MAI SKELETT / MULTISKELETT A NOVEL DESIGN PHILOSOPHY BASED ON TRUSS ELEMENTS

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1. Introduction

Automotive composite structures are often designed as thin shells and fabricated from non-crimp fabrics (NCFs), which inevitably suffer from significant scrap during cutting. To overcome this problem, a novel design philosophy was developed within the BMBF funded excellence cluster projects MAI Skelett and Multiskelett, which features an assembly of unidirectional fiber reinforced thermoplastic truss elements in combination with a thermoplastic injection molding. While the truss elements serve as the primary load carrying members within the part – much like a composite framework – the introduction and distribution of loads as well as stability are accomplished by the surrounding thermoplastic structure. The trusses can be manufactured by pultrusion using cost efficient heavy tows and easily pre-formed to their final shape, this minimises scrap and hence recurring costs of the overall process. Within this study, we investigate different aspects of this design approach using a composite windshield panel as a demonstrator part, which is shown in Fig. 2. In a first step, the structural analysis methodology was adapted to allow for robust sizing of the part. Subsequently, through the extensive application of numerical optimization techniques, the overall part topology was determined for maximum weight benefit under predefined manufacturing restrictions. An automated manufacturing concept was developed, which guarantees reduced cycle time and costs compared to the existing benchmark part.

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2. SKELETON DESIGN PHILOSOPHY

The skeleton design philosophy is based on three lightweight design construction methods:

1. 3D truss design
2. Local reinforcement
3. Tailored fiber placement

The reference design consists of two CFRP shell parts connected to a closed beam. In the same design space, we positioned four unidirectional fiber reinforced thermoplastic truss elements. These elements are positioned, such that there is no undercut for the following injection molding process and for a good bending performance. These elements are interconnected by a thermoplastic structure, which is responsible for the torsional stiffness and shear force transmission.

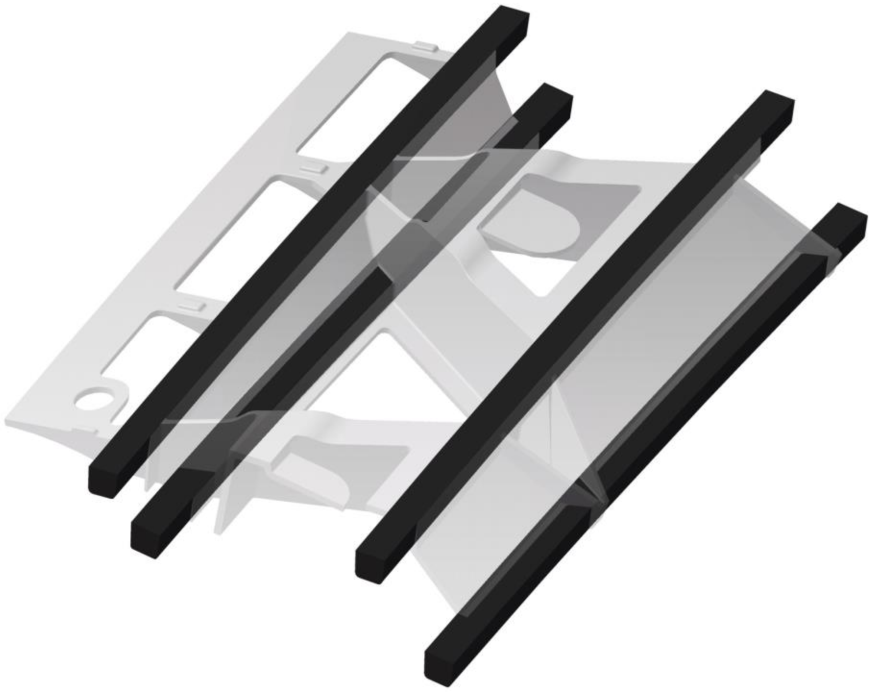

Figure 1. Skeleton Design Philosophy

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3. THE SKELETON DESIGN PART

We realized a composite windshield panel as a demonstrator part to have a direct comparison with a conventional CFRP shell based design.. The design space remained the same as in the reference part. The part considered also junctions for the roof; windshield; sideframe and sun shield. Already in the concept phase production-related concerns, like positioning of the truss elements in the injection molding tool during application and the molding were considered.

Figure 2. MAI Skelett windshield panel.

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4. PRODUCTION TECHNOLOGY

There are three process steps for the production of a part in skeleton design:

- thermoplastic pultrusion
- forming of the truss elements
- injection molding

The big challenge for the thermoplastic pultrusion process was to use 50k rovings and the big cross sectional area of the truss elements. In further improvements the quality of the impregnation was optimised.

