TAILORED STACKED HYBRIDS – AN OPTIMIZATION-BASED APPROACH IN MATERIAL DESIGN FOR FURTHER IMPROVEMENT IN LIGHTWEIGHT CAR BODY STRUCTURES

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ABSTRACT

In latest body-in-white (BIW) concepts, engineers take into account a wider range of different materials to pursue a multi-material design approach. However, the lightweight potential of common materials like steel, aluminum or even fiber-reinforcement plastics (FRP) is limited. In keeping with the motto "the best material for the best application", a new approach for a top-down material design is introduced. With the aim to develop an application tailored material, the multi-material concept is adapted for the thickness dimension of the component. Within this contribution a new optimization-based design methodology is applied on a stiffness relevant car body part. Starting with benchmark simulations of a reference BIW structure, a critical car body component is determined by an internal energy based method and a subsequent sensitivity analysis. The identified demonstrator component is later subdivided into multiple layers and submitted to a first optimization loop in which the developed methodology varies the material parameters for each single layer. Once an optimum for the through-thickness properties of the part is found, further optimization loops with concrete material pendants and manufacturing restrictions are carried out. The result is a hybrid laminate part consisting of steel and FRP plies. To achieve a further improvement in body characteristics and lightweight, the investigated part is redesigned by the aim of topology optimization. Finally, the tailored hybrid stacks are validated in BIW simulations and compared with the reference. The optimization-based approach allows a weight reduction up to 25 % while maintaining or even improving the BIW properties.

1 INTRODUCTION

Automotive lightweight design is a considerable measure to meet the worldwide need for reducing CO_2 emissions. In the past, this led to an excessive portfolio development of conventional metals like steel or aluminum. However, the lightweight potential of common materials like steel, aluminum or even fiber-reinforcement plastics (FRP) is limited. High strength steels play a significant role in the design of safe and light car body structures. Nevertheless, the high density and buckling problems related to reduced sheet thicknesses limit the achievable mass reduction. Aluminum alloys are well known for the potential to improve the strength to weight ratio of car bodies. Nonetheless, in terms of stiffness aluminum has a clear disadvantage due to a relative low Young's modulus. Even FRP components, which have superior light-weight characteristics, show limitations for the car body design, as catastrophic failure or high production costs. Hybrid materials combine metals and FRP in a manner to

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offset the drawbacks of every single material and reach an optimum of mechanical properties and costs. Nonetheless, the achievable lightweight potential of such materials heavily depends on the loading situation, geometry or cross section of the chosen material design.

To account for these limitations, a new approach is necessary. The "LHybS" (Lightweight Design with Novel Hybrid Materials) project aims high to design a material, which different than usual is not developed in a bottom-up way, but rather in a top-down manner. Within the scope of the project a new optimization-based process is developed, which provides for the first time a methodology that allows the design of sophisticated requirement-optimal layered materials. The through thickness property profile of the material takes into account not only loading dependent requests, but also demands that are related to the direct application of the material in the vehicle. The goal of the project is to develop a lightweight hybrid material with processing characteristics similar to materials conventionally used in body-in-white production plants [1].

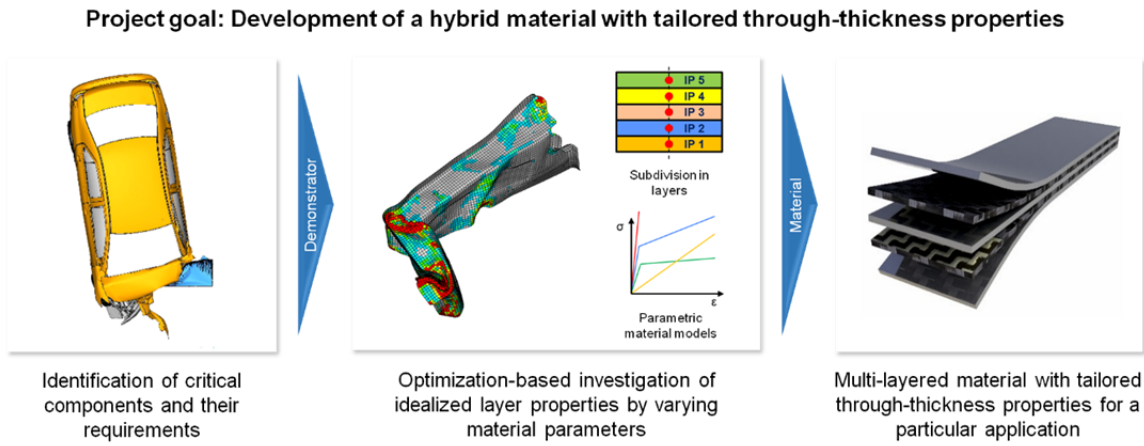

Figure 1: The approach of the LHybS project: from the application to the material profile [1]

