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INTRODUCTION OF A COMPUTATIONAL APPROACH FOR THE DESIGN OF COMPOSITE STRUCTURES AT THE EARLY EMBODIMENT DESIGN STAGE

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Abstract

The imminent climate change, the increasing environmental pollution or the dwindling of resources - all these points have made lightweight design more and more relevant for many different industries. Whenever masses in motion can be reduced, the energy efficiency, and therefore, the sustainability of a product is increased. A common way to reduce the weight of technical products or systems is the use of lightweight materials like aluminium or titanium. However, over the last few years and decades a novel material class has become more and more popular in lightweight design - the so called composite materials where a weak matrix material is reinforced with fibres. The aim of this paper is to show the challenges in the design of composite structures and, for the first time, to give a complete overview of a novel computational design approach which was developed over the last few years. It should be pointed out here that the regarded composite parts in this article are thin-walled parts made of endless CFRP with an unidirectional fibre reinforcement.

Keywords: Lighweight design, Virtual engineering (VE), Computational design synthesis, Design for X (DfX), Early design phases

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1 INTRODUCTION

The imminent climate change, the increasing environmental pollution or the dwindling of resources - all these points have made lightweight design more and more relevant for many different industries. Whenever masses in motion can be reduced, the energy efficiency, and therefore, the sustainability of a product is increased. A common way to reduce the weight of technical products or systems is the use of lightweight materials like aluminium or titanium. However, over the last few years and decades a novel material class has become more and more popular in lightweight design - the so called composite materials where a weak matrix material is reinforced with fibres.

Particularly in the aviation sector, the use of composites has been increasing rapidly over the last decades. Starting from a structural weight of composites of about three percent for the airplane Boeing 767 in 1982, the structural weight has been increasing to 52 percent for the Airbus A350 by the year 2014 (United States Government Accountability Office, 2011). And yet, an end of this development is not in sight since the energy efficiency of airplanes has become more and more relevant. Furthermore, the combination of different good mechanical and physical properties like high stiffness and strength or the low density make composites an attractive design material in many different industries far beyond the aviation sector. In the automotive sector, for instance, very contradictory requirements like high energy absorption and stiffness at low weight can be satisfied by the use of endless carbon fibre reinforced plastics (short: CFRP).

Despite these promising use cases, the use of CFRP for automobiles or other mass products has not been established, yet, since manufacturers are facing various challenges like high costs, complex and expensive manufacturing processes and a very complicated design process which is the focus of this article.

The aim of this paper is to show the challenges in the design of composite structures and, for the first time, to give a complete overview of a novel computational design approach which was developed over the last few years. It should be pointed out here that if the general term “composite” is used in this article there is talk of thin-walled parts made of endless CFRP with an unidirectional fibre reinforcement.

2 CHALLENGES IN THE DESIGN OF LIGHWEIGHT COMPOSITE STRUCTURES

The lightweight potential of CFRP can be defined as the specific material strength in relation to the specific Young's Modulus. It is very high compared to many conventional materials. An unidirectional reinforced laminate can have a specific material strength of up to 1800 MPa/(g/cm³) and a specific Young's Modulus of 100 GPa/(g/cm²) whereas aluminium has only got a specific material strength of about 300 MPa/(g/cm³) and a specific Young's Modulus of 25 GPa/(g/cm²) (Michaeli, 1994). However, in many cases the lightweight potential of composite materials is not fully exploited. During the design process of composite parts many different and mutually dependent parameters have to be defined. Additionally, the mechanical behaviour of composite structures is highly sensitive to the chosen parameters. Even small deviations of these parameters from the ideal result in a significant decrease of the mechanical behaviour. For all these reasons, the design process of composite structures is challenging and opaque for product developers.

In contrast to many conventional lightweight materials, composite structures have an inner structure which has a big influence on the mechanical behaviour of the part. In general, unidirectional composite structures consist of n different layers, altogether stacked to a laminate (see Figure 1). Each layer has got a fibre orientation angle α_n which defines the direction of the carbon fibres in the layer and a layer thickness t_n. The layer number, the layer geometry (= patch) and the thickness can be varied for different areas of the part. Especially in areas of high and complex stress states, the number of layers and each layer thickness has to be increased. In areas of low and unidirectional stress states, on the contrary, both parameters have to be kept low in order to decrease the part weight. However, the unique mechanical properties of composites can only be exploited if the right stacking sequence for the layers is chosen. A wrong order of the layers could result in an unfavourable load distribution within the laminate, and therefore, a decreased stiffness or even failure of the part. Beside the variety of parameters resulting from the inner laminate structure, there is another point which makes the design of composite parts further challenging - the mutual dependency of all these parameters.

