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# A NOVEL APPROACH FOR THE EVALUATION OF COMPOSITE SUITABILITY OF LIGHTWEIGHT STRUCTURES AT EARLY DESIGN STAGES

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*Keywords: evaluation tool, lightweight design, early design stages*

## 1. Introduction

Many different studies have shown that the carbon fibre market is an emerging market expecting double-digit growth in the next five years, where especially the industrial sector is forecast to increase its demand on carbon dramatically [Trechow 2013]. The reason for this very positive development can be found in the special characteristics of Carbon Fibre Reinforced Plastics (short: CFRP). High stiffness combined with high strength at very low weight make composites and particularly CFRP an ideal material for lightweight constructions and, therefore, an interesting material to solve different problems in the industrial or automotive sector (for example the reduction of masses in motion or lowering the overall weight of vehicles). Despite these very promising characteristics, the use of CFRP in mass products, especially in the automotive sector, has not been established, yet, because producers are facing various problems [Müller-Wondorf 2013]. Due to the high material prices and long cycle times in production, the use of CFRP is very expensive compared to other lightweight materials like aluminium. Furthermore, the mechanical behaviour of CFRP is highly anisotropic, which is the crux of the development of composite parts for product developers in general, because the material characteristics can only be fully exploited if the fibre alignment is in accordance with the load direction [Klein et al. 2013]. However, finding the ideal fibre alignment can be extraordinarily difficult, as many parts are subjected to different load cases inducing different stress states. This means that on the one hand, composite structures are very expensive due to high material prices and production costs, and in addition, the promising characteristics are highly dependent on the fibre alignment. On the other hand, there is no other material offering such an enormous lightweight potential. This tightrope walk between costs, exploitation of material characteristics and lightweight potential makes it very difficult for product developers to decide whether a composite material like CFRP is suitable for a lightweight structure or not. Within the following article a novel, computational approach is introduced to support product developers in this fundamental decision and to show which areas of the part have to be improved in order to increase the composite suitability. It should be pointed out here that if the general term “composite” is used there is talk of unidirectional reinforced composites because the evaluation approach is mainly intended for this kind of composite material. Nevertheless, large parts of the article can be used for all different kinds of composites.

## 2. Fibre Alignment - the crux of the development of composite structures

The anisotropic mechanical characteristics of composites are a big challenge in product development because the lightweight potential can only be fully exploited if the fibres are aligned correctly. Even small deviations from the ideal fibre direction result in dramatically lowered strength and stiffness characteristics of the part because the matrix (with significant lower strength and stiffness values) is increasingly loaded. Proof for this statement can be furnished with the help of the Classical Laminate Theory, assuming a plate under tension with a fibre orientation deviating from the force direction about the angle α (see Figure 1).

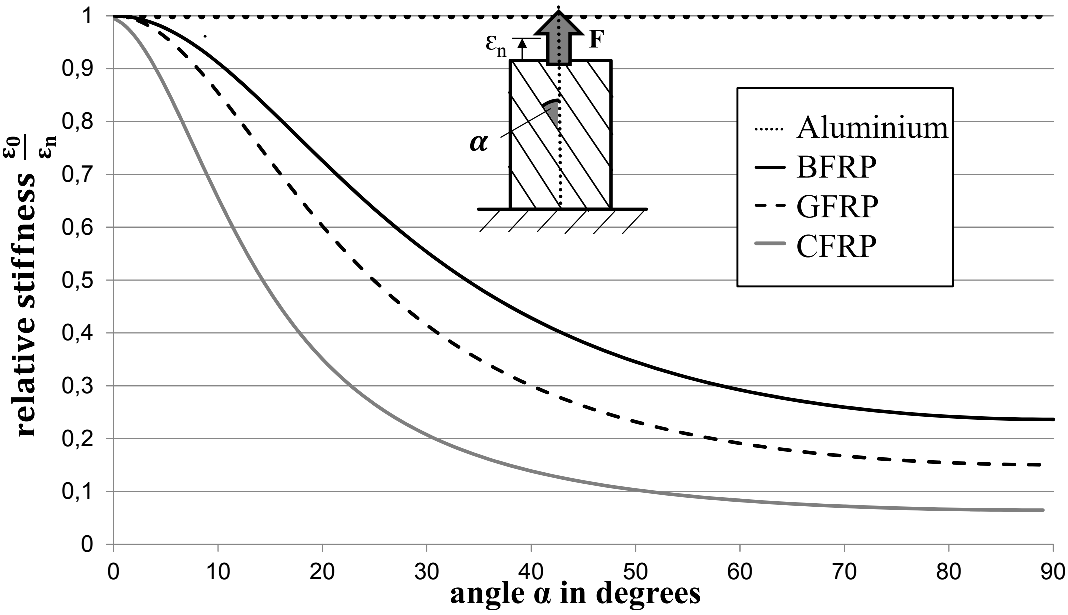


**Figure 1. Dependence of the relative stiffness on the deviation from the ideal fibre direction (according to [Klein et al. 2013])**

