system. It features a Load Introduction Rib (LIR) and a drive rib with integrated lugs for the attachment of the flap to the support structure of the wing, see Figure 2.

Figure 2: Typical wing cross section with flap and load introduction rib

The differential metallic design, consisting of C-ribs with riveted load introduction fittings is substituted by an integral composite rib, as shown in Figure 3. By applying constant thickness to complex sections of the component, manufacturing costs can be decreased. Thickness variations are however applied to less complex sections of the preform.
Figure 3: Innovative composite load introduction rib

The new design consists of an Omega-shaped composite rib, with integrated U- and L-profiles in the attachment regions. The flap is actuated by a drive arm located at the side of the load introduction rib. It currently consists of an external metallic bracket, which is attached to an internal metallic fitting. Both the bracket and fitting are also substituted with composite designs. The calculation of composite load introduction requires the implementation of 3D-elements for an accurate analysis of all composite stress components. For the LIR, this is achieved by the use of 3D continuum shell elements, which provide all stress components with an enhanced formulation for the transversal shear stresses. Since delamination is a common type of failure for composite fittings, transvers stresses are of high importance. The load introduction rib is attached to the surrounding structure (2D-elements) with rivets. These rivets are implemented as elastic connectors (1D Elements) in conjunction with rigid body elements, see Figure 4.

Figure 4: Design process for new composite load introduction rib

The HYPERMESH pre-processor is used for the set-up of the finite element model due to its enhanced capabilities in 3D meshing and extensive support of different solvers, see Figure 5. For composite fittings, delaminations are more common than in-plane fiber failure. This type of failure is commonly induced by discontinuities such as free edges, ply run outs and gusset fillers. An accurate discretization of these regions is therefore essential.

Figure 5: FE model of flap with integrated load introduction rib

Abaqus is used for the numerical investigations, using elements with a composite material definition. Several load cases are calculated with the Abaqus implicit solver and post-processed with Abaqus CAE. In addition the LIR is calculated with a 3D composite failure criterion by Cuntze (6). This action plane based failure criterion allows a precise analysis of matrix failure under combined inter- and intralaminar stresses.

Figure 1: Composite Load Introduction Rib and Drive Fitting

For the thinner rib area, damage tolerance criteria have to be applied with a high limitation of allowable strains. By using these strain limits a damage or delamination growth, by foreign object impact is highly unlikely. The thick composite lugs are sized for ply failure around
the shaft with sufficient reserve. Impacts on thick lugs usually do not inflict a ply failure, but rather a local delamination. The lugs are designed fail safe and all parts are attached using rivets. In case of a delamination growth, all components are still able to transmit loads into the flap. It is shown that the in-plane as well as the transversal stress components are uncritical for the new composite design, see Figure 6.

Figure 6: Strain results of composite load introduction rib

Additional extensive analysis of each rivet shows sufficient strength for the connection of the load introduction rib to the surrounding structure. The analytical calculation of the composite lugs is done with the approach in the following chapter.

4. Composite Side Stay Fitting

Another example of a radical composite design is the otherwise all metal main landing gear fitting, the so called Side Stay Fitting (SSF). The component is designed in carbon fiber reinforced composites (CFRP) in the framework of the EU project ALCAS (Advanced Low Cost Aircraft Structures, (7)). Due to the massive loads (up to 180 tons) and the compact dimensions, the component features wall thicknesses of up to 90mm, compared to a maximum height of the component of approximately 700mm. The aim is to reduce the weight of the component but also to provide a distinct cost benefit, in accordance with the overall project goal. Two prototypes of the fitting are produced, see Figure 7. Based on the gained manufacturing experience the cost benefit is evaluated for a possible serial production. An adapted version of the vacuum assisted process (VAP) is developed in order to maximize flexibility during the development phase of the component and to reduce the development costs in total. Using the process, a large number of components are manufactured for an extensive test program. In addition two full scale prototypes are manufactured. The entire manufacturing process is continuously optimized and refined. The gained experience is implemented and combined in a final study of a serial production of the CFRP fitting. In a final step the gained figures are compared to data from the standard metallic fitting. For the Side Stay Fitting an uncomplicated topology is developed, suitable for the manufacturing in carbon fiber reinforced plastics. This was found to be a fundamental condition for a successful completion of the task, and the design can hence be categorized as manufacturing driven.