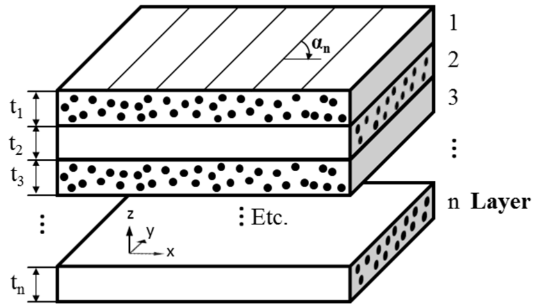

Figure 1. General structure of endless fibre reinforced composites

If one parameter is changed, the others will be affected. For example, if the fibre orientation has to be changed, the load distribution within the laminate is changed. Consequently, the stacking sequence, the layer thicknesses or both have to be adjusted. Especially for complex parts the definition of these parameters can be very challenging. Nonetheless, it is essential to find a laminate structure with a good load distribution because if the matrix is loaded the good mechanical characteristics of composites cannot be exploited. Even small deviations from the ideal might lead to a significantly decreased mechanical behaviour.

With the help of a simple plate it could be shown in Klein (2013) that even small deviations from the ideal fibre orientation lead to a tremendous decrease in mechanical part stiffness. A deviation of only 10 degrees from the ideal fibre orientation results in a decrease to 66 percent of the initial stiffness for CFRP. Indeed, this tremendous decrease is not only a phenomenon which occurs for CFRP. The relative stiffness of all the other composites, for example Basalt Fibre (BFRP) or Glass Fibre Reinforced plastic (GFRP) is highly sensitive to the fibre orientation (Klein et al., DESIGN 2014). Therefore, the choice of a suitable fibre orientation is crucial for many other composites, too (Gruber et al., 2012).

3 EXISITING APPROACHES ON THE DESIGN OF COMPOSITE PARTS

Over the last few years and decades, various different design approaches and design aids have been published. One of the first aids for the design of composite parts was the net theory. In this theory it is assumed that only in fibre direction loads can be transferred in some kind of net. However, the use of this aid is restricted to simple parts since the real conditions within composite parts are highly simplified. A more detailed design aid is the Classical Laminate Theory (CLT). In this method the stiffness of each single layer is modelled and all stiffness matrices are assembled together in an overall stiffness matrix. With the help of this overall stiffness matrix the strains and stresses for each layer can be computed and analysed in order to improve the part and, again, to compute the strains and stresses (Schuermann, 2007). Even today the CLT is widely spread in the industry and the basis of different commercial software tools for the early embodiment design. Beside this kind of design aids, more general methodological approaches from the first definition of requirements to the end of the laminate set-up exist (for example in the VDI 2014). The task of these methodological approaches is to structure the whole design process and give an advice when to use which aid in the design process.

The big problem about all these approaches and design aids is that for geometric complex parts with different load cases they often do not lead to the desired result. The complexity of designing composite parts makes the use of computational methods and design approaches inevitable even at the early embodiment design.

Therefore, different computational design approaches were published (e.g. in Gambling, 2013). Until now, the most promising approach is the approach according to ALTAIR which has already been successfully used in the industry. The approach by ALTAIR can be divided into three different steps in which the parameters of the composite structure are defined separately (see Figure 2). In the first step, the so called free-size optimization, a finite element model for each load case is created and the possible layers with respect to a user-defined coordinate system are pre-defined (for example a 0°-, 45°-, 90°- and -45°-layer). Based on this model the thickness of each layer in each element is determined using a free-size optimization algorithm.

