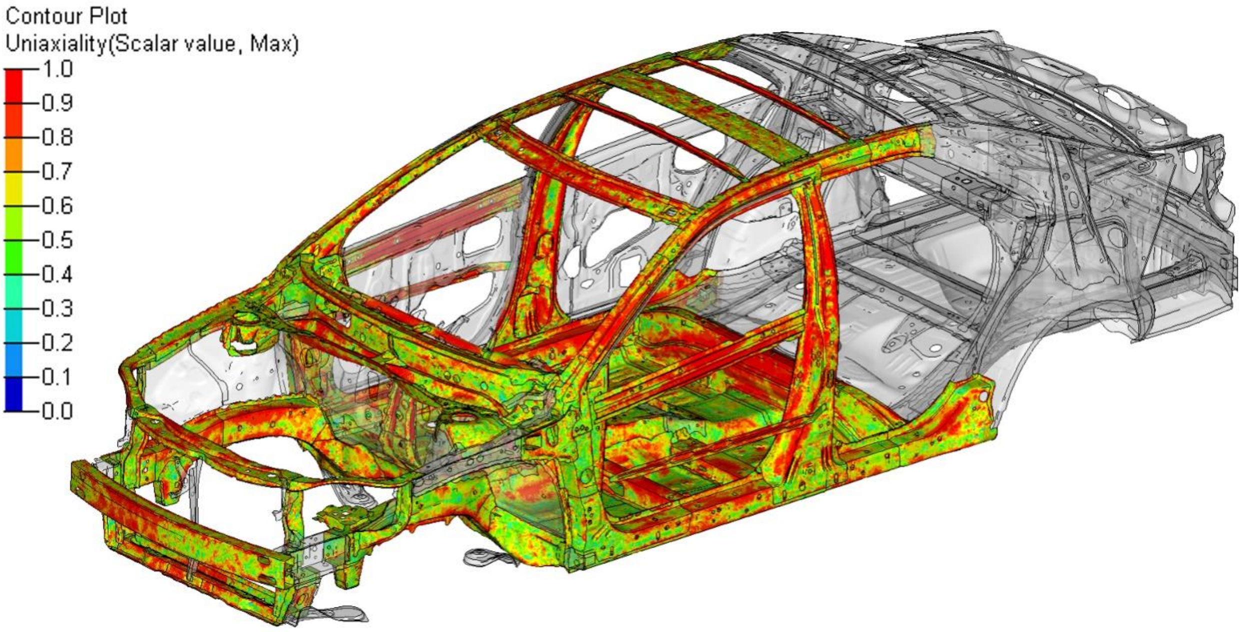

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# Stress-optimized, resource-friendly design of hybrid components

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BENTELER and the Institute for Lightweight Design with Hybrid Systems of the Paderborn University have collaborated in the development of a simulation-based approach for stress-optimized, resource-efficient design of hybrid components made of metal and fiber-reinforced polymers.

## Motivation

Increasingly stringent legal requirements for the reduction of the greenhouse gas carbon dioxide ($CO_2$) have forced car manufacturers not just to enter the field of E-mobility, but also to make use of higher-efficiency combustion engines, hybrid drivetrains and lower vehicle weights. The use of carbon-fiber reinforced polymers (CFRP) has been much discussed in recent years in order to permit further reductions in weight and has now also been implemented even outside of small series production cars [1]. Despite their excellent lightweight characteristics, these materials also have numerous disadvantages, which should not be disregarded (e.g. high $CO_2$ emission during production, unfavorable failure behavior, limited recyclability, high production cost).

The full potential of fiber-reinforced polymers for lightweight designs is particularly apparent when they are used systematically and in a load-adapted manner. A roving of endless fibers is always most efficient, when stress is applied in the direction of the fibers. Otherwise, several layers of fibers with different orientationsmust be used (e.g. for quasi-isotropic material behavior in 0°, ±45° and 90° direction). However, this has a negative impact on the lightweight design potential as well as the costs and the necessary $CO_2$ emissions during production.

