Computational optimisation strategies of tailored fibre placement in polymer matrix composites based on local shear stress minimisation

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Abstract. The aim of this paper is to present optimisation strategies of Tailored Fibre Placement (TFP) in polymer matrix composites using FEM analysis with the principal stress criterion. In this work we will shed some light on the differences of typical engineering approaches which are state of the art for TFP and semi-consistent schemes where stress states and fibre orientation are coupled.

The criterion is presented in a coupled procedure, where several iterations lead to a good agreement of fibre directions and principal stress vectors. Furthermore some deficiencies of the applied optimisation scheme are addressed and proposals for overcoming these problems are given.

INTRODUCTION

Trees and their ability of adaptive growth have generated some major attention in engineering applications. Especially their ability to deal with their orthotropic material properties in an optimum way have led to an optimisation criterion how to adapt fiber alignment in composite materials.

Considering a publication of Mattheck [1] trees have the ability to align their fibres along the direction of the uniaxial force flow. Therefore trees exhibit an extraordinary structure were fibres are subjected only to beneficial loads, namely to tensile and compressive stress. Shear stresses are minimized. This also implies that this adaptation of the structure minimises the material usage to withstand external or internal loads.

In many composite structures the material with its anisotropic properties is not fully exploited. Often the layup and stacking sequence with only straight fibres is a compromise of varying material angles to carry multiaxial stresses in the structure. Usually the stacking ends in a quasi-isotropic structure to ensure a multiaxial load carrying. With such a layup the outstanding mechanical properties due to the high anisotropy of for example one single layer with a unidirectional fibre orientation are not fully used. This leads to a limitation of weight and cost effectivity of the composite structure. Therefore optimisation of the material layup for different externally applied loadings is of high interest in composite structure engineering.

Optimisation techniques which are usually used for optimising composite structures have been addressed several times in literature [1, 2, 3, 4 and 5]. A recent review of several methods can be found in [6].

From our point of view a very promising approach to optimise fibre alignment in technical applications is to implement a criterion for minimising local shear stresses. This corresponds to the structural optimisation as this is done in nature by trees for example. Consequently the optimisation strategy requires the determination of the main stress trajectories with proper computational methods. Computer aided methods based on finite elements have been developed by Kriechbaum [7] and Reuschel [8] for this purpose. These methods calculate principal stresses in a linear plane stress analysis in a local point (Gauss point) according to an external loading, where the underlying material behaves purely isotropic. Then fibres are aligned in the direction of principal stresses and hence they should predominantly be subjected to tension and compression. Shear stresses should disappear in the composite and therefore failure due to excessive shearing should be omitted. Since this approach is a highly coupled problem between the structure´s stress state, the orthotropic material behavior and fiber orientation angle an iterative solution algorithm is chosen in these publications. Several plane stress analyses are carried out and fibre aligned in a reordered way following the principal stress trajectories of the end state.

However, for engineering approaches often the optimisation according to the above mentioned procedure is used with the neglection of an iterative stress state-fiber orientation coupling. In such a case good optimisation results can be obtained for simple structures, which are loaded such that even local stress states are characterized by a high pronouncement of a single stress trajectory. However, the more complex the geometry of the structure and the loadings are, the more problematic is the neglection of the stress state- fibre orientation coupling. [9]

This has been already demonstrated by Tosh et al. [10] by calculating a plate with defect (hole) where the plate is under tension. In the before mentioned publication also an example of a pin loaded whole is given. This increases the complexity and shows clearly that for this case a coupling of the stress state and the fibre orientation is required. The general example of a loaded plate with a hole has been investigated in [8] and [11] and shows potential for optimisation by principal stress trajectories. Crothers et al. [11] showed in experiments an improvement of the specific structure strength of 45 % by using the fibre steering technique.