By relating the initial strain, $\varepsilon_0$, calculated with the ideal fibre orientation, $\alpha = 0$, to a strain, $\varepsilon_n$, calculated with an increasing deviation, α, from the ideal fibre orientation, a measurement for the stiffness of the plate can be derived – the so called relative stiffness (a more detailed derivation can be found in [Klein et al. 2013]). The resulting graphs for aluminium, Carbon Fibre (CFRP), Glass Fibre (GFRP) and Basalt Fibre Reinforced Plastic (BFRP) show that the relative stiffness decreases dramatically with increasing deviation from the ideal fibre orientation. In the case of CFRP, a deviation of only 10 degrees from the ideal fibre direction results in a decrease of about 30 percent in relative stiffness. This dependency of the mechanical behaviour of composite structures on the correct fibre alignment makes the choice for the engineering material a challenging task for product developers. In some cases the chosen part geometry or the different load cases inevitably lead to an inadequate loading of the fibres and, as a consequence, the exploitation of the unique lightweight potential of composites decreases dramatically.
Since it is not obvious which parts or areas of a part will lead to such a decreased exploitation of lightweight potential, product developers have to be supported with the help of an evaluation criterion which can be used at the early design stage, when changes in the product characteristics are least cost-intensive.

## 3. The evaluation criterion according to Durst

In literature, one existing evaluation criterion which was published by Durst in [2008] can be found. Durst's intention in this publication is to find parts within car bodyworks which are suitable for composite materials. Therefore, he evaluates the anisotropy, orientation and magnitude of stress states and computes values between 0 and 1 for each part where 0 denotes an unsuitable and 1 a highly suitable part, but in the approach according to Durst a few simplifications are used which limit its applicability. First of all, the evaluation of the orientation is based upon the assumption that the characteristics of composites decrease linear with an increasing loading of the matrix. However, it can be shown with the help of Classical Laminate Theory and the resulting curve in Figure 1 that the decrease of the material characteristics is non-linear. Secondly, he assumes that there is only one

single resulting fibre orientation for a part and if all element mean stress orientations point in direction of this fibre orientation, the part will be highly suitable for composites. However, the ideal fibre orientations within composites only seldom point in only one single direction (mainly only in the case of pure tension or pressure stresses, see chapter 4.1). In [Klein et al. 2013] it could be shown with the help of a simplified b-pillar that a unidirectional fibre layout can lead to a much worse mechanical behaviour than the CAIO method, which is used for the evaluation criterion in this article. An additional point which is not considered in the approach of Durst is the fact that one major advantage of composite structures, besides their good stiffness characteristics, is their high strength, which has to be evaluated, too.
For all these reasons, a novel approach for the evaluation of composite structures will be introduced by using completely different evaluation criteria. The intention of this new evaluation criterion is to support product developers in their first assessment of a structure with respect to its composite suitability at the early design stages. The big challenge in this context is the fact that the information density at this early stage is low since many parameters (e.g. material parameters or fibre orientation) are not available and, therefore, have to be assumed with reasonable accuracy. Additionally, it is a crucial task at the early design stage to evaluate and improve several concepts iteratively in order to find a suitable geometry. As a result the model set-up and the evaluation has to be possible at little effort in order to keep the development time low. However, this is only possible if a few simplifications are made.

## 4. The novel approach for the evaluation of composite suitability

Despite the rough boundary conditions at the early design stages, it is one of the principle aims of the evaluation criterion to give an estimate of composite suitability based on physical facts like the exploitation of stiffness and strength characteristics with as little information as possible.

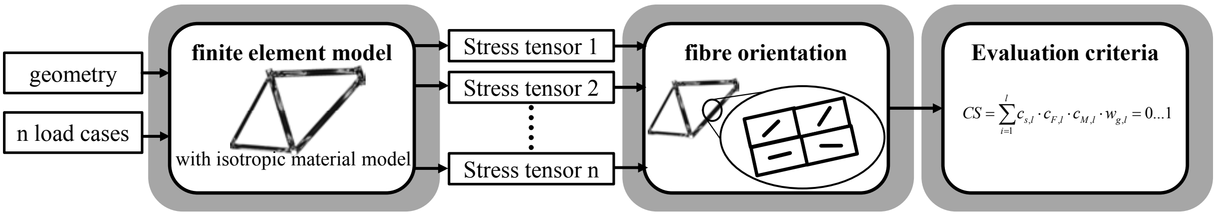


**Figure 2. Process for the evaluation of composite suitability**

Consequently, only the geometry of the part and the *n* different load cases have to be known in order to be able to create a finite element model with one single layer for each load case using an isotropic material model for the evaluation approach (see Figure 2). This first step is adopted from the approach according to Durst because it is considered the most suitable way to get as much information as possible about the structure, with little effort at the early design stage. With the help of the resulting element stress tensors from the finite element analysis the best fibre orientation for each element can be computed (see chapter 3.1) which is the basis for the formulation of the overall evaluation criterion for composite suitability (CS)

$$\mathrm{CS} = \sum_{i=1}^{l} \mathrm{c}_{\mathrm{s,l}} \cdot \mathrm{c}_{\mathrm{f,l}} \cdot c_{m,l} \cdot \mathrm{w}_{\mathrm{g,l}} = 0...1 \tag{1}$$