During the collaborative project presented in this article, the partners took an adapted, more efficient design approach. Fiber-reinforced polymers are only used as unidirectional tapes and carry dominating stress fractions in a unidirectional direction. The remaining stress components are carried by an isotropic metal material, creating a stress-adapted hybrid material, figure 1.

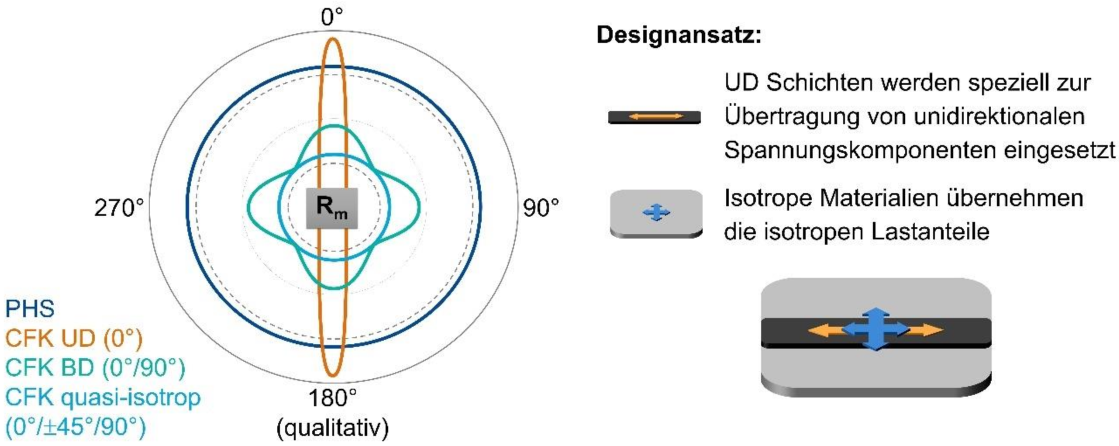


**Figure 1** Stress-optimized hybrid component design (© BAT, LiA)

The main challenge of this approach is to identifycomponents of the car body with a dominant stress direction in the various possible crash load situations. Once this information is made available, it is possible to integrate a fiber tape on a metal base component and to create in this way a tailored hybrid structure that meets the global load requirements in the context of a full vehicle.

## Approach for determining stress uniaxiality

To address the above-mentioned challenges, an approach already known from [2] and [3] was enhanced. This approach is based on the definition of a scalar variable, which characterizes the uniaxiality *U* of the stress tensor. This variable is between 0 (equibiaxial) and 1 (uniaxial), figure 2.

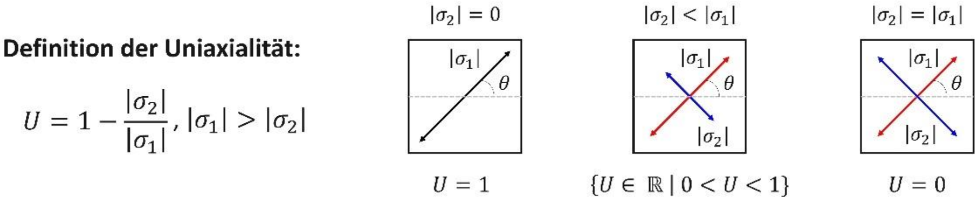


**Figure 2** Uniaxiality of selected stress states (© LiA)

One important aspect of the implemented enhancement is the strategy for accumulating the uniaxiality across several time increments and load cases. In this strategy, the individual stress components are added up, while a systematic modification of the stresses ensure that this summation does not suppress values with different signs. At the same time, it is ensured that the original major directions and absolute values of the stresses are maintained. The advantage of this approach is that both the information about the direction of the resulting stress and a value-based weighting of the individual time intervals and load cases is provided during summation. In the final step, the scalar value of uniaxiality is calculated from the absolute values of the principal normal stresses of the accumulated stress tensor.