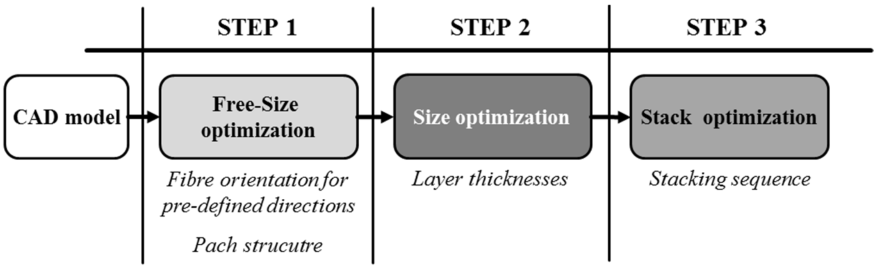

Figure 2. Overview of the approach according to ALTAIR

The result is a thickness distribution over the part wherein unnecessary layers have a thickness of zero. Based on this thickness distribution the patches can be defined. In the first step of the approach each element can have an individual thickness but each patch can only have one single thickness, so far. Additionally, it is a common design rule to split one thick patch into numerous different patches. Therefore, in step 2 the defined layers are split and the thicknesses of the patches are computed with the help of another optimization algorithm. In the last step the stacking sequence of the patches considering various designs and manufacturing constraints is determined with the help of another optimization algorithm (Ming et al., 2009).
Though this design approach is very promising and useful for the design of composite structures, disadvantages can be encountered. First of all, the fibre orientations have to be pre-defined in step 1. However, if a wrong fibre orientation is chosen there can be a large deviation from the ideal fibre orientation. Considering the example with the 0°-, 45°-, 90°- and -45°-layer, the deviation can be 22.5° if the ideal fibre lies between two pre-defined fibre orientations. This could result in an enormous decrease in part stiffness (see Klein, 2013). Additionally, the fibre orientation is defined with respect to a user-defined coordinate system. Thus, the results are dependent on the correct definition of the coordinate system. Especially for geometric complex parts, the definition of these coordinate systems can be a big challenge because product designers do not know the fibre orientation at this stage and have to choose coordinate systems based on experience. In an investigation using a very simple model the high dependency of the part stiffness on the choice and number of coordinate systems could be shown. A bad choice of coordinate systems led to an increase of the measured deformation of 87 % compared to the best result. Furthermore, various different optimization algorithms have to be used in order to determine the parameter set. The problem is that in the early embodiment design stage the use of various different optimization algorithms is not suitable since according to PAHL and BEITZ (2013) many different concepts have to be pursued using an iterative process to improve the initial design. The use of complex optimization algorithms at this design stage results in high computation and modelling times as well as a complicated handling.

4 A NOVEL COMPUTATIONAL APPROACH ON THE DESIGN OF COMPOSITE PARTS

In the following chapter, a novel computational approach will be presented. The primary goals of the approach are to unfold the mutual dependency of the parameters as far as possible so that the parameters can be defined separately. The approach must be coordinate invariant and basic engineering considerations instead of various different and complex optimization algorithms shall be used. The proposed design approach consists of four different steps in which the parameters are defined on one another (see Figure 3). Starting point of the design approach is a CAD model which represents the geometry of the part. In the first step, a so called Modified Multi-Layer CAIO Method is used to compute the fibre orientations and the number of layers which are needed to transfer the loads within the part. Based on these results, areas of comparable fibre orientations can be computed using a novel cluster algorithm. The highlighted clusters serve as a first proposal for the manual definition of a patch structure. After this, a stacking sequence can be defined in step 3, before the layer thicknesses are computed with a genetic algorithm in step 4. The result of the design approach is a first laminate

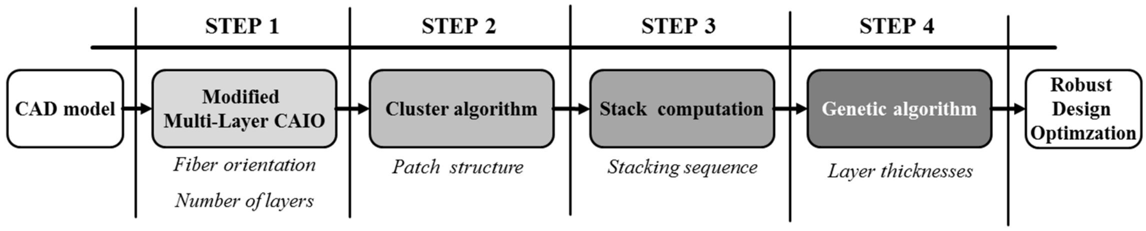

Figure 3. Overview over the design approach

structure for the part which can be used as a starting point for Robust Design methods which were presented in Eifler (2013).

It is very important to point out that in general, the result of the approach is not a laminate structure completely ready to manufacture if it is the aim of the product developer to exploit the whole lightweight potential of composites. Various variances, for example, in the material or in the manufacturing process have to be considered during the design process since the mechanical properties of composites are highly sensitive to these variances (Kellermeyer, 2012). The result of the introduced design approach shall be a first intelligent design proposal in order to reduce the computation time and quality of the Robust Design Optimization.

Unfortunately, all the existing design approaches neglect the importance of variances for the behaviour of composite parts. On the other hand, for Robust Design Optimizations Methods very often models are used which were designed by experience. Therefore, the results of the Robust Design Optimization as well as the mechanical behaviour of the part may be not satisfactory.

4.1 STEP 1: Modified Multi-Layer CAIO

For a simple geometry like a plate it is very easy to define a suitable fibre orientation. Defining a suitable fibre orientation for a complex part can be a challenging task. To solve this problem, a new method to compute the fibre orientations in geometric complex structures - the so called CAIO (Computer Aided Internal Optimization) method which aligns the fibres in Finite Element models (= FE model) in mean stress directions iteratively - was developed in (Kriechbaum, 1994). This computational method is based on an observation made in (Mattheck, 1991). He observed that wood fibres grow along the mean stress directions in an iterative manner in order to obtain a fibre orientation with a minimum of fibre shear stress. If the fibre orientation of the CAIO method is used for the design of composite parts, the mechanical properties of the part can be increased significantly (Klein et al., 2013).

Unfortunately, this basic CAIO method cannot be used within this design approach without some modifications because there are disadvantages in the practical use. First of all, the method is restricted to single layers but real parts consist of various different layers (see chapter 2). Additionally, the fibres are aligned in direction of the maximum mean stress direction. However, in some areas of the part isotropic mean stress states can occur which means all mean stresses have the same absolute value. In this case one direction has to be chosen and all the others are neglected. To overcome these problems the basic CAIO method has to be modified.