In this criterion $c_{s,l}$ symbolises the coefficient of stiffness, $c_{f,l}$ the coefficient of fibre strength, $c_{m,l}$ the coefficient of matrix strength and $w_{g,l}$ a weighting coefficient to give load cases with higher stresses within the element higher relevance. These coefficients are computed for all load cases *l* and summed up for each element. The result of the evaluation criterion is a value between 0 and 1 where 0 denotes "unsuitable" and 1 "highly suitable". The meaning of theses coefficients as well as the computation of the fibre orientation will be explained in the following.

## 4.1 Computation of a resulting fibre orientation (for different load cases)

The computation of the fibre orientation is of fundamental importance to the whole evaluation process as even small deviations from the ideal fibre alignment result in a significantly lowered relative stiffness. However, in contrast to a simple plate, the fibre orientation within a complex part cannot be computed with the help of an analytical method like the Classical Laminate Theory. This is the reason why Kriechbaum developed in [1994] the so called CAIO (Computer Aided Internal Optimisation) method to compute fibre orientations within an arbitrary structure based upon the observation that wood aligns its fibres along the stress trajectories (= directions of mean stresses) iteratively [Mattheck 1998]. In many different observations (see [Temmen 2006], [Klein et al. 2013]) it could be proven that, with a fibre orientation according to the CAIO method, the mechanical behaviour of composite parts can be improved significantly. However, this method has one big disadvantage - the CAIO method does only work for one single load case. For this reason a new way of computing the fibre orientation has to be developed to make the evaluation of parts with multiple load cases possible. The principle computation process is shown in Figure 3. To receive a comprehensive explanation, two load cases called *a* and *b* are assumed.

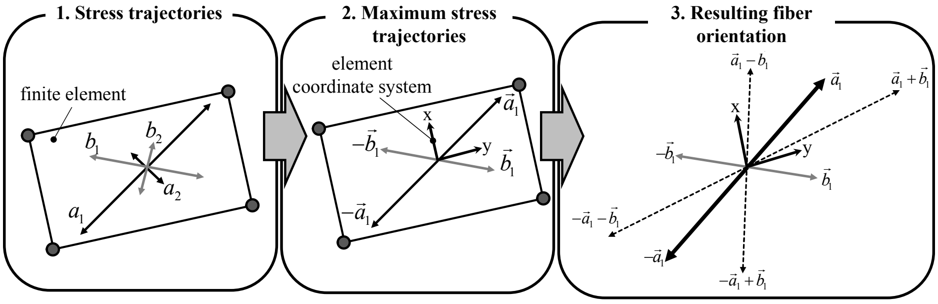


**Figure 3. Computation of a resulting fiber orientation**

Similar to the CAIO method, the basic idea of this new proceeding is to align the fibres along the stress trajectories with the biggest absolute value. Therefore, in the first step the stress trajectories $a_1$ and $a_2$ resulting from load case *a* as well as $b_1$ and $b_2$ resulting from load case *b* within each element are computed (1). After that, the stress trajectories with the biggest absolute value within each load case, in this case the trajectories $a_1$ and $b_1$, are selected and transformed to vectors (2). As the vectors pointing in the direction of the stress trajectories $a_1$ and $b_1$ can either be positive or negative, four different vectors, $\vec{a}_1, -\vec{a}_1, \vec{b}_1$ and $-\vec{b}_1$ ,exist. In order to find the resulting fibre orientation, each vector from load case *a* is added up with each vector from load case *b* resulting in four different vector sums (3). From these four vector sums again the direction of the vector sum with the biggest absolute value ($\vec{a}_1 + \vec{b}_1$ and $-\vec{a}_1 - \vec{b}_1$) is selected representing the resulting fibre direction.

In this context it has to be mentioned that it is usually wrong to neglect the lower stresses $a_2$ and $b_2$ because both can have an absolute value which is just slightly lower than the absolute value of the maximum mean stresses $a_1$ and $b_1$. But a small difference between the absolute values of maximum and minimum mean stress means that an isotropic stress state exists, which is unsuitable for composites, and therefore leads to a degradation of the element with the help of the stiffness coefficient (see chapter 4.2).

## 4.2 The Stiffness Coefficient $c_s$

In order to evaluate the composite suitability of a part, the exploitation of the stiffness characteristics has to be taken into account for the good stiffness characteristics are one big advantage of composites. In the following, the basic reasons for an insufficient exploitation of stiffness characteristics will be explained and a stiffness criterion will be introduced.