Figure 7: Second Side Stay Fitting prototype with asymmetric lug thicknesses, mounted to a demonstrator display unit.

The FE analysis is performed with stacked composite brick elements, utilizing the standard FE code MSC.MARC (8) with the standard pre- and post-processor MSC.MENTAT. Highly loaded composite fittings suffer from load insertion and load allocation problems. The load insertion often requires a hole in the laminate,
creating a discontinuity. Free edges are created causing substantial stress concentrations. In addition, the loads have to be distributed away from the load insertion area into the adjacent structure. This will add to the shape complexity of the component and usually results in unfavorable shapes, such as curved sections and sharp corners. Here pure in-plane stresses are transformed into transverse stresses with low allowables. A typical load case is illustrated in Figure 8 and Figure 9.

Figure 8: T-Section test setup.

Figure 9: T- cross section under axial load.

4.1 Manufacturing

For thick and ultra-thick laminates a new derivative of the standard open mold vacuum assisted process (VAP) is used, see also (9). Curing thick composites and thus large amounts of resin potentially leads to an uncontrolled thermal event due to the large amount of exothermal heat generated by the chemical process. Thus, a new process, referred to as ‘integrated tooling’ is applied, as described in (10). Here the laminate is manufactured in steps, where essentially dry fibers were applied on top of cured but not tempered sections until the required thickness is reached. The SSF is manufactured with non-crimped fabric (NCF) and the RTM6 resin system. The standard curing cycle is adjusted (reduced temperature) to prevent overheating. The SSF manufacturing process can be split into the manufacturing of the sub-components and the assembly of these, to form the final fitting. In general there are three different folding processes, one for each sub-component of the fitting, as shown in Figure 10. None of these folding processes creates a fiber overlap. The center section however will create an enclosure due to the spring back effect. Demolding is facilitated by using an adjustable tooling. The dry NCF fabrics are consolidated, infiltrated and cured to reach a thickness of 30mm. In a second step additional plies are added on top of the precured sections, until a total thickness of 45mm is reached. The process is hence referred to as ‘integrated tooling concept’, since the pre-cured laminate serves as a tooling for the next portion of the dry fibers. Finally all sections are arranged in an assembly, infiltrated and cured again for the inner dry NCF. The entire laminate is tempered in a final stage.

Figure 10: Stepped manufacturing of ultra-thick laminates.
5. Process Induced Deformations and Process Optimization

Several manufacturing trials are conducted in order to validate the process and to avoid uncontrolled thermal reactions. For that purpose the manufactured samples are equipped with temperature sensors. Figure 11 illustrates the first manufactured UTL samples. For the infiltration the RTM6 resin system is used and the generated temperature plots are deployed to adapt the standard cure cycle. Especially thicker samples indicate that the generated heat during curing quickly renders the cycle out of control. A new cycle is characterized by a reduced cure temperature with a longer cure phase. Samples with a thickness of up to 80 mm are manufactured in one shot. In addition spring-in tests are conducted with the new cure cycle.

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\Delta \theta(t) = \Delta \theta_{TE} + \Delta \theta_{CS}
\]

Here ‘TE’ stands for thermal expansion and ‘CS’ for the cure shrinkage. There are numerous parameters with significant influence, such as the interaction with the tooling and possible material imperfections. These have to be understood in order to achieve required tolerances. The final fitting consists of several individual components that are joined in a final process. Each component introduces shape distortions that have to be accounted for in the design of the tooling.

To quantify this effect and to evaluate if the spring back angle is reproducible, curved NCF components are produced. The parts are manufactured with the standard VAP method and on an adjustable metal mold, as illustrated in Figure 13. Debunking is performed in four steps with 40 layers of NCF with a quasi-isotropic orientation with 39 layers of binder fleece.