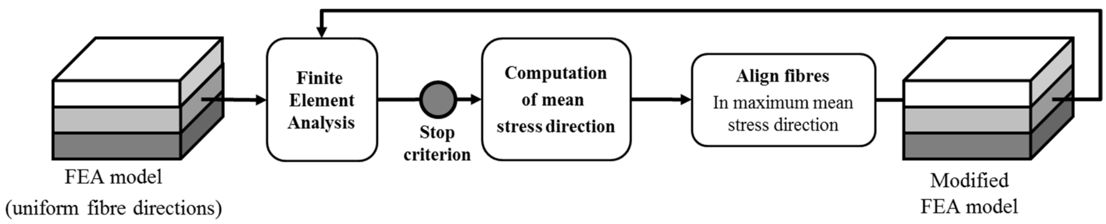

Figure 4. Structure of the Multi-Layer CAIO (based on Reuschel,1999)

The principle of this Multi-Layer CAIO (ML-CAIO) is shown in Figure 4. At first a FE model with shell elements and all necessary boundary conditions like constraints, loads, etc. is created. Each shell element in the model is a so called layered shell element which means that each shell consists of different layers which are modelled with the help of through thickness integration points. At the beginning of the ML-CAIO, the number of layers and the fibre orientations are arbitrary but constant for all shell elements. This first FE model is solved, the mean stress directions in each element layer are computed and the fibres of the FE model are aligned in the mean stress directions (each element and layer separately). In this case, the alignment of the fibres in the mean stress directions is permissive due to the consideration of each mean stress for the computation of the layer number at the end of this chapter. The modified FE model is solved again and the fibre orientations of the new model are compared to the preceding one. If the difference is significant a new iteration starts, otherwise the algorithms stops. The result of the ML- CAIO is the mean stress directions within each layer for the regarded load case.

However, there is more than one single load case for many parts. Therefore, many different runs of the ML-CAIO have to be performed in order to compute all the stress states which occur for the part (see Figure 5a).

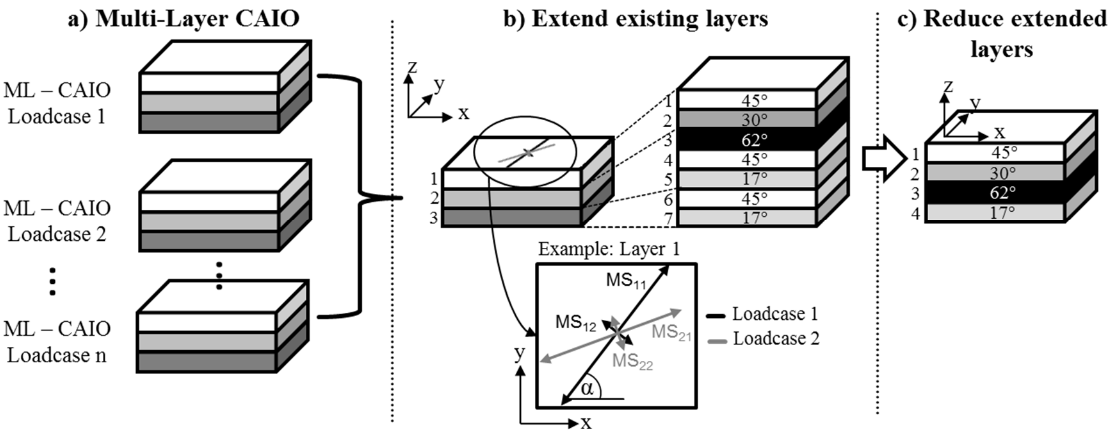

Figure 5. Computation of the layer number and fibre orientations

After this, all stress states are collected (see Figure 5b). The collected stress states are the basis for the layer number computation and the fibre orientations because whenever there is a significant mean stress, a layer is needed to bear the load. To explain the computation procedure, layer 1 and two different load cases are chosen as an example (see Figure 5b again). The result is the mean stresses MS_{11} and MS_{12} from load case 1 as well as MS_{21} and MS_{22} from load case 2. At first, mean stresses with a small absolute value are deleted because it is assumed that these stresses do not need an own layer. As a result, only the mean stresses MS_{11} and MS_{21} remain. After this, the directions of the remaining stresses are compared. If there is no significant difference between the orientations, the mean stress vectors are added up. In this case, the difference between MS_{11} and MS_{12} is significant and both mean stresses need an own layer. Thus, layer 1 is extended to two different layers with the orientation (= angle α) of MS_{11} for the first one and of MS_{21} for the second one. This procedure is performed for each layer of each finite element in the model. However, the extension of the initial layers may lead to layers with equal fibre orientation. For this reason, all double layers are deleted so that for each fibre orientation only one layer is remaining (see Figure 5c). In contrast to the approach according to ALTAIR, no fibre orientation is pre-defined in this procedure and no result is coordinate invariant since the mean stresses are used. For this reason, there is no deviation from the ideal fibre orientation at this stage.