## Evaluation of a complete vehicle for uniaxialities occurring during a crash

The freely available full vehicle model of the Toyota Camry 2012 is used for verifying this method [4]. The vehicle model is evaluated based on several crash load cases that are typical for vehicle development. Limiting the evaluation to structurally relevant components and use of a threshold for critical stress values permit a reduction of the data volume requiring evaluation. Once the results of the load case calculation are available, all relevant elements are subjected to a calculation routine and a contour plot of uniaxiality can be created (see opening image). An additional presentation of resulting stress directions permits the assessment of suitability for fiber use with regard to the orientation.

## The development approach for stress-optimized structural components

The accumulated uniaxiality of the components served as a starting point for the component development undertaken. The A pillars and the front roof frame were selected as a demonstration assembly. These components show a high uniaxiality and are part of the rigid passenger compartment. These are both excellent prerequisites for an efficient use of CFRP.

At the beginning a topology study was performed, considering the available installation space and the relevant load cases. Several design concept drafts were derived from the ideal component topology. These were evaluated and compared using simplified FE models. The most promising concept - a continuous extruded section made of aluminum with unidirectional reinforcement tapes - was developed in detail in further stages of the development. The design method developed in the project was the decisive factor for the arrangement of the reinforcement fibers. This method was based on determining the sensitivity of individual profile cross sections, which was then weighted based on the uniaxiality of the corresponding cross section. The uniaxiality-weighted sensitivity determined through this method permitted a design adapted to areas of high uniaxiality and simultaneously ensured cost-effective use of the relatively expensive reinforcement fibers at positions which are crucial for component behavior, figure 3.

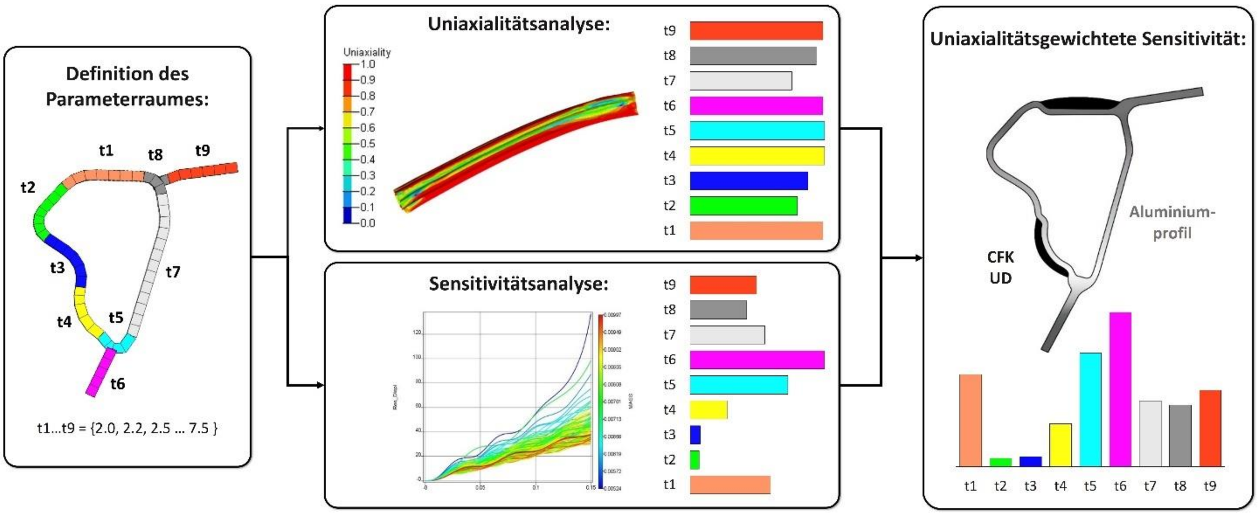


**Figure 3** Uniaxiality-weighted sensitivity method for designing hybrid components with fiber reinforcements (© LiA)

The lower section of the A pillar was designed as a shell structure due to predominantly multiaxial stress. The press-hardened steel structure, which was adapted to the bending moment, permitted stress-optimized fastening of the hybrid A pillar section. The connection between the extruded aluminum section and the steel sheet shells was established through conventional resistance spot welding thanks to patented SWOPtec joining points. In this process, pre-coated steel elements are stamped into the aluminum joining member. Despite its high uniaxiality, the front roof frame was manufactured as a monolithic aluminum sheet component using BENTELER's patented Flash Forming Process [5], as a hybrid design did not lead to a significant weight reduction. The connection of the front roof frame and the A pillar was established using a node made of an extruded aluminum section which had been adapted to the load path by topology optimization, figure 4.