![Figure 12: Process induced deformations.](image1)

![Figure 13: PID tool.](image2)

The investigation has shown that the spring back angle is reproducible and constant with 1° for the applied process parameters. No significant fiber distortions are identified after curing. Fiber undulations, or fiber waviness, have been shown to have notable influence on the behavior, see Chun et. al. (11). These undulations which are undesired in the radius due to the presence of normal stresses, are also reduced to a minimum due to several debunking steps.
Figure 14: First L-corner for spring-in investigation.

The process is analyzed and the curing process is optimized. It is found that the process may either be optimized to minimize spring-in effects, or to reduce the manufacturing times. An example is given in Figure 15, which illustrates a slightly optimized cure cycle for a 30mm thick curved laminate. The initial cure temperature is increased in order to rapidly initiate the resin cure. Afterwards the temperature is reduced in the actual cure phase to reduce the temperature difference which causes a major portion of the spring in. According to the calculations spring-in is reduced by 25%.

Figure 15: Optimized curing cycle for spring in reduction.

6 Cost and Weight Assessment

6.1 Cost Reduction

For the presented load introduction rib a cost reduction of approximately 5% is calculated for the composite solution with all metallic fail safe parts compared to the all metal solution.

For the example of the Side Stay Fitting, ultra thick laminates provide a significant cost benefit of 20% compared to the metallic counterpart. For the cost analysis lessons learned from the prototype manufacturing are used to analyze a possible serial production of the composite fitting, see Figure 16. The metallic fitting in its original shape is not directly transferable to the CFRP design. Thus for the new CFRP fitting a suitable topology and manufacturing process had to be developed. This is found to be a fundamental condition for a successful completion of the task, and the design can hence be categorized as highly manufacturing driven. It should also be mentioned that although the open mold VAP process does provide distinct benefits for the development of a component, a closed mold process such as RTM might be beneficial for a high volume production rate. But, considering the fact that composites are classically used for thinner and shell like structures, it does seem encouraging to provide such a distinct cost and weight benefit for a compact and highly loaded fitting manufactured in CFRP.

Figure 16: Comparison of the production costs of the SSF, related to the initial productions costs of the prototype
6.2 Weight Reduction

With the innovative and integral design of the composite load introduction rib a weight reduction of over 30% is achieved. In addition the thermal stresses by the former hybrid designs are eliminated.

For the Side Stay Fitting, a weight reduction of 6% is achieved for the prototype. An optimized design achieves a weight reduction of 18%, see Figure 17.

![Figure 17: Weight comparison of standard metallic fitting and CFRP counterparts, first & second prototype](image)

**Conclusions**

The lack of out of plane material properties is a serious shortcoming for the design of UTL. Most failure modes are driven by transverse normal or shear stresses. A test setup designed for out of plane testing is proposed by M. Arcan et.al (12)), see Figure 18. A modified version of the rig is deployed by D. Hartung et.al (13) and J.Y. Cognard et.al. (14). A significant reduction in material strength is expected, primarily caused by manufacturing defects such as porosity, and thermally induced stresses, as shown by Shepheard et. al. (15). Based on these findings additional test are currently being planned.

![Figure 18: ARCAN test samples.](image)

If reliable 3D materials are available, the overall test effort may be reduced significantly, thus reducing development costs. Within the aircraft industry, composites are increasingly becoming the subject of interest for compact structural components.

The weight and cost potential of ultra-thick laminates (UTL) used for a compact structural component is demonstrated. The FE- analysis has proven to be a usable tool even for extreme laminate thicknesses of up to 90mm. For that purpose several isoparametric brick elements are used to gain a stress distribution over the thickness of the laminate.

Compact and highly loaded composite structures have shown their potential and in combination with improved analysis and test methods are destined to be part of any major aircraft program. The behavior of thick composites can only be fully understood by using a combination of empirical tests and improved analysis methods. Every test increases the costs of the project. Hence it is necessary to quickly improve the analysis capabilities in order to minimize the development costs. Early studies are conducted with standard 2D composite elements. However the results quickly indicated the need for a full 3D finite element analysis. But, in order to be able to assess the results from a 3D analysis, the performance of available element types has to
be investigated and verified with empirical results. For the manufacturing program two major goals are established; providing test samples for validation and developing and optimizing the manufacturing process itself.

References