### Reasons for an insufficient exploitation of stiffness characteristics of composites

Basically, there are two different loading scenarios within an element which can lead to decreased stiffness characteristics (see Figure 4). As it has already been mentioned in chapter 4.1, it is best to align the fibres in the direction of the stress trajectories with the biggest absolute value. But within loaded structures the stress states being induced by the loads can be isotropic, too (see Figure 4, left). In this case both $a_1$ and $a_2$ can be selected as ideal fibre direction and in both cases a significant loading of the matrix will occur due to the other trajectory pointing in the orthogonal fibre direction with the same absolute value. This is the first reason why in some elements the value for the composite suitability has to be degraded. The second reason for the degradation of the composite suitability is the existence of different stress states within an element due to different load cases.

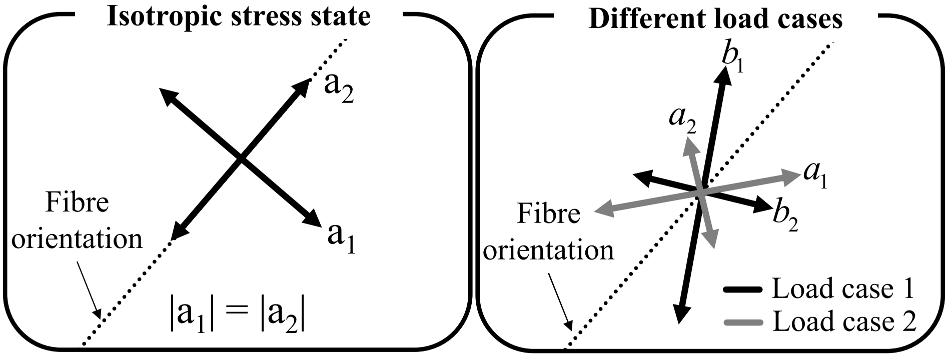


**Figure 4. Reasons for a reduced exploitation of stiffness characteristics**

Since it is assumed that there is only one possible fibre direction within an element, very different stress states can result in a significant loading of the matrix, and therefore, the composite suitability decreases (see Figure 4, right). In the following, a novel stiffness criterion will be introduced, which allows the observation of both isotropy of stress state and different load cases within one single criterion.

**Introduction of the stiffness coefficient**

The principle idea of the stiffness coefficient is based upon the observation on the non-linear dependency of part stiffness S on the deviation α in Figure 1. With the help of the Classical Laminate Theory the decrease of relative stiffness S with increasing deviation α from the ideal fibre alignment can be expressed as

$$S=\frac{1-\upsilon_{12}}{\cos^2(\alpha)+\frac{E_1\sin^2(\alpha)}{E_2}-\upsilon_{12}\left(\cos^6(\alpha)+\sin^6(\alpha)+3\sin^2(\alpha)\cdot\cos^2(\alpha)\right)}=0..1 \tag{2}$$

This function, S, is only dependent on the deviation, α, the Young's modulus, $E_1$, in fibre direction, the Young's Modulus, $E_2$, in orthogonal fibre direction and the Poisson's ratio, $\upsilon_{12}$, and returns a value between one and zero [Klein et al. 2013]. Since the material properties are known or can be assumed with reasonable accuracy, only the deviation, α, from the ideal fibre orientation has to be computed to get a measurement for the exploitation of the stiffness characteristics. However, the computation of the deviation, α, turns out to be very difficult as both the anisotropy and the deviation of the load cases have to be related to the function, S. Furthermore, in this case the stress state can be evaluated best in the fibre coordinate system. This is why the following proceeding to compute the stiffness coefficient is pursued. The first step is the transformation of the element stress tensors into the fibre coordinate system, 1-2, taking into account the changing stress state.

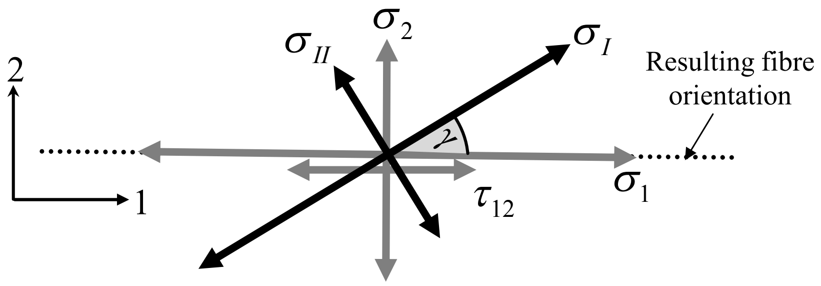


**Figure 5. Transformation of stresses into the fiber coordinate system**

In Figure 5 the transformation is sketched out. In this example the stress trajectories or simply the mean stresses $\sigma_I$ and $\sigma_{II}$ have to be transformed into the fibre coordinate system about the angle $\gamma$. This transformation can be carried out with