4.2 STEP 2: Computation of the patch structure with a cluster algorithm

The result of step 1 is the number of layers as well as the fibre orientation for each single finite element individually which means that both parameters can vary over the part. Especially in areas of load introduction, the number of layers increases and various different fibre orientations are needed whereas in areas of low stresses fewer layers and fibre orientations are sufficient. However, this kind of laminate structure with different fibre orientations and number of layers for each finite element is obviously not manufacturable. For many different manufacturing processes (e.g. hand lamination) areas in the part must be defined where carbon fibre mats or prepregs (= patches) can be placed and various different restrictions in the manufacturing process have to be considered.

To support product developers in the definition of a manufacturable patch structure, a cluster algorithm is used after step 1 because there is one thing all patch structures have in common: the fibre orientation within a patch does not change. Therefore, a cluster algorithm is used which finds and

highlights areas of constant fibre orientation. The resulting clusters offer a first impression where patches could be placed in order to realize as much of the computed fibre orientations as possible.
In Figure 6a, the resulting finite element model from step 1 with different layer numbers and fibre orientations is shown. As explained, the target is to find areas of constant fibre orientation. Therefore, a starting element and the first layer of this element is selected (Figure 6a) and a first cluster with this layer is opened. In the following, all the neighbour elements are identified (see Figure 6b) and the fibre orientation of the starting layer is compared to all the layers of the neighbour elements. If the difference between the fibre orientations is within a given tolerance, the layer of the neighbour element is added to the cluster. To illustrate the comparison process, in Figure 6b the finite element which was computed in Figure 5 with the 45°-, 30°-, 62°- and the 18°- layer and two of the neighbour elements are shown. The starting layer is the 45°-layer.

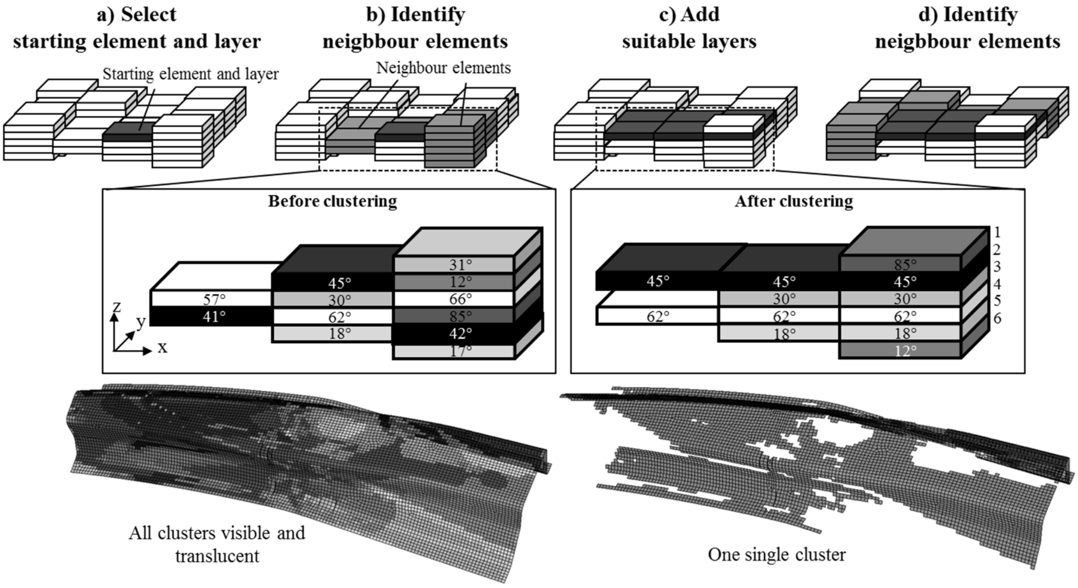

Figure 6. Overview over the cluster algorithm

In this example, a tolerance of ±5° is chosen for the comparison, and therefore, the 41°-layer in the left neighbour element as well as the 42°-layer in the right neighbour element is added to the cluster. After all suitable layers of the neighbour elements have been added to the cluster, the new layers get the fibre orientation of the starting layer. This means the 41°-layer in the left element and the 42°-layer in the right element get a fibre orientation of 45° (see Figure 6c). In the following, the neighbour elements of the grown cluster are identified (see Figure 6d) and again the fibre orientations of the neighbour elements are checked and added to the cluster if the difference is within a given tolerance. To reduce computation times, only the layers in neighbour elements which have not been checked, yet, are considered. This iterative process proceeds until no new layer of a neighbour element can be added to the cluster. In this case the cluster is closed and a new one is opened, selecting the next layer of the starting element as first layer in the cluster (in this case the 30°-layer). The whole algorithm stops when each layer of the model has been added to a cluster.
At the end of the cluster algorithm the computed clusters can be highlighted to visualize areas of constant fibre orientation. In Figure 6, a simplified b-pillar is shown as an example. On the left all clusters are visible and translucent. On the right, only one single cluster with a constant fibre orientation is shown. With this visualization, product developers are supported in the definition of patches which are both manufacturable and as close to the computed fibre orientation as possible. Additionally, the results can support in finding a suitable manufacturing technology (Klein et al., CIRP Design 2014) because not every patch structure can be produced with arbitrary manufacturing technologies. It has to be pointed out that the visualized clusters are only an aid for product developers to define the patches manually. A direct use of the clusters as patches is not recommended at the moment.