In subsequent workshops, a concept on the forming process of the truss elements was developed. We implemented a method to stretch the fibers during the forming process. Due to the thermoplastic resin, very high degrees of deformation are possible during the forming process of the truss elements. Filling simulations lead to improvements in the injection molding tool concept because of the high viscosity of the molding materials with high fiber content. Another important focus of the work was to deposit the truss elements in the tool. All these process steps were automated. When we heat the truss elements for the forming in a paternoster oven, we can reach for all 3 steps a cycle time of 75s.

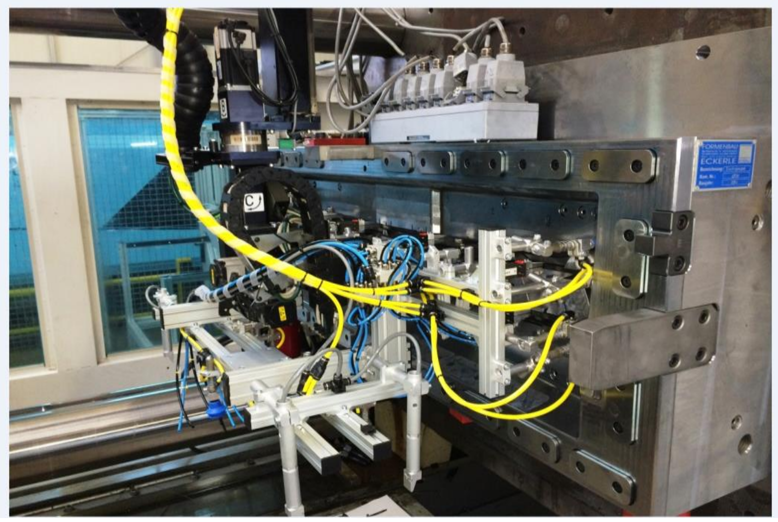

Figure 3. equipment to applicate truss elements in the injection molding tool.

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5. PERFORMANCE

For performance tests, we compared the skeleton windshield panel with the reference part in dynamic and quasi-static 3-point bending and compression tests. In all tests, we outperfomed the results in terms of maximum force as well as energy absorption of the reference design. However, the skeleton design has a lower torsional stiffness.

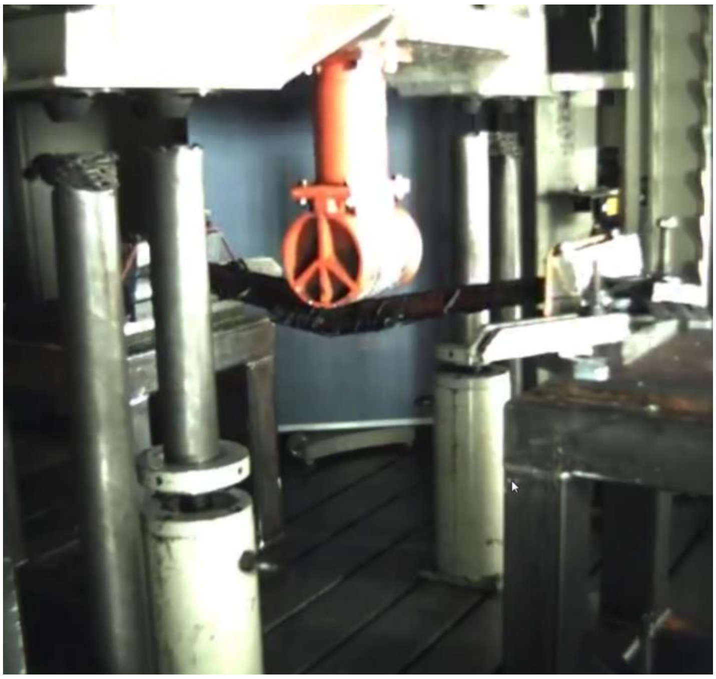

Figure 4. dynamic 3-point bending test.

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6. OPTIMISATION OF THE CRASH POST-FAILURE BEHAVIOUR

This composite windshield panel is a complex component especially when it comes to its post-failure behaviour. A clear understanding of the post-failure behaviour of the presented composite framework, which is an assembly of unidirectional fibre reinforced thermoplastic truss elements in combination with a thermoplastic injection molding, is fundamental for optimising it.

Using CAE, we are able to do so. Throughout the whole project the CAE-model has continuously been improved and calibrated by hardware-tests. One of the main challenges was a realistic modelling of the connection between the trusses and the injection molding. At the end of this process there was a well-fitting simulation that allowed us to make accurate predictions about the post-failure behaviour of the windshield. This is the base for a reliable optimisation.