2 PROPOSED OPTIMIZATION METHOD FOR TAILORED HYBRID STACKS

2.1 LHybS Ordered Multi-Material Interpolation

Structural optimization has been studied extensively over recent decades [2]. Among a variety of approaches for continuum topology optimization, the density-based "Solid Isotropic Material with Penalization" (SIMP) [3][4] method had gained a wide popularity and has been successfully integrated into commercial software, such as, for example OptiStruct or Tosca [5]. In SIMP, every single element within the defined problem space is coupled to an elasticity-density-scaling function with the aim to control the elemental mass and stiffness tensor. The elemental material properties are usually expressed by using a power-law function (1), where ρ is the notional density variable, E_0 the upper bound of the elastic modulus, and p the penalty factor. The possibility of an element-wise variation of density and elasticity allows finding a load-optimal material distribution. However, state-of-the-art topology optimization has been implemented for single-material design problems what limits the achievable weight savings by this method.

$$E(\rho) = \rho^p E_0, \qquad \rho \in [0;1] \wedge p > 1 \tag{1}$$

To overcome these limitations a modified interpolation scheme for multiple materials was introduced in [6]. The proposed extension of the classical SIMP can be formulated for two materials as (2), where E_1 and E_2 are the elastic modulus for material 1 and material 2, respectively. By letting $E_2 = 0$ the classical SIMP definition from (1) can be recovered.

$$E(\rho) = \rho^p E_1 + (1-\rho^p)E_2, \qquad \rho \in [0;1] \wedge p > 1 \tag{2}$$

In general, the extension proposed in [6] requires $(m-1)$ design variables for each element to take into account m materials in the optimization. As a consequence the computational cost increases significantly.

An alternative formulation can be found in [7], where an Ordered Multi-Material SIMP Interpolation is proposed to solve multi-material optimization problems without introducing any new variables. In the proposed method, the multiple materials are sorted in an ascending order of the normalized density variable ρ_i :

$$\rho_i = \frac{\rho_i^{tech}}{\rho_{max}}, \quad i = 1, 2, 3, \dots, m \tag{3}$$

Where ρ_{max} is the maximum density and m the number of all candidate materials. Introducing additional coefficients A_E and B_E, a scaling and a translation coefficient, respectively, and using the normalized density variable ρ_i, the single-material power function (1) can be extended as:

$$E_e(\rho_e) = \rho_e^p A_E + B_E, \qquad \rho_e \in [\rho_i, \rho_{i+1}] \wedge p > 1 \tag{4}$$

$$\text{where} \qquad A_E = \frac{E_i - E_{i+1}}{\rho_i^p - \rho_{i+1}^p} \wedge B_E = E_i - \rho_i^p A_E \tag{5}$$

Where E_i and E_{i+1} are the elastic modulus of ascending ordered material i and $i+1$, respectively [7].

While the Ordered Multi-Material SIMP Interpolation in (4) is able to describe monotonically increasing trends of elasticity in respect to the normalized density (3), this may not always be the case for real lightweight applications. By a way of example, common materials taken into account for multi-material design, such as steel, aluminum and CFRP do not exhibit a monotonic increase of these properties. For this reason the approach presented in [7] is revisited in the present paper. Instead of a strictly monotonically increasing function, a coupled exponential function (6) is used to describe the relation between the normalized material properties of common lightweight materials. Analogous to [7], the LHybS Ordered Multi-Material Interpolation expresses the properties of candidate materials in respect to the independent discrete normalized density variable ρ_i (3). The elastic modulus is regarded as a continuous function with respect to density, obtained from a fit of normalized candidate material data by a two-term exponential function:

$$E(\rho_i) = a * e^{b*\rho_i} + c * e^{d*\rho_i}, \qquad \rho_i = \frac{\rho_i^{tech}}{\rho_0}, \quad i = 1, 2, 3, \dots, m \tag{6}$$

$$E_i = \frac{E_i^{tech}}{E_{max}}, \quad i = 1, 2, 3, \dots, m \tag{7}$$

Where ρ_0 and E_0 are the maximum density and elastic modulus of the candidate materials, respectively, and a, b, c, d are fitting parameters of the exponential functions. For simplification, all materials are assumed as isotropic and have a Possion ratio equal to 0.3.

By applying Equation (6) on a set of common automotive lightweight materials, whose properties are listed in Table 1, the interpolation curve of normalized elastic modulus with respect to normalized density shown in Figure 2 is obtained.