**Figure 4** Technology demonstrator of a hybrid design assembly group (© BAT, LiA)

The characteristics of the new hybrid A pillar were confirmed by full vehicle simulations (figure 5) and by experimental component tests. These showed that the weight of the A pillar was reduced by 27 percent compared to the baseline structure of the Toyota Camry 2012, while providing improved crash performance. Compared to the press-hardened steel variant, which meets today's crash requirements, it even achieved a weight reduction of 46 percent.

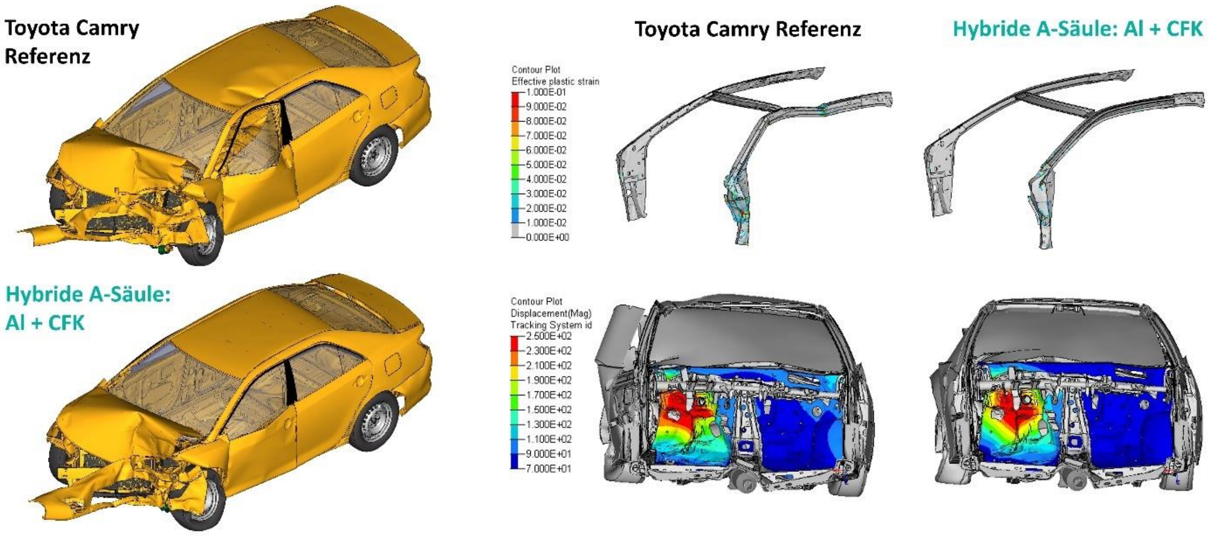


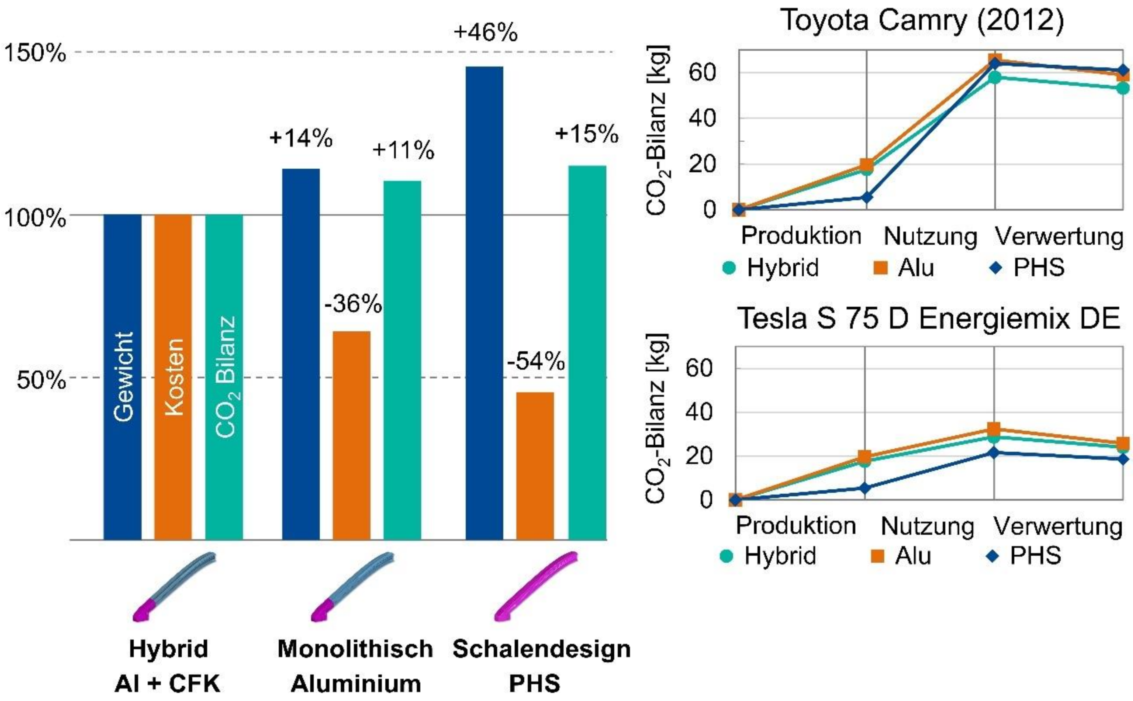
**Figure 5** Performance comparison in the Euro NCAP front offset deformable barrier test at 64 km/h (© LiA)

**Cost and environmental performance**

When designing weight-optimized structural components in vehicles, it is important to take not just the weight but also the effects on production costs and environmental effects across the entire component life cycle into account. This analysis was completed for the hybrid A pillar, figure 6.

For the cost analysis, production of 60,000 vehicles per year was assumed. This corresponds to the usual quantity in a premium segment, for which the use of CFRP would be realistic. Despite highly targeted use of CFRP, no cost neutrality was achieved compared with conventional variants (saving potential for aluminum variant 36 percent or press-hardened variant (PHS) 54 percent). At lower quantities, this cost advantage is reduced, meaning that the hybrid variant may still be economically efficient, for instance for derivative products.

The ecological performance analysis focusing on $CO_2$ emissions considers the entire life cycle of a combustion engine vehicle (Toyota Camry 2012) with a use phase of 150,000 kilometers based on database information. $CO_2$ emissions during production of the hybrid A pillar are comparable to the aluminum A pillar