In general, the optimisation of structural parts consists of an objective function, which will be minimized or maximized, and some additional restrictions such as a stiffness constraint, geometrical boundaries of a given design space or manufacturing constraints.
Depending on the load case the requirements for the considered composite framework can vary greatly. Nevertheless, there are three things that are necessary for all possible load cases:

1. Avoidance of a complete breakthrough of the windshield panel.
2. The remaining load carrying capacity should be as high as possible.
3. The maximum stiffness should be within a given range.

Furthermore, the choice of the design variables within the optimisation could be the particular thicknesses of the framework, the materials used (especially the percentage of carbon fibre within the injection molding as well as the choice of the matrix) or both combined.
Based on the above mentioned requirements and the design variables, the optimisation was performed by coupling the explicit FE-Solver Abaqus with the numerical optimiser DAKOTA.

In this project the maximisation of the remaining load carrying capacity was used as the objective function. Furthermore, the avoidance of a complete breakthrough of the windshield was defined as a global constraint within the optimisation as well as some specific restrictions regarding the design variables, such as a minimum and maximum thickness.

The achieved results are impressive regarding the crash post-failure behaviour of the windshield. By changing only a few particular thicknesses of the framework the remaining load carrying capacity could already be increased by 130% compared to the original design with a constant high performance of the windshield. Additionally, by adding the material as a design variable, a 250% increase in the remaining lifting capacity was achieved.

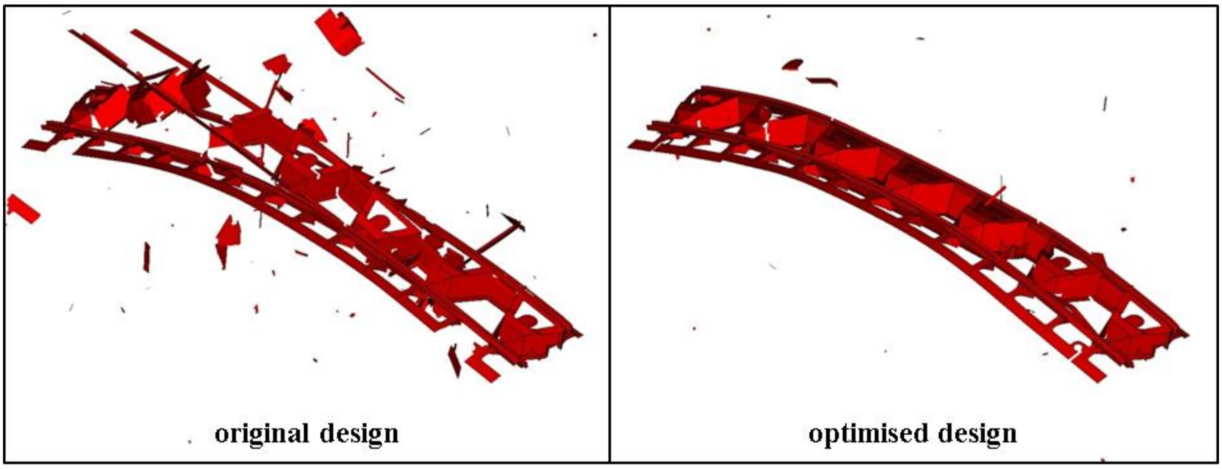

Figure 5. optimisation of the post-failure behaviour

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7. SUSTAINABILITY

For the injection molding, we used secondary carbon fibers granulate. We developed a direct compounding process. All parts in the project were produced with this injection mold material with fiber content of 30% and 40%. For the future there will be the possibility as shown in figure 7 to use used parts to produce injection granulate.