Table 1: Material properties of considered automotive lightweight materials and corresponding fitting parameters of Equation (6)

Material	ρ_i^{tech} [ton/mm^3]	E_i^{tech} [MPa]	ρ_i	E_i
CFRP	1.488e-09	133e+03	0.19	0.63
GFRP	1.996e-09	45e+03	0.26	0.21
Aluminum	2.693e-09	70e+03	0.34	0.33
Steel	7.829e-09	210e+03	1.00	1.00
Fit. param. Eq.(6):	a	b	c	d
	1.977e+13	–165.8	0.1571	1.852

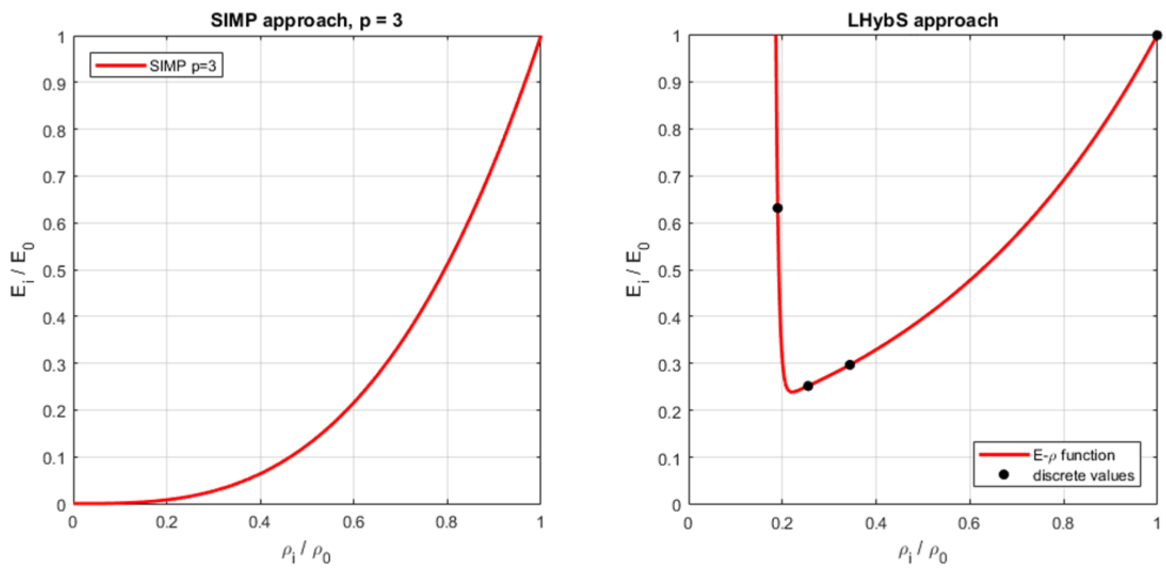

Figure 2: Comparison between the classical SIMP and the LHybS approach for scaling the stiffness and density

While the LHybS Ordered Multi-Material Interpolation is able to describe the trend of normalized properties of real lightweight materials, the zero density for void representation typically found in SIMP is lost. However, with the introduced interpolation method we rather want to choose between candidate materials than between solid or void. An alternative method for solving this kind of material optimization problems was introduced in [8] as Discrete Material Optimization (DMO), where the element constitutive matrix is expressed as a weighted sum of constitutive matrixes of each candidate material. This conception however is disadvantageous, as each candidate material demands its own design variable, while the LHybS approach uses solely the normalized density as design variable.

2.2 Optimization methodology

The LHybS Ordered Multi-Material Interpolation can be applied directly on multi-layered shell element structures. The only difference to topology optimization is that the material parameterization is invoked at the level of shell integration point layers instead on solid element level. Further, to ensure manufacturability and uniform properties at stack layers, the integration points of all elements on a given layer are clustered into plies. That in turn enables to realize layers of different properties within the investigated component and the design of an application-optimal hybrid material. However, the

LHybS interpolation approach is still limited to optimize material distribution problems and additional design variables, such as material thickness or orientation cannot be changed during one optimization run.

To account for this limitation, the developed material design process consists of two main optimization runs. After benchmarking the monolithic reference design, the chosen part is subdivided into N^l integration point layers k, while the overall wall thickness t of the part remains unchanged. The first optimization run follows in which the algorithm optimizes the material parameters for each ply following Equation (6). The optimization problem of the first run of compliance minimization can be expressed as in (8), where C is the structural compliance; K, u and P are the global stiffness matrix, displacement vector and force vector, respectively; φ_M is the mass fraction; M and M_0 is the mass of the current and the reference design, respectively; and the superscripts e and l refer to "element" and "layer".