$$\underbrace{\begin{bmatrix} \sigma_1 & \tau_{12} \\ \tau_{12} & \sigma_2 \end{bmatrix}}_{\underline{\sigma}^*} = \underbrace{\begin{bmatrix} \cos(\gamma) & \sin(\gamma) \\ -\sin(\gamma) & \cos(\gamma) \end{bmatrix}}_{\underline{T}'} \underbrace{\begin{bmatrix} \sigma_I & 0 \\ 0 & \sigma_{II} \end{bmatrix}}_{\underline{\sigma}} \underbrace{\begin{bmatrix} \cos(\gamma) & -\sin(\gamma) \\ \sin(\gamma) & \cos(\gamma) \end{bmatrix}}_{\underline{T}} \tag{3}$$

where T is the transformation matrix, σ the initial stress tensor and σ* the resulting stress tensor in the fibre coordinate system. After the stress transformation the new stress state in fibre direction can be visualised (see Figure 6).

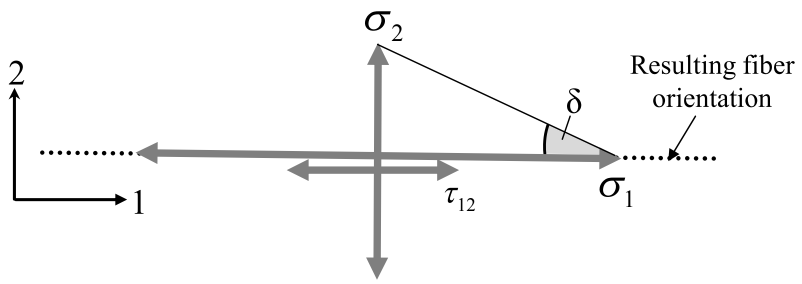


**Figure 6. Resulting stress state in the fiber coordinate system**

Since the normal stresses $\sigma_1$ and $\sigma_2$ can both be positive and negative, they are visualised with an arrow at each end of the line. Through this visualisation, a measurement to evaluate the stiffness exploitation with the help of equation (2) can be derived. It is the so called stress angle δ within a triangle constructed with the help of the normal stresses. This angle be calculated with the simple formula

$$\tan(\delta) = \frac{\sigma_2}{\sigma_1} \tag{4}$$

With a simple derivation it can be shown that this stress angle, δ, equals the angle α in Figure 1 and, therefore, represents the stress state on which the introduction of the relative stiffness, S, was based in chapter 2. In Figure 7 a plate with an applied load F and a fibre orientation deviating from the ideal fibre direction about the angle α is shown.

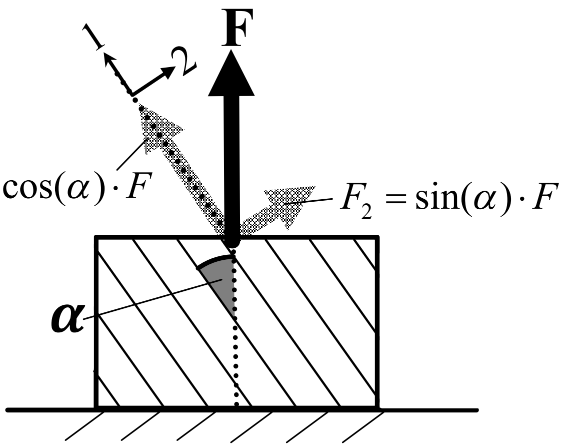


**Figure 7. Derivation of the stress angle δ - plate under tension**

The loading of the plate results in a force $F_1$ in fibre direction and a force $F_2$ in matrix direction. With the help of this relation it can be proven that the angle δ equals the angle α:

$$\tan(\delta)=\frac{\sigma_2}{\sigma_1}\underset{\sigma=\frac{F}{A}}{=}\frac{F_y}{F_x}=\frac{\sin(\alpha)\cdot F}{\cos(\alpha)\cdot F}=\tan(\alpha) \tag{5}$$

Knowing that the angles α and δ are identical, the last step of the procedure of determining the stiffness coefficient can be made. The angle δ for the stress state of every single load step is inserted in equation (2), which returns a value between 1 and 0 dependent on the anisotropy of the stress state and the deviation from the fibre orientation.

The use of the stress angle δ is advantageous in many different ways. Firstly, the anisotropy of the stress state as well as the deviation of the loading direction from the fibre direction can be considered at one time, with only one single criterion and based upon a physical fact. Particularly at the early design stage when the effort has to be kept low this is a big advantage. Furthermore, this procedure works for both one single loadcase and multiple load cases in the same way.

### 4.3 The Strength Coefficients $c_f$ and $c_m$

Besides the good stiffness characteristics, composite materials have another big advantage compared to conventional lightweight materials like aluminium or hardened steel – their high strength values. But again, the strength characteristics are highly dependent on the fibre alignment and product developers have to be very careful. This is the reason why they have to be informed and warned if the product design is endangered by material failure.