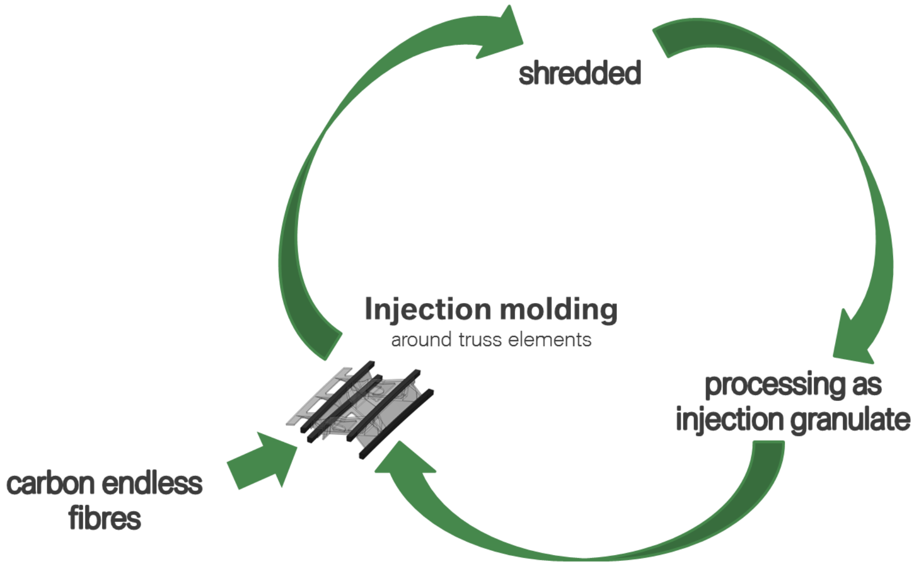

Figure 6. recycling concept

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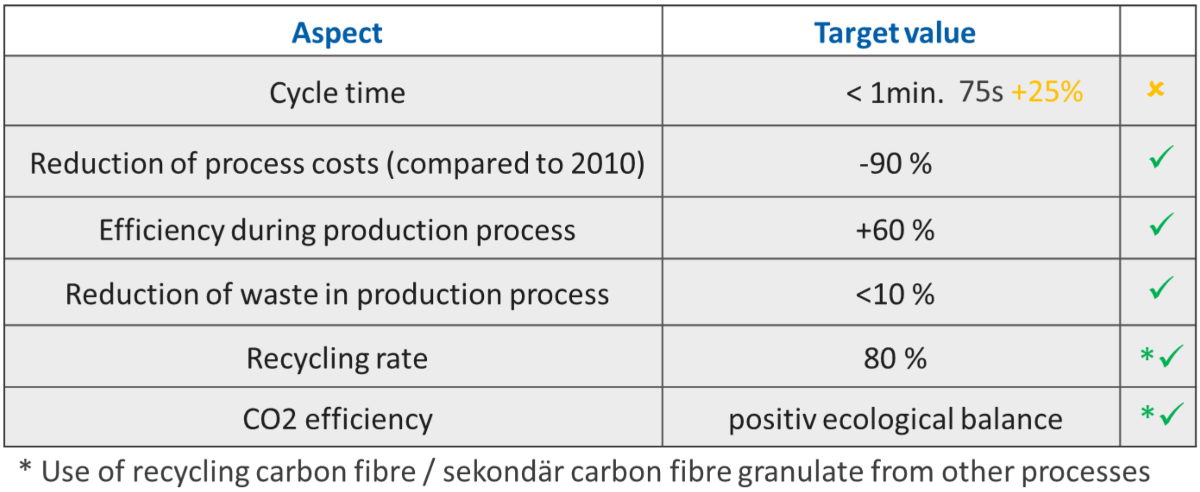
8. CONTRIBUTION TO THE MAI CARBON TARGETS



Aspect	Target value	
Cycle time	< 1min. 75s +25%	×
Reduction of process costs (compared to 2010)	-90 %	✓
Efficiency during production process	+60 %	✓
Reduction of waste in production process	<10 %	✓
Recycling rate	80 %	*✓
CO2 efficiency	positiv ecological balance	*✓

* Use of recycling carbon fibre / sekondär carbon fibre granulate from other processes

Table 1. Contribution of MAI Skelett to the MAI Carbon targets.

9. MAI MULTISKELETT

The aim of the project MAI Multiskelett is to transfer the good results of MAI Skelett to applications with multiaxial load. The main challenge will be how to design and produce the joinings of the truss elements.

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10. THE NEW CHALLENGE JOININGS OF TRUSS ELEMENTS

For more complex geometries, the truss elements may be interconnected or interlaced to transfer loads within the part. For an efficient design of such a composite node, the prediction of its mechanical response is a key factor. We have developed a parametric model in the commercial FE software ABAQUS, which allows us to predict the non-linear behavior up to final failure and further assess the performance of different designs architectures. As we expect a three-dimensional stress state in the overlapping region of the node, a modelling approach using a full continuum mesh would be favorable. However, for the sake of numerical efficiency, a simplified approach using continuum shell elements is implemented here, as it enables us to apply readily available composite failure criteria to assess damage inside the material. For an accurate representation of the fibre orientations in the overlapping region after manufacturing, an interpolation algorithm was implemented. This algorithm uses user-defined orientation vectors from the underlying CAD geometry and maps these orientations to the corresponding elements after a volumetric interpolation has been performed. This approach allows us to capture the natural transition in fibre in-plane and out-of-plane misalignment due to the change in cross-section. An arbitrary combination of external loading can be introduced at both ends of the truss elements. Through various combinations of in-plane loading scenarios, a failure envelope can be created and mapped to a structural part simulation with multiple nodes.

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