Once a global optimum was found by choosing multiple sampling points, the still idealized material properties of each layer are compared with a material database and replaced by concrete pendants by taking into account real material properties, as for example anisotropy. Within the last optimization run the layers are optimized in terms of thickness and material orientation. Following (9), the objective is again compliance minimization, but here, since the multi-material distribution is known, only layer thicknesses t^l and orientations θ^l are optimized. The boundaries for t^l and θ^l are set in a way to meet manufacturing limitations.

Figure 3 depicts a flowchart for the task of multi-material optimization defined in the introduced optimization methodology.

$$Objective:\ \min_{\rho} C = u^T K u$$

$$Subject\ to: \begin{cases} M \leq \varphi_M M_0 \\ Ku = P \\ K = \displaystyle\sum_{m=1}^{N^e} \int_V K_m^e, \qquad K^e = \sum_{k=1}^{N^l} \int_V \left(B_k^l\right)^T C_k^l B_k^l \, dV \\ M = \displaystyle\sum_{m=1}^{N^e} M_m^e, \qquad M^e = \sum_{k=1}^{N^l} V_k^l \rho_k^l \end{cases} \tag{8}$$

$$Objective:\ \min_{t,\theta} C = u^T K u$$

$$Subject\ to: \begin{cases} M \leq \varphi_M M_0 \\ C \leq C_0 \\ \theta_{min}^l \leq \theta^l \leq \theta_{max}^l \\ t_{min}^l \leq t^l \leq t_{max}^l \end{cases} \tag{9}$$

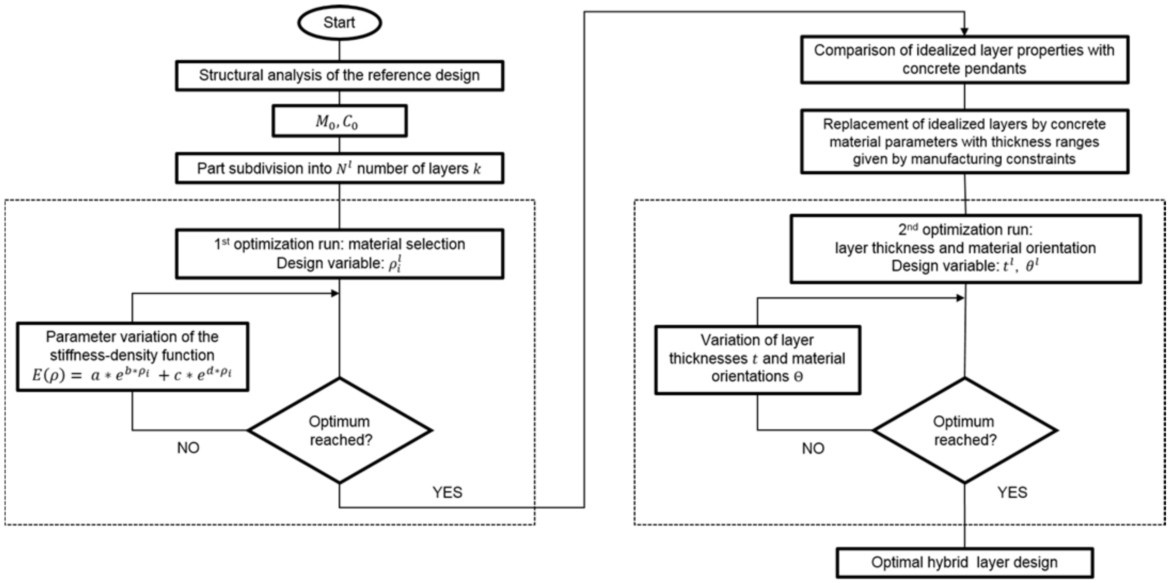

Figure 3: Flowchart of the developed method for an optimization-based hybrid design

3 REFERENCE STRUCTURE BENCHMARK

As a basis for the material development the thyssenkrupp InCar® plus model is used. The InCar® project started back in 2006 as a customer-independent car body structure project. The goal of the InCar® project was to develop a base for the potential analysis of new material grades and processing concepts. A further development and an adjustment to newest crash safety demands was realized in 2014 as InCar® plus. The steel-intensive structure of the InCar® plus represents the current state of the art by utilizing the usage of hot formed, ultra-high and high strength steels [9], [10]. The stiffness and noise-vibration-harshness (NVH) properties of the InCar® plus BIW are investigated in OEM specific methods to set a benchmark for the development of the new tailored hybrid materials. The benchmark analysis is carried out by tests described below.