4.3 STEP 3: Defining the stacking sequence

At the beginning of step 3 a first patch structure based on the finite element mesh has been defined for the part. The result for a simple example can be seen in Figure 7a. Two manufacturable patches with an irregular, dissimilar geometry were defined, both patches overlap in some areas and the stacking sequence of these patches is unknown at this stage. To compute the best stacking sequence for the defined patches, again the premise to put fibres whenever there is a significant load is used. The basic idea of the procedure in step 3 is to compare the fibre orientations of the patches from step 2 to the mean stresses from step 1 and to find the stacking sequence with the biggest overlap (see Figure 7b).

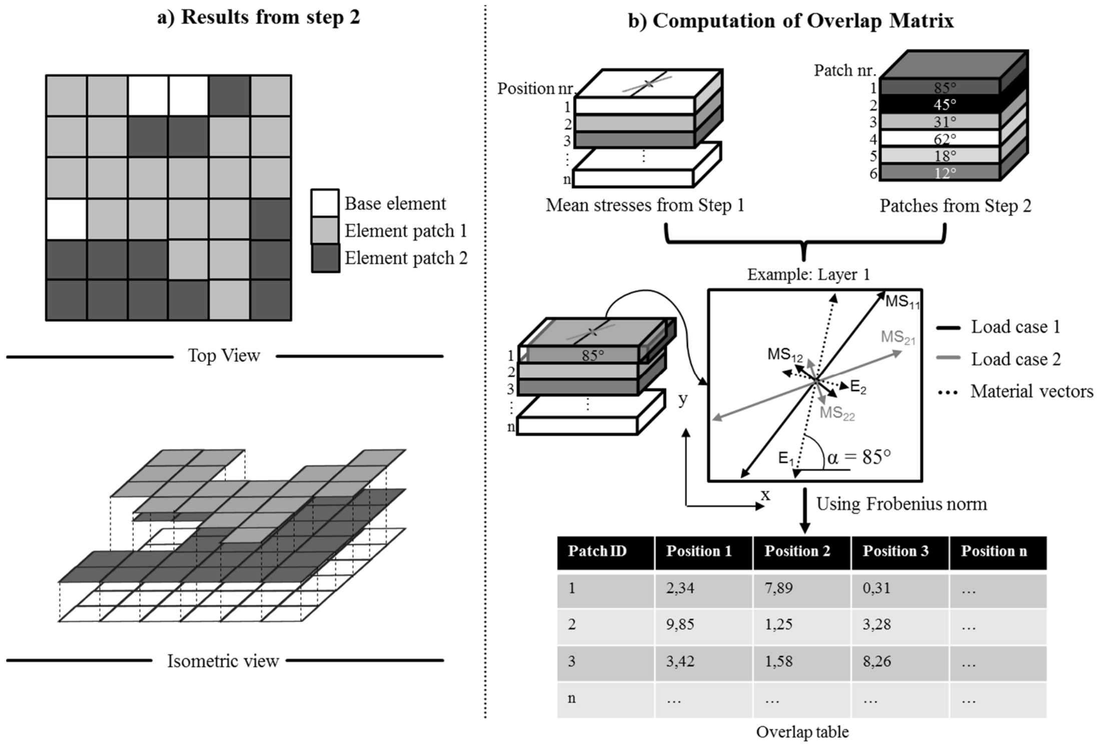

Figure 7. Computation of the stacking sequence with the help of an Overlap Matrix

For this reason, each patch from step 2 is put into each layer from step 1 and a value for the overlap of the fibre orientation of the patch and the mean stresses is computed. Based on these values the stacking sequence with the biggest overlap is chosen. To illustrate the procedure for one single finite element, the first layer from the element in step 2, the 85° layer, is selected and put into the first position of the model from step 1 with the mean stresses MS_{11}, MS_{12}, MS_{21} and MS_{22}. In the following, the so called material vectors, E_1 in fibre orientation and E_2 in orthogonal fibre orientation, with the Young's Moduli of the fibre and the matrix are introduced to represent the composite material and its mechanical properties. To compute a single value for the overlap, the Frobenius norm is used because this norm is computationally much more efficient than existing approaches with ellipses (see Gruber, 2013). However, before this norm can be used a mathematical description for the problem has to be found. Therefore, a material matrix with E_1 and E_2 for the fibres and a stress matrix with MS_{11}, MS_{12}, MS_{21} and MS_{22} is created and both matrices are multiplied:

$$\begin{bmatrix} E_1 e_{1,x} & E_2 e_{2,x} \\ \underbrace{E_1 e_{1,y}}_{E_1} & \underbrace{E_2 e_{2,y}}_{E_2} \end{bmatrix} \cdot \begin{bmatrix} \sigma_{11,x} e_{MS_{11},x} & \sigma_{12,x} e_{MS_{12},x} & \cdots & \sigma_{n1,x} e_{MS_{n1},x} \\ \underbrace{\sigma_{11,y} e_{MS_{11},y}}_{MS_{11}} & \underbrace{\sigma_{12,y} e_{MS_{12},y}}_{MS_{12}} & \cdots & \sigma_{n2,x} e_{MS_{n2},x} \end{bmatrix} = \begin{bmatrix} P_{11} & P_{12} & \cdots & P_{1,n} \\ P_{21} & P_{22} & \cdots & P_{2,n} \end{bmatrix} \quad (1)$$

The resulting matrix P is the projection of the mean stresses on the material axes E_1 and E_2. Based on the matrix P the Frobenius norm with

$$\|A\|_F = \sqrt{\sum_{i=1}^{2} \sum_{j=1}^{n} |P_{ij}|^2} \quad (2)$$

can be used to compute one single overlap value. This procedure is used for each single finite element of the patch and at the end an average Frobenius norm value for all elements of the patch is computed. The result is one single overlap value for the patch in position one. The next step would be to put the 85° patch in the second position and compute an overlap value, again. The final result of the whole algorithm is an overlap value for each patch in each position as the overlap table in Figure 7 indicates. With the help of this table the stacking sequence with the biggest overlap can be defined.
However, it is important to mention at this point that design rules for composite structures have to be considered while defining the stacking sequence. For example, the layer set up has to be symmetric in order to prevent unwanted bending moments and it is recommended to split one single layer into numerous thinner layers and distribute these layers over the cross-section of the part. At the current stage, these design rules have to be considered by the product developer manually and the stacking sequence has to be defined in an iterative manner but it will be a future work to include those design rules into the algorithm.

4.4 STEP 4: Computation of the layer thicknesses using a genetic algorithm

The final step of the design approach is the computation of layer thicknesses. This is the first time in the design approach, where a simple genetic optimization algorithm is used. The basic principle of the optimization algorithm is based on the conventional procedure of genetic algorithms.

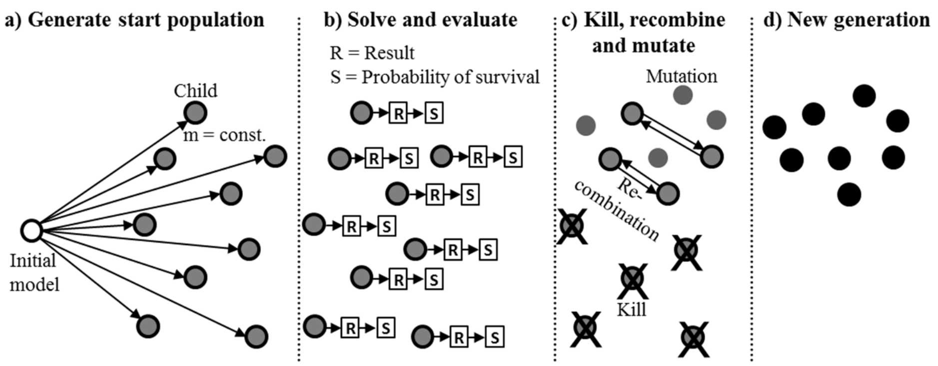

Figure 8. Computation of thicknesses with a genetic algorithm

At the beginning of the algorithm, an initial model with unknown patch thicknesses exists (see Figure 8a). Based on this model, the first child generation with different thicknesses for the patches is created. However, it is very important that the mass of each model is constant, otherwise the algorithm increases the thicknesses endlessly. In the next step, each model is solved and a value to evaluate the fitness of each model is extracted from the results. For this article, mainly the deformation of the part is used but there are various other possibilities like the compliance of the model or different strength criterions for composites. Based on the extracted value, the rank of each individual in the generation is defined and with the help of the rank the probability of survival can be computed using

$$p(I_K)=\frac{2}{N}\left(1-\frac{k-1}{N-1}\right) \quad (3)$$

where N denotes the number of children and k the rank of the child. Based on the probability of survival bad individuals are killed and the others are recombined which means that thickness parameters between individuals are exchanged. Additionally, new individuals with new patch thicknesses are generated which is called Mutation (see Figure 8c). After this, a new iteration with a new generation starts. The whole algorithm stops, if a child has got a deformation value below a previously defined value. At the end of step 4, all parameters of the laminate structure are defined and the model can be used as first intelligent starting point for a Robust Design Optimization.