due to the systematic and efficient use of CFRP, however they are approximately four times higher than for the steel variant. Nevertheless, the lower weight during the use phase compensates for this. After approximately 100,000 kilometers, the hyprid A pillar reaches the break-even point in comparison to the steel variant. Throughout the entire life cycle, the hybrid A pillar achieves 11 percent lower $CO_2$ emissions than the pure aluminum variant and 15 percent lower emissions than the steel variant.



Kostenbasis: 60.000 Fahrzeuge (Verbrenner) pro Jahr

**Figure 6** Comparison of variants and environmental performance (© BAT, LiA)

When these results are transferred to an electric car, the production phase and recycling phase become significantly more important compared to the use phase and the steel variant achieves the best $CO_2$ footprint throughout its life cycle.

## Summary and future perspectives

The analytical tool for the identification of components with high uniaxial stress components in different potential crash scenarios developed in the collaborative project permits systematic use of unidirectional fibers together with conventional isotropic metal materials. This makes even the use of carbon fiber reinforced polymers comparatively low-cost and resource-efficient. Nevertheless, the cost of hybrid components is significantly higher than the cost of conventional components and whether these higher costs are justified should be decided on a case-by-case basis.

When the test results are applied to electric cars, the $CO_2$ footprint for the entire vehicle life cycle shifts to make steel the more advantageous material. The increase in renewable energy sources will make the production and recycling phase increasingly important in the future, making the development of sustainable material and component concepts even more vital.

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