The improvement in a laminate structure using above mentioned method can be seen by having a look at the failure body of the Tsai-Wu failure criterion [12], which is widely used for anisotropic composite materials. The body is displayed in Figure 1. By having a look at the cut section of the body stresses in fibre direction (σ_1) and perpendicular to the fibre direction (σ_2) form an ellipsoidal failure plane. The area of the failure plane is dependent on the state of shear stress level. By increasing the shear stress (τ_{12}) level (indicated by the arrow) the area becomes smaller and failure is more likely to occur. The optimisation criterion with principal stress trajectories aims to avoid these shear stresses and therefore improve overall composite bearing capacity.

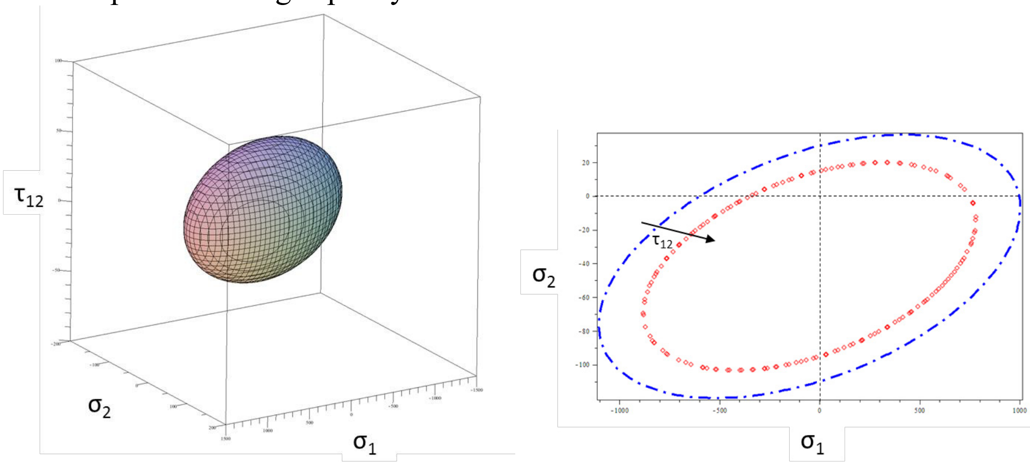

Figure 1: Tsai-Wu failure body and shrinkage of failure plane due to composite shear stresses for a transversal isotropic material behavior under in plane loading.

The aim of this paper is to shed some light on the optimisation strategy where the coupling of local stress states with the fibre orientation is taken into account. Therefore a complex structure with loading cases with a high potential for local multiaxial stress states is investigated. Special focus is put on studying the fiber realignment according to coupling effects over several coupling iterations. Also the number of iterations required for a converging system should be addressed. Furthermore the differences between optimisation results obtained by a typical engineering approach and those results obtained by the coupling strategy are compared and discussed.

In the current coupling approach the applied criterion uses the principal stress information of only one layer of a predefined composite laminate structure and hence updates an existing predefined laminate according to the orientation information of the reference layer. For complex structures the usage of both, major and minor principal stresses for orientation information seems of particular importance. This is done in the used optimisation procedure by the predefined layup.

MODEL

Geometry Selection and Model Setup

For the investigation of the principal stress trajectory approach a complex U shaped cantilever beam is investigated. Figure 2 illustrates this U Beam. The geometry represents an example of a more complex structure, where optimal fibre trajectories are less clear. The U Beam is fixed on one side and a displacement boundary condition is set on the other side as this is shown in Figure 2. For the later investigation three observer elements have been selected as reference and are labelled in Figure 2.

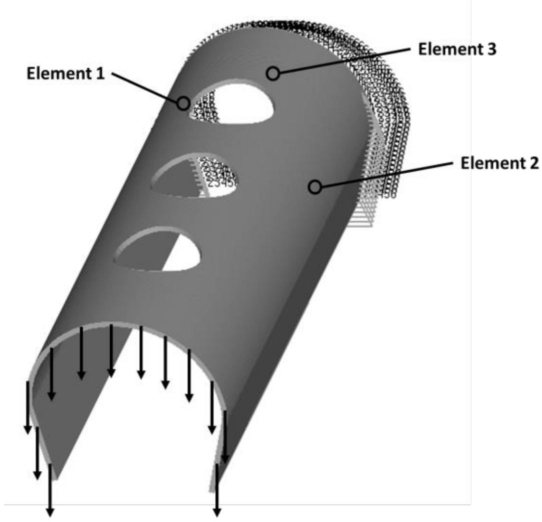

Figure 2: U Beam: Model geometry which is set up for the investigation of principal stress trajectories.