In general, there are two different failure mechanisms for unidirectional laminates: Fibre Failure (FF) and Inter Fibre Failure (IFF) (A more detailed description can be found in [Schürmann 2007]). In order to describe the failure of unidirectional laminates, many different failure criteria have been created, like the Tsai/Wu criterion or the Hashin criterion. One of the most popular criteria is the so called PUCK criterion which is an extension of the hypotheses of Mohr and Coulomb to composites (see [Puck 1996] and [Puck et al. 2002]). This criterion is the basis for the evaluation of composite suitability with respect to strength. But in order to keep the expense for the evaluation of strength low, the Puck criterion has to be simplified, because Puck considered three different fracture modes to describe matrix failure. Within this evaluation approach only the Puck criterion for IFF fracture under tension is taken into consideration and it is assumed that the following equation also belongs to stress states with pressure stresses. This simplification leads to a more strict evaluation because the pressure strength is in general higher than the tension strength. The equation for the Puck IFF criterion, $p_{IFF}$, under tension can be written as

$$p_{IFF} = \sqrt{\left(\frac{\tau_{12}}{R_{\perp\|}}\right)^2 + \left(1 - p_{\perp\|}\frac{R_{\perp}}{R_{\perp\|}}\right)^2 \left(\frac{\sigma_2}{R_{\perp}}\right)^2} + p_{\perp\|}\frac{\sigma_2}{R_{\perp\|}} \leq 1 \qquad (6)$$

where $R_{\perp\|}$ denotes the transverse/parallel shear strength, $R_{\perp}$ the transverse tensile strength and $p_{\perp\|}$ the inclination parameter for which a value between 0.3 and 0.35 can be assumed. The stresses needed for the equation result from the stress transformation in chapter 4.2.
The Puck criterion for FF is much simpler than the one for IFF since FF only occurs when the stress in fibre direction exceeds a certain value. For this reason the equation for the Puck fibre criterion $p_{FF}$ can be written as

$$p_{FF} = \frac{R_{\|}}{\sigma_1} \leq 1 \qquad (7)$$

with the strength $R_{\|}$ in fibre direction and the stress $\sigma_1$ in fibre direction [Puck 1998].
Both equations provide one single positive value where values above 1 denote matrix or fibre failure. However, as the criterion for composite suitability provides a value of 1 for highly suitable product designs the values from equation (6) and (7) have to be subtracted from '1'. Additionally, in order to give only elements with 'marginally acceptable' (= PUCK value near 1) stress states high relevance, the resulting values from the Puck criterion are squared. With this modification, the strength coefficients $c_M$ and $c_F$ are

$$c_M = 1 - \left(p_{IFF}\right)^2 = 0...1 \qquad (8)$$

and

$$c_F = 1 - \left(p_{FF}\right)^2 = 0...1 \qquad (9)$$

#### 4.4 The Weighting Coefficient $w_g$

In the evaluation process the coefficients for stiffness, $c_S$, as well as the coefficients for strength, $c_M$, and, $c_F$, for each element and each single load cases are computed and multiplied by each other in order to get a value for the composite suitability of the element. However, the different load cases do not have the same relevance for the element as some load cases may lead to high stress states whereas other load cases can be neglected. To take into account the differing impact of the load cases on the composite suitability of the element a weighting coefficient is computed. It is based on the assumption that a load case causing a high stress state is more relevant than a stress state causing only low stresses. The weighting coefficient $w_g$ can be computed via

$$w_g = \frac{\left|\sigma_j\right|}{\left|\sum_{i=1}^{n} \sigma_i\right|} = 0...1 \qquad (10)$$

In equation (10) the numerator symbolises the stress $\sigma_j$ caused in load case j and the denominator the sum of all stresses $\sigma_i$ caused by the load cases. The result of the computation is a value between 1 and 0 for each load case according to the stress state which is caused by this load case.

## 5. Using the approach for the evaluation of parts

Within the following chapter the approach will be tested using two different examples. The principle aim is to show that the results of the evaluation criterion are plausible and can be used in order to evaluate or possibly improve the structure for composites. All examples consist of one single layer. However, the extension to multi-layer composite structures is part of future work (see chapter 6).

### 5.1 Evaluation and optimisation of a simple plate

The first example to be presented for the evaluation of the approach is a simple plate under a bending load (see Figure 8).