3.1 Global bending stiffness

The global bending stiffness of the body-in-white is investigated by boundary conditions adapted from [11]. For this purpose, two static forces are distributed and applied to the front seat attachment points while the BIW is constrained in a static determined manner at the front and rear damper carriers. To suppress the influence of local structure stiffness on the determined global value, an evaluation approach from [12] and [13] is used. By this approach the maximum rocker deflection and a corrected reference line given by the clamping points is taken into account. The global bending stiffness follows from equation (10).

$$c_B = \frac{\sum F_z}{u_{z,max.rocker\ corr.}} \tag{10}$$

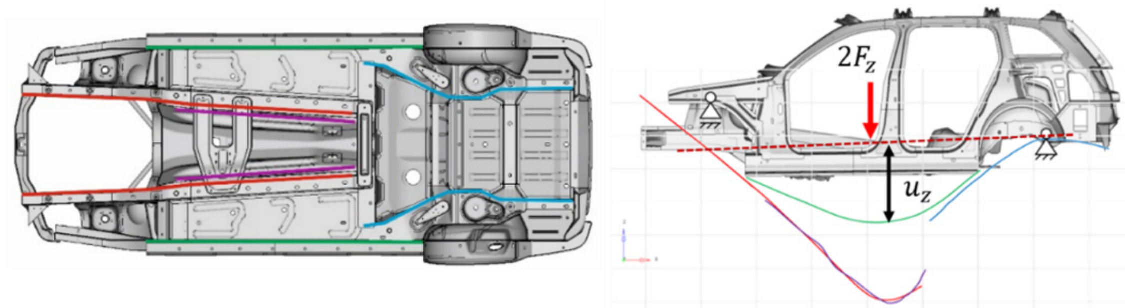

Figure 4: Evaluation of the global bending stiffness – loading conditions and the resulting deflection lines of the underbody

3.2 Global torsion stiffness

The determination of the global torsion stiffness is based on a method proposed in [14]. Here, the BIW is loaded by applying a couple of opposing forces on the strut towers while constraining the rear damper carriers. To suppress a possible bending of the BIW structure, an enhancement of the boundary conditions from [12] is introduced. Hereto, an additional constraint at the middle of the front bumper beam is defined to ensure a global torsion of the body. The torsion stiffness is then calculated from the twist angle between the strut towers and the introduced torque, see equation (11).

$$c_T = \frac{M_x}{\Phi_x} \left[\frac{Nm}{deg}\right] \tag{11}$$

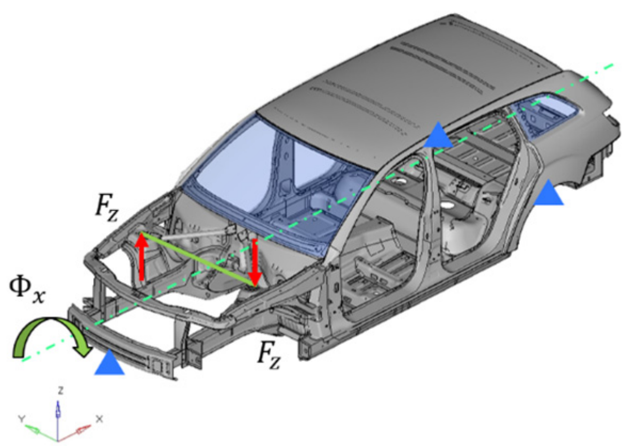

Figure 5: Loading and boundary conditions used for the determination of the global BIW torsion stiffness

3.3 Modal analysis

To characterize the NVH properties of the BIW an eigenvalue analysis is performed. As reported in [15] the eigenfrequencies should be analyzed in free-free boundary conditions. It should be note that due to the chosen boundary conditions the first six eigenmodes are related to the rigid body motion and are not relevant for the BIW design. Therefore, the first three symmetric modes are evaluated. The 7th and 9th mode correspond to the first and second bending mode respectively. The 8th mode corresponds to the first torsion mode, see Figure 6.

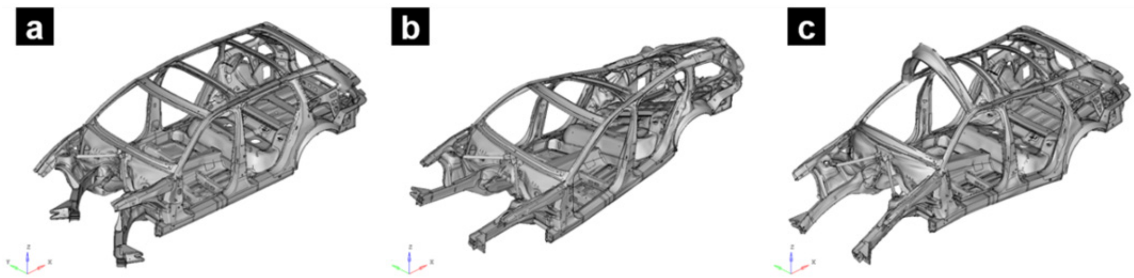

Figure 6: The first three symmetric eigenmodes of the BIW: a) Mode 7 – first bending mode; b) Mode 8 – torsion mode; Mode 9 – second bending mode