The mechanical properties used for the unidirectional (UD) fibre reinforcement (layer) are summarised in Table 1.

Table 1: mechanical properties of a UD layer

Young´s Modulus 0° (MPa)	40000
Young´s Modulus 90° (MPa)	8000
In-plane shear modulus (MPa)	4000
Poisson´s Ratio	0,25
Ult. Tensile Strength 0° (MPa)	1000
Ult. Tensile Strength 90° (MPa)	30
Ult. Comp. Strength 0° (MPa)	600
Ult. Comp. Strength 90° (MPa)	110
Ult. In-plane shear strength (MPa)	40

The stacking sequence has been chosen in the following way: both, the direction of the major principal stresses and minor principal stresses have been used to orientate a 0/ 90 laminate structure, where the laminate structure is kept as a symmetrical assembly ($(0/90)_S$). The optimized aligned fibres have been stacked as well in a symmetric order with a constant ply thickness. No thickness variation has been applied to directly compare the optimized structure with the non-optimized $(0/90)_S$ structure.

The first layer (cover layer) is the reference layer for all plies over the laminate following the major principal stress directions. The second and the third layer are perpendicular to the first layer with exact the same thickness and therefore following the minor principal stress directions. The fourth layer again follows the fibre direction from the first layer.

Results and Discussion

The geometry is analysed regarding its potential to optimisation with the principal stress criterion. In total 15 iterations has been carried out whereupon the iteration algorithm has been executed fully automatically, using FEM-analysis, post processing and rewriting the FEM input deck.

Figure 3 shows the evolution of fibre alignment of the first iterations starting from 0 degree layer to the orientated layer according to major principal stress trajectories in the following coupling iterations.

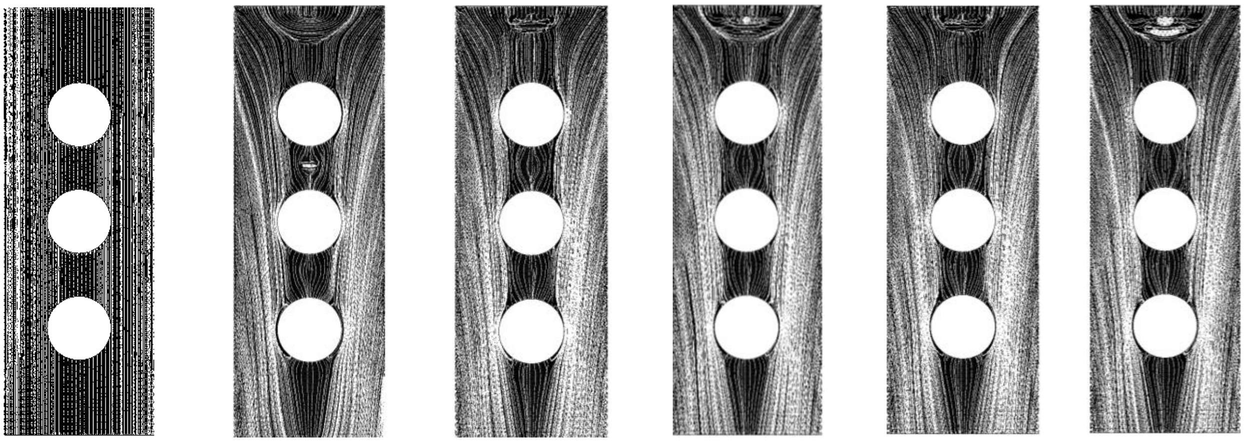

Figure 3: Fibre orientation over the first iterations.

For the structure the evolution of the maximal local composite shear stress over the coupling iterations is shown in Figure 4. As it is expected the maximum shear stress is reduced by this approach, however reaching the minimum level of 0 shear stress fails.