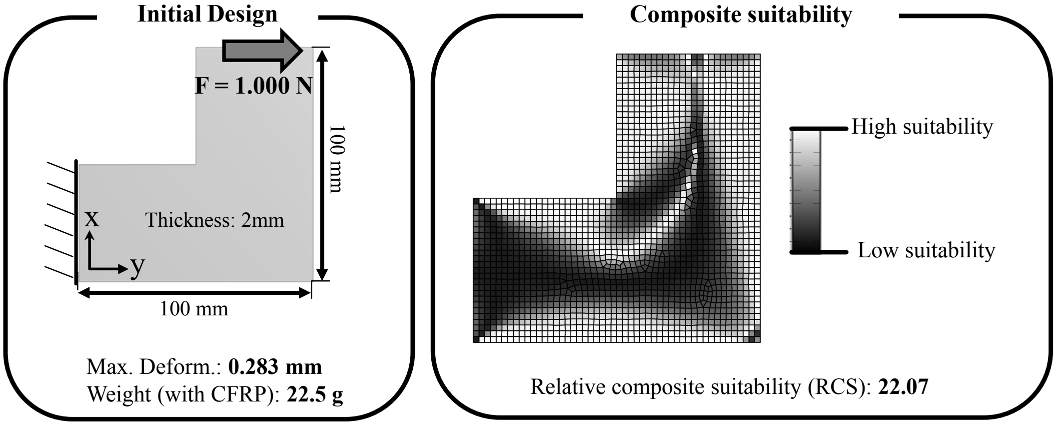


**Figure 8. Load case and resulting composite suitability for a simple plate**

For this model the composite suitability pursuing the process in Figure 2 is determined and the maximum deformation in y-direction with a fibre orientation from the CAIO method as well as the weight of the part is computed. Considering the results for the composite suitability of the part, two main areas can be found where the product design is unsuitable. The first one is the area in the middle of the plate which is unsuitable because of the change from tension to pressure and the resulting isotropic stress state close to the neutral fibre of bending. The second one is the area close to the notch where the composite suitability is decreased because of the complex stress state and the high stress values, which lead to a decreased exploitation of both stiffness and strength. To receive a value for the classification of the overall composite suitability of the part and to make a comparison between two part designs possible, the so called Relative Composite Suitability, RCS, is introduced. For the computation of the RCS it is assumed that it is more important to have a high composite suitability in areas of high stresses than in unloaded areas. The equation can be written as

$$\mathrm{RCS}=\sum_{i=1}^{l}\frac{\sum_{l=1}^{n_e}\mathrm{CS}\cdot\sigma_{max}}{n_e} \tag{11}$$

where the products of the composite suitability, CS, and the maximum mean stress value, $\sigma_{max}$, of each element are summed up and divided by the number of elements, $n_e$, to get the average value of all elements. In the case of several load cases, *l*, the resulting values can be summed up again to get only one single value. For the plate from Figure 8 a value of 22.07 can be computed. However, as it has already been mentioned, this part design is unsuitable for a composite material in large areas and, therefore, has to be modified. The first critical area around the notch can be improved with the help of a simple rounding to reduce the locally high stresses and the complexity of stress state. The composite suitability in the middle of the part can be increased with a geometry inspired by a topology optimisation. Due to this design optimisation based on the evaluation criterion, the weight of the part can be decreased by 57.6 % without a significant decrease in part stiffness (see Figure 9).

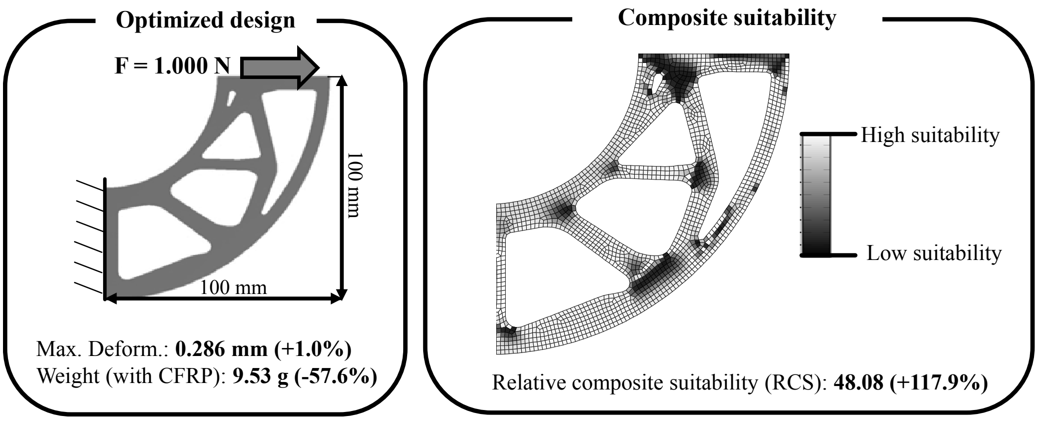


**Figure 9. Load case and resulting composite suitability for the optimized plate**

This improvement of the structure can also be quantified with the help of the RCS, which can be increased by 117.9 % to a value of 48.08. The reason for this dramatic increase in composite suitability can be found in the rod system which consists of simple tension and pressure rods. Therefore, the stress trajectories point in axial direction of the rods without a considerable stress in the orthogonal matrix direction, which is highly suitable for composites. However, the suitability decreases in the area of the nodes where the different rods come into contact with each other, because at these nodal points the stress states become very complex and, additionally, the resulting trajectories in this area indicate an isotropic stress state. As a consequence, the suitability for a composite design is decreased in this area.