3.4 Lightweight Index

To quantify the trade-off between stiffness and lightweight the so-called "Lightweight Index" L is introduced. The Lightweight Index describes the purposeful material and package utilization within the car body structure and follows from equation (12). As shown in the equation, the global torsion stiffness is crucial for the lightweight index. However, as reported in [16], an improvement of the torsion stiffness usually leads concurrently to an improvement of other stiffness properties of the BIW.

$$L = \frac{m_{RK}}{c_T * A} \left[\frac{kg}{Nm/\deg * m^2}\right] * 10^3 \tag{12}$$

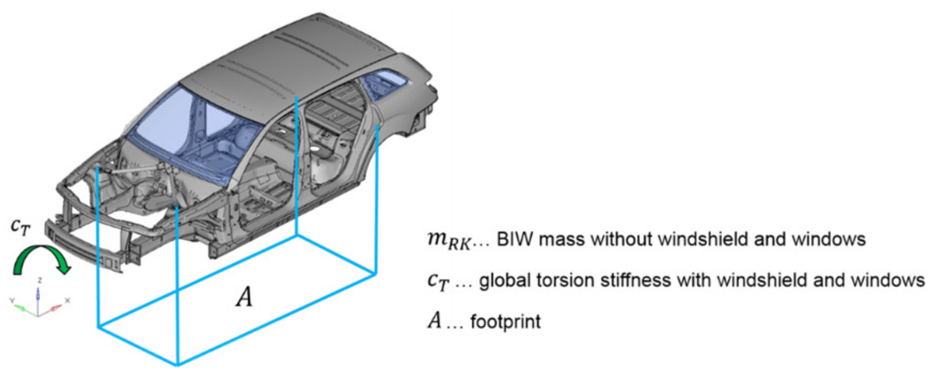

Figure 7: Evaluation of the Lightweight Index L

3.5 Component selection

The investigated body-in-white properties result from an interaction of all car body components. Every single part accomplish in terms of a body structure a particular function and contributes with its specific characteristics to the global body-in-white properties. Depending on the external load, singular parts and component groups could be more or less involved in the deformation resistance of the body structure. To classify the BIW parts into load case relevant groups and evaluate their importance, a strain energy based method introduced in [1] is used. The assessment of a potential component is further supplemented by a sensitivity analysis to identify structural parts with a significant impact on the global stiffness. With the aim to reduce the computational effort of the sensitivity analysis, the results from the prior step are used for a domain reduction. Thus, the sensitivity is analyzed only for ten components with highest prorate strain energy values. By increasing the elasticity modulus of these particular components, the influence of an improved material on the global characteristic can be evaluated. In that manner, it can be ensure that the material improvement will be realized on parts that show a high relevance for the global BIW properties and so, additional costs can be justified by better overall vehicle characteristics [1].

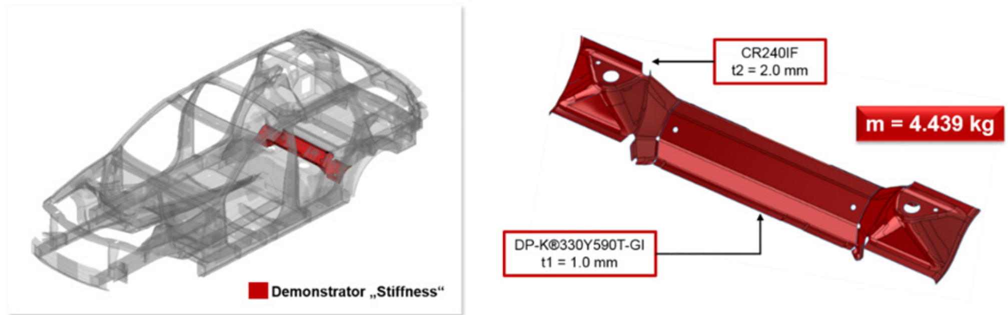

Figure 8: Selected demonstrator part: InCar® plus rear cross member

As a result of the described procedures the rear cross member is selected for a tailored material design trail, see Figure 8. In addition to mechanical requirements that have to be satisfied by the new material, there are secondary demands for this particular part, as for example damping characteristics, corrosion protection or joinability that have to be taken into account within the material design process. These needs are investigated and defined in a specific requirement catalogue.

4 BIW COMPONENT OPTIMIZATION

4.1 Hybrid material design

Since the global stiffness is directly affecting the “Lightweight Index” L of a car body, see equation (12), the load case “global torsion” is defined as design relevant. So, the investigation of an optimal layer-wise material selection within the selected component is carried out for “global torsion”. To ensure a symmetric material design, one left and one right twisting “global torsion” load case is defined, what leads to a multi-objective optimization.