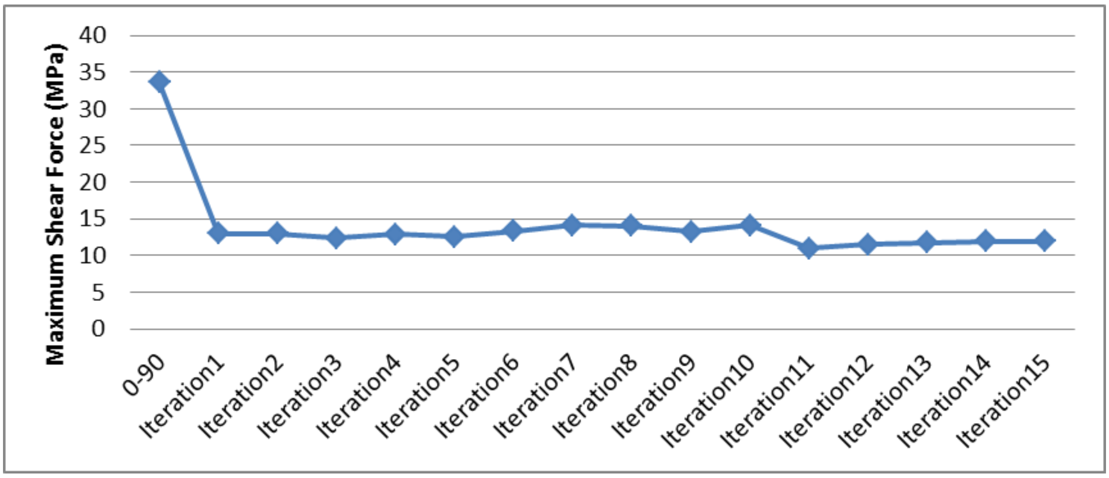

Figure 4: Maximum shear stress for the highest elemental shear stress in the structure

In the next figure the overall composite failure calculated by the Tsai-Wu criterion [12] is illustrated for 15 iterations. Using the Tsai-Wu criterion allows coupling the stresses in the failure hypothesis, which is contrary to maximal stress criterion. An increasing global Tsai-Wu failure is detected for the local most critical element in the structure.

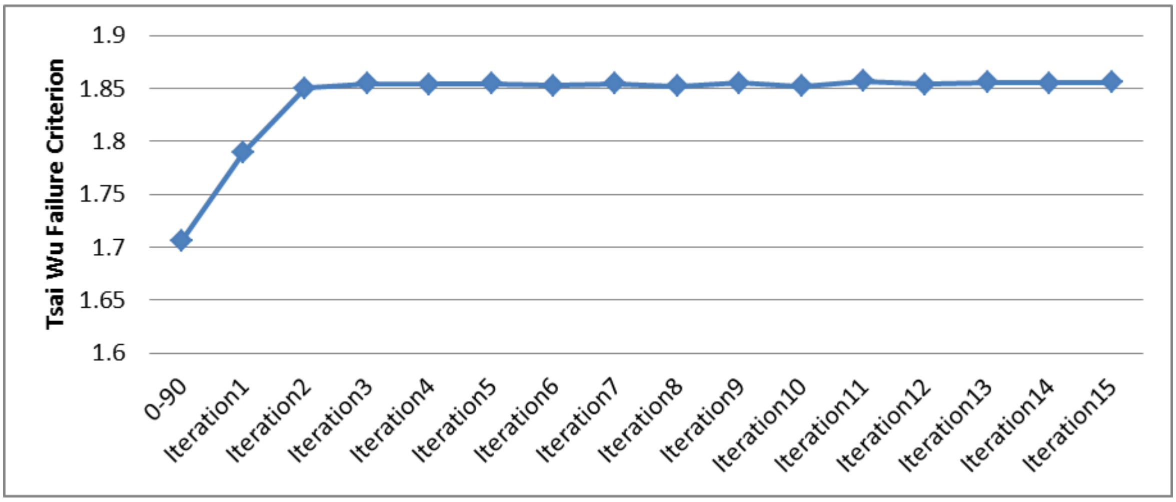

Figure 5: Tsai-Wu Failure Criterion for the most critical elment in the structure

Referring to the above presented results there is some mismatch to the expected behaviour by the optimisation criterion. For clarifying this behaviour a detailed discussion of 3 elements across the structure is presented. The position of the elements in the structure is shown in Figure 2. Element 1 shows intermediate critical effects regarding the global failure behavior according to Tsai-Wu. Element 2 is a representation for a typical structure continuum without any critical effects. Element 3 is situated in a multiaxially loaded zone and shows the highest shear stresses in the structure.