Nevertheless, this kind of rod system is highly suitable for composites, as it will be shown with the help of a bike frame.

### 5.2 Evaluation of a bike frame

In Figure 10, the concept of a bike frame is shown for which two different load scenarios are assumed. The first load case considers the weight of the cyclist while riding the bike on a plane street and the second load case tries to imitate the load while riding over an obstacle.

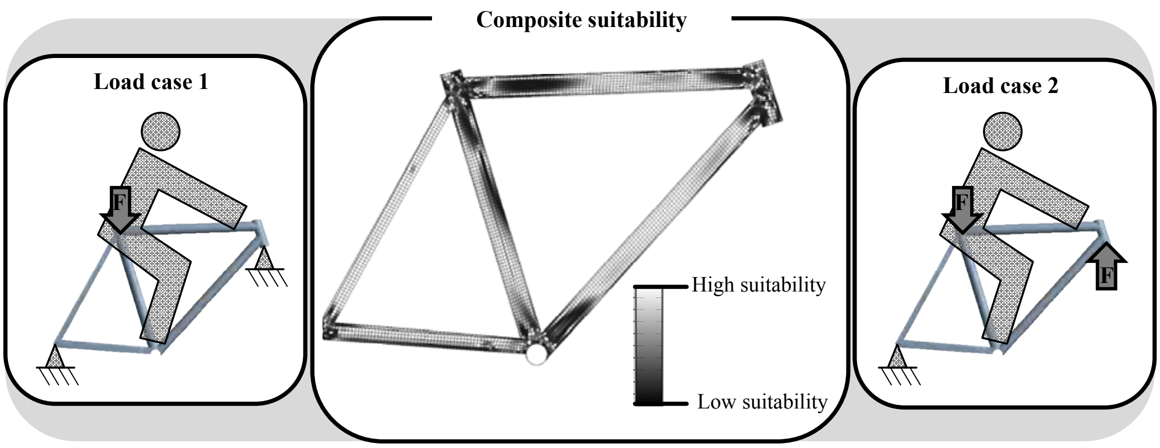


**Figure 10. Load cases and result of the evaluation of a bike frame**

In order to evaluate this frame concept with respect to its composite suitability, again a finite element model for each load case with an isotropic material model (in this case a simple material model for steel) is created and used for the evaluation process. It becomes obvious that the composite suitability of the observed bike frame in general is very high, and, especially in the area of the rods, the frame is highly suitable for a composite design. However, in the area of the nodes a decreased composite suitability is indicated as the stress state in this area is complex, isotropic and has high absolute values. As a result, an exploitation of the stiffness and the strength characteristics of CFRP is only possible to a limited extent. Nevertheless, the generally good results for the composite suitability meet the expectations for such an evaluation tool since many bike frames have already been developed and manufactured of CFRP with great success and the weight of bike frames is constantly decreasing. Furthermore, if you take a quick look at these modern bike frames, it becomes obvious that the nodal points of the rods have been improved for a composite design as it is indicated by the evaluation tool.

## 6. Summary and future work

The use of composite materials is a tightrope walk between costs and lightweight potential for product developers as the higher price for composite materials can only be justified if the material characteristics and as a consequence the lightweight potential is fully exploited.

Within this article, a novel approach for the evaluation of the composite suitability of lightweight structures was introduced, which is intended to give support to product developers. It is based upon the assumption that in general the most important characteristics of composites for product developers are the high stiffness and strength characteristics. However, both stiffness and strength are highly dependent on the fibre orientation. Therefore, a suitable fibre orientation for multiple load cases is computed (chapter 4.1) and the exploitation of the strength (chapter 4.3) and stiffness (chapter 4.2) characteristics for each load case and within each element is observed taking into account the resulting fibre orientation. Besides the computation of a resulting fibre orientation for multiple load cases, a special novelty within this article is the introduction of a stiffness criterion, which unifies the consideration of the anisotropy of stresses and load case related matrix loading within one single criterion. In the last chapter it could be shown, with the help of some examples, that the introduced evaluation criterion provides good results and can be used in order to evaluate lightweight structures.

However, within this article only one single layer is used to show the principle of the evaluation criterion. Since composite structures often consist of more than one layer, it is a future task to extend the approach to multiple layers and observe the change of the evaluation results of a multi-layer evaluation. Therefore, an element type which allows a multi-layer model is used for the finite element model (see Figure 2). With these elements multiple layers can be modelled with through thickness integration points and each layer can be evaluated according to the approach in this article. Nevertheless, an extension to a multi-layer evaluation is linked to higher expenses and the use at the early design stage should be considered thoroughly.

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