To access a layer-wise variation of the part material parameters, the reference part is divided into seven layers. To find the optimal material for each layer, the approach from section 2.1 is used. Based on equation (6), the algorithm varies the density and calculates the elastic modulus. It changes automatically the material parameters in each layer which allows finding the optimal material distribution for the hybrid laminate. Possible materials are steel, aluminum, GFRP and CFRP. As mentioned in section 2.1, both fiber-reinforced plastics are implemented as an isotropic material to reduce the computational effort within the first optimization loop. The optimization results in a stacking sequence that consists of steel top layers and a multiple layer CFRP core.

In the second optimization step, the variation of the thickness of each layer and the orientation of every FRP-layer is automatized, while complying with the following constraints. The minimal deliverable thickness of steel ranges from 0.5 mm to 0.6 mm, the thickness for one layer of unidirectional CFRP is set to 0.05 mm and the thickness for one layer of CFRP-fabric is set to 0.35 mm. This second step includes a loop, in which the routine automatically varies the thickness and the orientation of the CFRP in 5° steps. Furthermore, it checks after each variation whether the parameters of the new hybrid laminate improved compared to the original steel component. These parameters are global torsion stiffness and mass.

Due to selected FRP pre-products and available material thicknesses, different solutions exist and three alternatives of the hybrid laminate are listed in Table 2. The first variant (A) includes 0.5 mm thick steel top layers and a CFRP core consisting of 5 unidirectional layers. Based on the different material orientations of the CFRP, it is possible to maintain the torsional stiffness while simultaneously reducing the mass by 25 %. In variant B a change from unidirectional CFRP to CFRP-fabric is realized, what reduces the achievable mass reduction by 2 %. At the same time, the torsional stiffness increases slightly (+ 0.37 %). The main difference between variant B and C is the thickness of the steel sheet. In the latter variant C, the thickness is changed from 0.5 mm to 0.6 mm. Therefore, the thickness of the CFRP-fabric can be reduced from 1.05 mm to 0.7 mm (2 layers instead of 3 layers CFRP-fabric) and as a consequence the mass of the component increases. Nevertheless, with this design the mass can be still reduced by 14.6 % compared to the reference. The torsional stiffness remains unaffected.

The influence of these variants on further BIW properties is investigated in section 5.

Table 2: Result list of different hybrid stack variants

	Variant A	Variant B	Variant C
Layer 1	Steel 0.5 mm	Steel 0.5 mm	Steel 0.6 mm
Layer 2	CFRP 0.2 mm 40°	CFRP 0.35 mm +45°/–45°	CFRP 0.35 mm +45°/–45°
Layer 3	CFRP 0.1 mm 145°	CFRP 0.35 mm +45°/–45°	CFRP 0.35 mm +45°/–45°
Layer 4	CFRP 0.3 mm 180°	CFRP 0.35 mm +45°/–45°	Steel 0.6 mm
Layer 5	CFRP 0.2 mm 145°	Steel 0.5 mm	-
Layer 6	CFRP 0.1 mm 140°	-	-
Layer 7	Steel 0.5 mm	-	-
Global torsional stiffness	+0.03 %	+0.37 %	+0.37 %
Component mass	–25 %	–23.2 %	–14.64 %
Lightweight Index	–0.42 %	–0.60 %	–0.49 %

4.2 Geometry design

As reported in [17] the deep-drawing of stacked hybrid laminates can lead to complex failure modes, as for example delamination, buckling or wrinkling, which, however, can be avoided by an adapted part design and special processing techniques. To meet these new material-related manufacturing requirements a redesign of the part geometry is necessary.

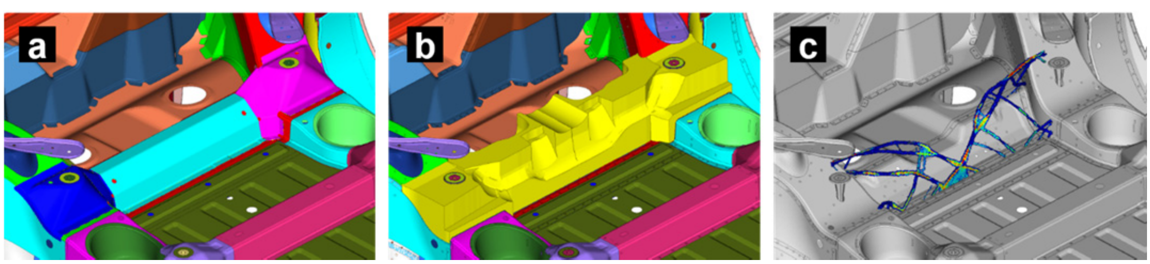

Figure 9: Topology optimization of the rear cross member – a) reference design; b) package model of the available space; c) result of the optimized topology

At the outset, an investigation of the optimal part design within the available package is carried out by the aim of SIMP-based topology optimization. As depicted in Figure 9 c, the torsion-optimal structure consists of only few bars forming a truss in the rear underfloor area of the car body.