For the three elements the Tsai-Wu Failure Criterion develops as shown in Figure 6. For elements 1 and 2 the trend of failure behaves to be nearly the same. There is a reduction in failure of the fibres aligned to the major principal stress (layer 1 and 4). However, the composite failure in layer 2 and 3 increases. These layers are aligned perpendicular to layer 1. For element 3 the failure criterion does not reach a constant level and failure behaviour deteriorates for all layers.

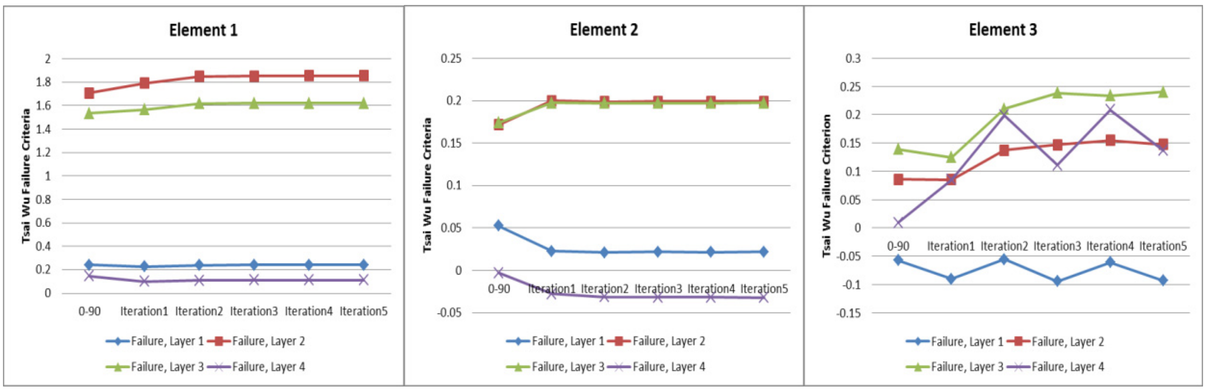

Figure 6: Tsai-Wu Failure for the 3 different elements

For interpretation of the achieved ply based failure behaviour a more detailed observation of the before mentioned elements is made. In element 1 the composite stresses develop as shown in Figure 7. P1, Major is the major principal stress in the specific layer. Normal X is the stress in fibre direction, Normal Y is the stress perpendicular to the fibre direction and Comp XY is the shear stress. All stresses are given as averaged element stresses. It can be stated that the shear stress reduces to approximately zero in the element, which is in accordance with the goal of the applied optimisation approach. For layer 1 and 4 the stress in fibre direction totally adjusts to the value of the major principal stress, which is fairly high in this element. The fibres can easily handle this high stresses and have no negative effect on the failure behaviour of element 1 (see Figure 6). However the Normal X stress in layer 1 and 4 are directly coupled to the Normal Y stress in layer 2 and 3. Therefore it leads to high stresses transverse to fiber direction, which are higher than the maximum bearing capacity of the matrix-fibre interface and lead to failure of these layers.

To verify the optimisation criterion, the principal stress angle is calculated for the element, which should be reduced to zero along the iterations. For Element 1 the angle is reduced to a value close to zero in all layers, which is shown in Figure 8.

Same results are also achieved in element 2. In elements 1 and 2 the iteration progress already reaches a constant level after 2 iterations.

