Holistic development of high-quality composite parts based on automated preforming

The reduction of production costs and the realization of lightweight targets for composite forming parts can only be successfully achieved by thinking and planning quality aspects in an integral way. Using the example of automated preforming, this article introduces a holistic development approach that covers process selection and process design as well as error detection and mechanical analysis of manufacturing effects on part performance.

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In series production of composite parts, some of the most important challenges are quality, reproducibility and reliability. Fabric forming technologies show a high potential for automation and are suitable for medium- to high-volume production when they are combined with liquid composite moulding (LCM) processes.

Quality issues as reasons for increasing cost and weight
The preforming process step plays an important role in overall quality issues. The defects that occur at this stage can lead to the rejection of whole preforms, influence the subsequent process steps or result in tool damage due to folds and wrinkles. Beyond that, geometries that are not suitable for composite forming can cause time-consuming modification loops of the manufacturing tools. Furthermore, the fibre angles and other quality aspects that dominate the final mechanical properties are revealed only after forming on the geometry. Since the actual preform quality and its structural impact are typically unknown, composite parts tend to be overdimensioned to compensate the uncertainties related to part quality. Fibre sliding, fibre waviness or the loss of structural integrity of the fabrics have a direct influence on part performance, but are rarely taken into account at the initial component dimensioning stage [1]. Therefore, a holistic quality approach contributes not only to the reduction of production costs, but can also improve the weight saving potential and structural performance if already embedded at an early stage of part and process design.

Optimizing and ensuring quality by holistic approaches
For high-performance composite parts, there is a strong interaction between the manufacturing process and the lightweight design objectives. The sooner these dependencies are considered in the overall development process, the faster the development cycles for new parts and products can be.

Fig. 1: The four pillars of quality improvement using the example of automated preforming
The approach presented here for the holistic quality optimization of composite forming structures is based on four pillars: process planning, manufacturing, defect analysis and structural analysis, where each field requires an exchange of information with the other ones (figure 1). In this context, local quality criteria for preform production result from numerical analysis since global limiting samples do not meet the complex stress behaviour in composite materials.

**Quality planning using software-aided methods**

For CFRP forming processes, the achievable quality depends on the interaction of geometry, fabric and process and is strongly coupled to the resulting mechanical material properties. These complex interactions have to be taken into account during the planning stage to ensure optimum solutions.

Database tools can provide the required process knowledge for a bottom-up process selection but cannot replace detailed studies with coupled process and part simulation. For preforming processes, this is done using draping simulation [2]. Beyond the knowledge related to possible optimization strategies within the process, this also requires meaningful material characterization at the fabric level. Figure 2 shows examples for shear, binder and interaction characterization. Based on experimental measurement of the fabric integrity and the assessment of formability, the draping characteristics of different fabrics can be determined and the producibility of a part can be studied using simulation methods [3].

**Achieving quality through part-specific process development**

To guarantee fast process development, module-based morphological methods are used. This leads to high transparency and cost control for the customer and helps to build up a systematic development process as early as the planning phase. For example, the degree of automation and the quality demand can be adapted to the customer and part requirements. Many solutions can be integrated to improve the part quality (e.g. active material manipulation systems and tool design [4]). The benefits are particularly evident for components that previously were manufactured using a cost-intensive prepreg process. These components can now be produced efficiently for a lot size ranging up to 10,000 parts/year with simple automation solutions using high-quality preforming of textiles and subsequent liquid resin infiltration. Especially, process design and layer sequence show a huge influence on the achievable preform quality. Using the example of multilayer draping of semi-finished fabric parts on an L-shaped geometry, figure 3 shows two preform results without (A) and with (B) a “tailored drape” active material guiding system [5]. The area with heavy fibre waviness in the central part of preform A can be reduced significantly by adapting active process control and by changing the component design. The use of ply-specific material manipulation systems and active friction reduction in multi-layer forming proved effective, particularly for complex-shaped geometries, highly stressed components and visible surfaces [4]. Automation is only applied where it is useful for part quality and, therefore, the specified high quality can be achieved at minimum cost in small- and medium-volume production.

**Quality measurement and defect analysis**

To assess the preform quality resulting from different process variants during the development stage and in series production, relevant features are measured on the formed part. A robot-based optical sensor for preform analysis is used for this task, which was developed at the Institute of Aircraft Design in Stuttgart in cooperation with FIBRE in Bremen [6]. The system allows automated, high-quality capture of the surface texture of complex part geometries and the
subsequent detection of fibre angles, waviness or gaps based on image analysis (figure 4).

The process chain for 3D preform analysis covering the whole part surface consists in a virtual image planning and robot programming step, the optical capture of the part and the subsequent mapping of measured fibre angles to a customer-specific FE format for visualization and processing (figure 5). This means that the measuring results are available in the same format as the draping simulation results, so that they fit perfectly inside existing CAE process chains. Preforms A and B of the L-shape are captured and compared using the system (figure 6). The influences of process handling on the resulting shear angle of the formed fabric become visible and assessable. Therefore, the system helps improve the development processes for CFRP parts as it enables accurate evaluation and documentation of fibre orientations. Furthermore, it is suitable for quality assurance within series production and scatter analysis during preform manufacturing.

Quality assessment with numerical simulation
Using numerical simulation methods, the influence of preform quality on mechanical performance can be evaluated at an early stage without extensive experimental testing. Therefore, the measurement results of the 3D preform analysis are mapped directly into the FE model. The boundary conditions of a numerical test case using the example of the L-shaped form are shown in figure 7, using the fibre angles from the preform measurement. As a reference, an additional model with idealized fibre orientations is considered, where process influences are neglected. This simplification is typically used during part dimensioning today.

The evaluation of maximum ply stresses in the transverse direction (figure 8) clearly shows the influence of draping. While the model with idealized fibre angles predicts very low transverse stresses, the fabric shearing caused by draping in preforms A and B leads to stresses of about 25 MPa in the transverse direction, which is already a critical level for the appearance of inter-fibre failure.

The improved quality of preform B leads to lower ply stresses and less displacement under loading conditions. The latter is about 20% lower compared to preform A and about 10% lower compared to the idealized model with projected fibre angles (figure 9).

This example demonstrates the necessity to consider real fibre angles in the structural simulation of composite parts, as they strongly influence the overall structural behaviour and the anisotropic ply stresses. However, an idealized approach can lead to serious risks during part dimensioning. Using failure models, the real fibre orientations can be applied in a similar way to improve strength and damage prediction in crash simulations [7].

Summary and outlook
Holistic approaches for part and process development are required to establish
CFRP as a lightweight material with high quality standards suitable for series production. This was demonstrated here using the example of automated preforming. Close coupling of part development, composite manufacturing, failure detection and structural analysis provides a basis for high quality, reliability and optimum use of the weight saving potential. At the same time, this enables the customer to reduce production costs. Based on the present process development knowledge, low-cost automation solutions can be provided even for small- and medium-volume production. The combination of optical preform analysis for the assessment of quality and numerical simulation creates the opportunity to define local quality criteria that suit the nature of composite materials. This leads to a greater degree of freedom for active process design and lowers the requirement for cost-intensive quality improvements in zones with minor structural sensitivity against process influences.

References

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