5 SUMMARY AND FIRST RESULTS

The design of composites structures is challenging because various different and mutually dependent parameters have to be defined. However, existing design approaches are either too simple to exploit the whole lightweight potential for complex parts or too complicated and computationally inefficient to be suitable for the early embodiment design. Therefore, a novel design approach was introduced. The main advantages of the approach are the coordinate invariance and that no fibre orientation has to be pre-defined. Additionally, the design approach is based on basic engineering considerations instead of complex optimization algorithms. As a result, the computation time and the complexity of the algorithm can be decreased. In a first very simple observation the laminate structure for an easy part considering two different loadcases was designed with the introduced design approach. In addition, a model with the CAIO fibre orientation was created for each loadcase because according to theory this fibre orientation must result in maximum stiffness. The layer thicknesses in all models were adjusted so that the mass of all parts was the same and to evaluate the stiffness of the part the deformation was computed for all models. At the end it could be shown, that the design approach shows very good results compared to the results of the CAIO method. However, due to the restricted space of the article, a more detailed description of the results must follow in future articles.

REFERENCES

United States Government Accountability Office (2011) Aviation Safety - Status of FAA's Actions to Oversee the Safety of Composite Airplanes. Report to Congressional Requesters, p. 5 Stichling, J., Hasenberg, V. (2010) Recycling im Automobil-Leichtbau, p. 3

Michaeli, W., Huybrechts, D. and Wegener, M. (1994) Dimensionieren mit Faserverbundkunststoffen. München: Carl Hanser Verlag

Klein, D., Witzgall, C. and Wartzack, S. (2014) A novel approach for the evaluation of composite suitability of lightweight structures at early design stages. In: Marjanovic, D., Storga, M., Pavkovic, N. and Bojcetic, N. (eds) International Design Conference - DESIGN 2014, Dubrovnik, University of Zagreb

Schuermannn, H. (2007) Konstruieren mit Faser-Kunststoff-Verbunden, Berlin: Springer

VDI Gesellschaft Kunststofftechnik (2006) VDI 2014 Part 3. Development of FRP components (fibre-reinforced plastics) Analysis. In: VDI Handbuch Kunststofftechnik

Ming, Z., Fleury, R. and Warren, D. (2009) Composite Design Optimization – from Concept to Ply-Book Details. 8th World Congress on Structural and Multidisciplinary Optimization, Lisbon, Portugal

Gambling, M. and Wang, S. (2013) The Development of TruPly, an Efficient Composite Optimization Tool for Simulia Abaqus. 10th World Congress on Structural and Multidisciplinary Optimization, Orlando, Florida

Pahl, G., Beitz, W., Feldhusen, J. and Grote, K.-H. (2013) Konstruktionslehre: Grundlagen erfolgreicher Produktentwicklung. 8. Auflage. Berlin: Springer Verlag

Klein, D., Scheler, K. and Wartzack S. (2014) Computation and visualization of patch geometries for the design of carbon fibre reinforced parts at early design stages. In: Moroni, G.; Tolio, T., Proceedings of the 24th CIRP Design Conference 2014, Milan

Kellermeyer, M. and Wartzack, S. (2012) Numerische Untersuchung der Einfluesse von Streuungen auf Versagenskritierien von Composite Strukturen. In: Design for X. Beiträge zum 23. DfX-Symposium 2013, TuTech Verlag

Gruber, G., Klein, D., Ziegler, P. and Wartzack, S. (2012) Consideration of Anisotropic Material Properties in Mechanical Design within Early Design Steps. In: Kyvsgård Hansen, P.; Rasmussen, J.; Jørgensen, K. A.; Tollestrup, C. (Hrsg.): Proceedings of the 9th Norddesign, Denmark

Gruber, G., Koessler, J. and Wartzack S. (2013) A visualization methodology for evaluating parts made of short fiber reinforced thermoplastics regarding their lightweight potential. In: Lindemann, U., Venkataraman, S., Kim, Y.S., Lee, S.W., Clarkson, J. and Cascini, G. (eds.) Proceedings of the 19th International Conference on Engineering Design 2013

Kriechbaum, R. (1994) Ein Verfahren zur Optimierung der Faserverläufe in Verbundwerkstoffen durch Minimierung der Schubspannungen nach Vorbildern der Natur. In: Bericht KfK 5406, Kernforschungszentrum

Reuschel, J. D. (1999) Untersuchung der Faseranordnung natürlicher Faserverbunde und Übertragung der Ergebnisse auf technische Bauteile mit Hilfe der Finite-Elemente-Methode. Dissertation. Forschungszentrum Karlsruhe

Mattheck, C. (1991) Trees: The Mechanical Design. Berlin: Springer.

Klein, D., Caballero, S. and Wartzack, S. (2013) Evaluierung unterschiedlicher Theorien zur Berechnung beanspruchungsgerechter Faserorientierungen in CFK-Strukturen. In: Design for X. Beiträge zum 24. DfX-Symposium 2013, TuTech Verlag

Eifler, T., Ebro, M. and Howard, T.J. (2013) A classification of the industrial relevance of robust design methods. In: Lindemann, U., Venkataraman, S., Kim, Y.S., Lee, S.W., Clarkson, J. and Cascini, G. (eds.) Proceedings of the 19th International Conference on Engineering Design 2013, ICED13, Design For Harmonies, Seoul, Republic of Korea.