Based on the optimal component geometry, space restrictions and forming limitations a new part geometry is developed. Additionally, in order to avoid changes in the joining sequence, the quantity and location of connection points to adjacent parts are kept unchanged. As shown in Figure 10 b, the new part geometry uses almost the entire free package and avoids leaps in the drawing ratio. That guarantees a high stiffness and manufacturability of the new hybrid part at the same time. The possibility of a later subdivision into three separate components is also provided by this geometry design.

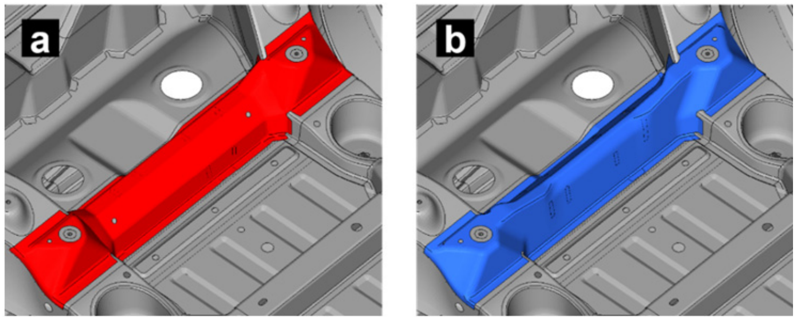

Figure 10: a) the reference rear cross member design; b) new hybrid-optimal rear cross member design

Strictly, the optimization-based material design process introduced in section 2.2 should be repeated for the new part geometry, since the changed geometry can lead to a different optimal layer design. Nevertheless, as a proof of concept the stacking sequence of variant C is applied to the new part geometry (variant D, Table 3). Due to a higher overall surface of the new part geometry the achieved mass reduction is marginal. However, in comparison to the reference geometry, it is possible to increase the torsional stiffness by 5.89 % and decrease the lightweight index by –5.38 %. A further improvement in lightweight potential can be gained by performing a full material design process. This will be the subject of future work.

Table 3: Result list of the optimized new hybrid rear cross member design

Variant D		Change in BIW Properties		
Layer 1	Steel 0.6 mm	Torsional stiffness	Mass	Lightweight Index
Layer 2	CFRP 0.35 mm +45°/–45°			
Layer 3	CFRP 0.35 mm +45°/–45°	+5.89 %	–0.45 %	–5.38 %
Layer 4	Steel 0.6 mm			

5 VALIDATION

Finally, the developed materials undergo a series static and dynamic BIW stiffness simulations. The results are compared with the InCar® plus reference to highlight the potentials of the tailored hybrid material design. In all cases, a redesign of the through thickness properties by a tailored hybrid stack leads to a weight reduction while maintaining or even improving the overall vehicle properties, compare Table 4.

Table 4: Comparative assessment of static and dynamic stiffness properties of the tailored hybrid stacks

	Variant A	Variant B	Variant C	Variant D
Mass	–25 %	–23.2 %	–14.64 %	–0.45 %
Bending stiffness	–0.71 %	–0.71 %	–0.72 %	–0.40 %
Torsional stiffness	+0.03 %	+0.37 %	+0.37 %	+5.89 %
Lightweight index	–0.42 %	–0.60 %	–0.49 %	–5.38 %
1st bending mode	unchanged	unchanged	unchanged	+0.02 %
1st torsion mode	+0.27 %	+0.40 %	+0.33 %	+2.32 %
2nd bending mode	+0.07 %	+0.07 %	+0.04 %	+0.02 %

6 CONCLUSIONS AND OUTLOOK

Numerical optimization processes introduced within the scope of this contribution allowed to design novel requirement-optimal hybrid materials directly within a BIW. These materials led to a weight reduction of up to 25 % and hold further light-weight potentials. The developed materials were hitherto investigated only in numerical simulations and coupon based experimental tests. The experimental validations on real component geometries are still pending. The chosen demonstrator component will be subjected to a series of crash, stiffness and durability tests to point out the qualification for automotive applications. Further, the developed approach will be consolidated to a user-friendly numerical tool to provide usability in the serial development of mechanical systems. Distal the automotive field the approach could be used for other disciplines, as for example in the aeronautical or energy sector.

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LHybS

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