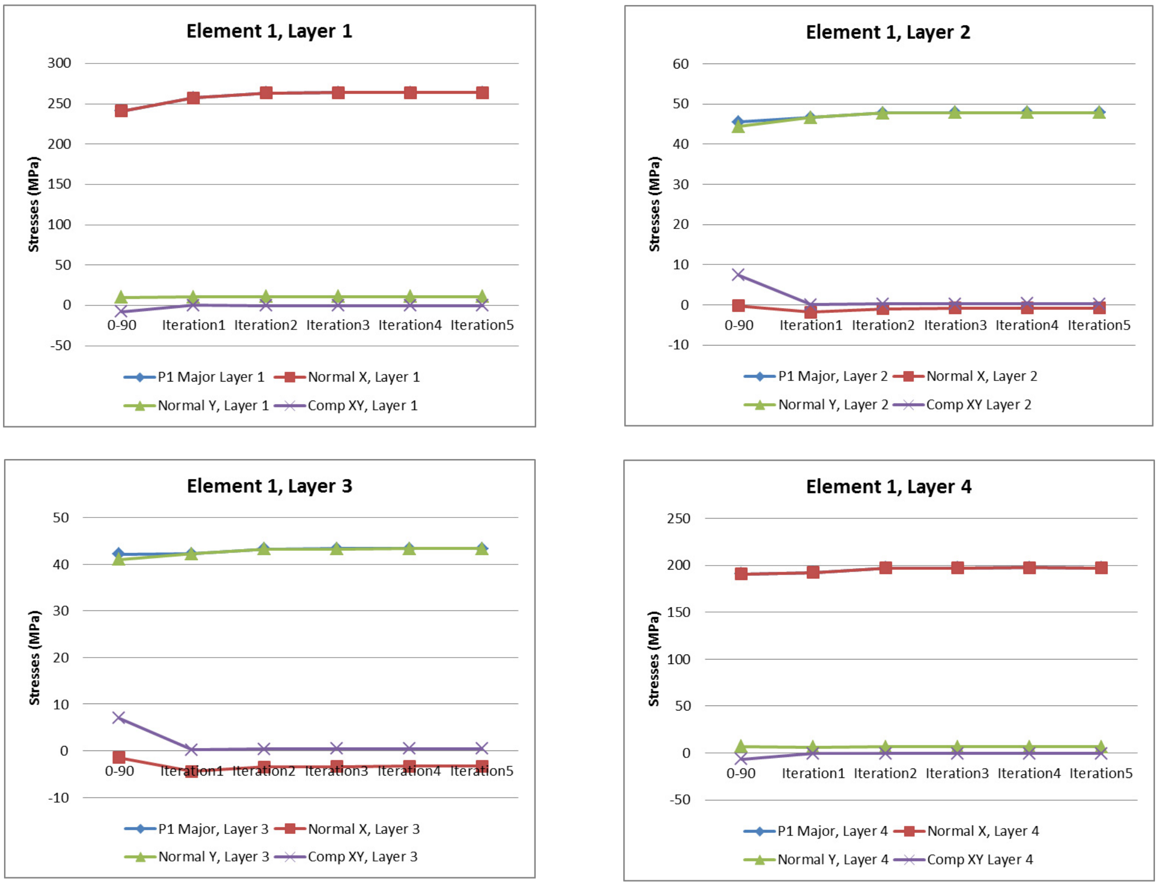

Figure 7: Composite stresses in element 1, layerwise inspection

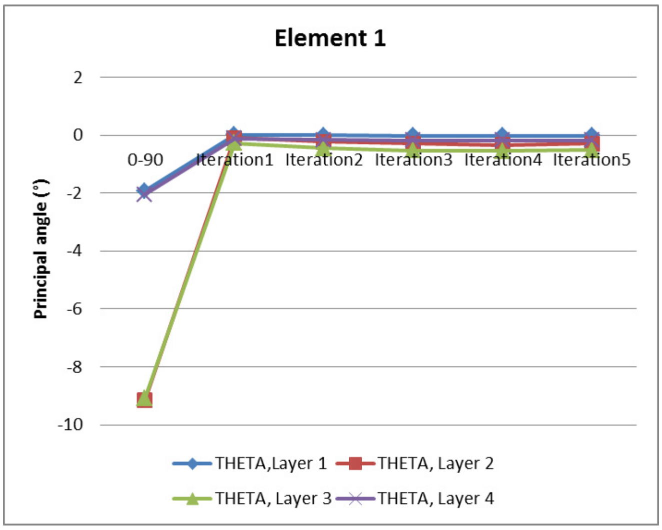

Figure 8: Principal angle for element 1

In some regions the coupling of principal stress fibre alignment and shear stress reduction to zero is not valid. In the structure a specific level of shear stresses is sustained as shown in Figure 9. Considering element 3 possible reasons are investigated. The position of element 3 is shown in Figure 2.

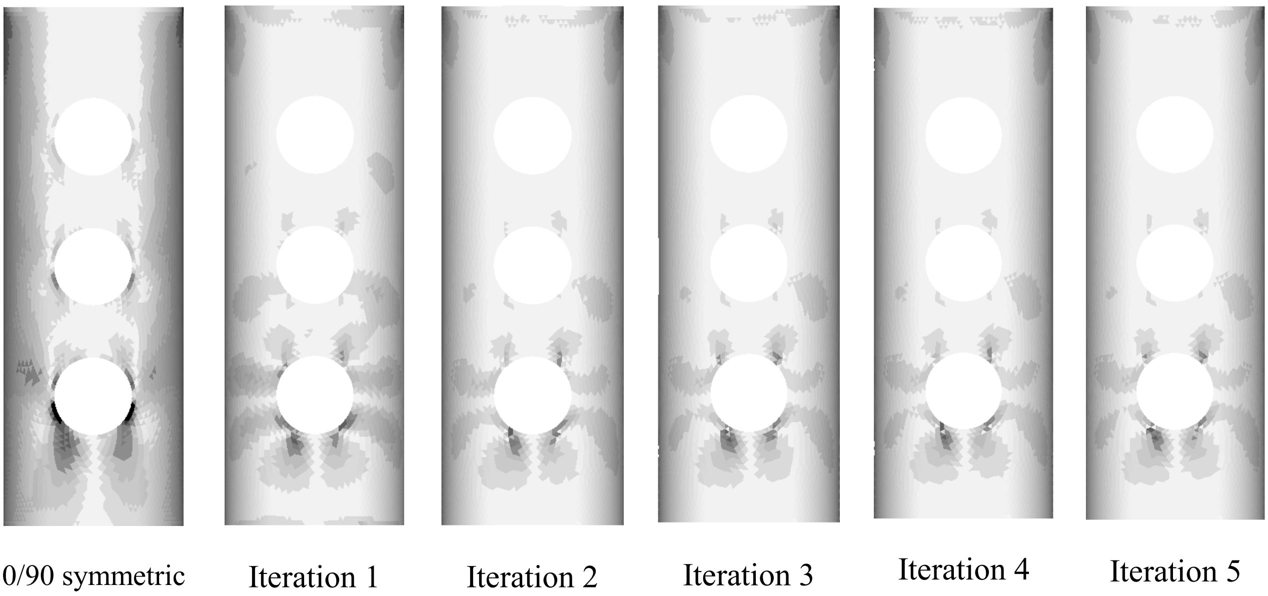

Figure 9: Illustration of maximum composite shear stresses across the whole structure. Shear stresses are normalized to a constant value in all 6 illustrations.

For element 3 no specific optimum can be found along 5 iterations. Stresses in general show a fluctuation over the iterations (Figure 10). For element 1 the normal stress in fibre direction (Normal X) adjusts to the principal value. For the other layers across the thickness a deviation to the principal stress value is detected. This proposes that a deviation in the principal angle is present, which is indicated in Figure 11. The optimum value zero of the principal angle is not reached in any layer of this element. Actually the element is highly multiaxially loaded and no convergence can be reached. The principal stress state also shows a very inhomogenious developement across the thickness, where the major directions are varying. A small deviation in the principal angle (see layer 4) already results in shear forces in the composite. The optimisation by the principal stress information of only one layer (top layer) seems therefore detrimental to specific elements.

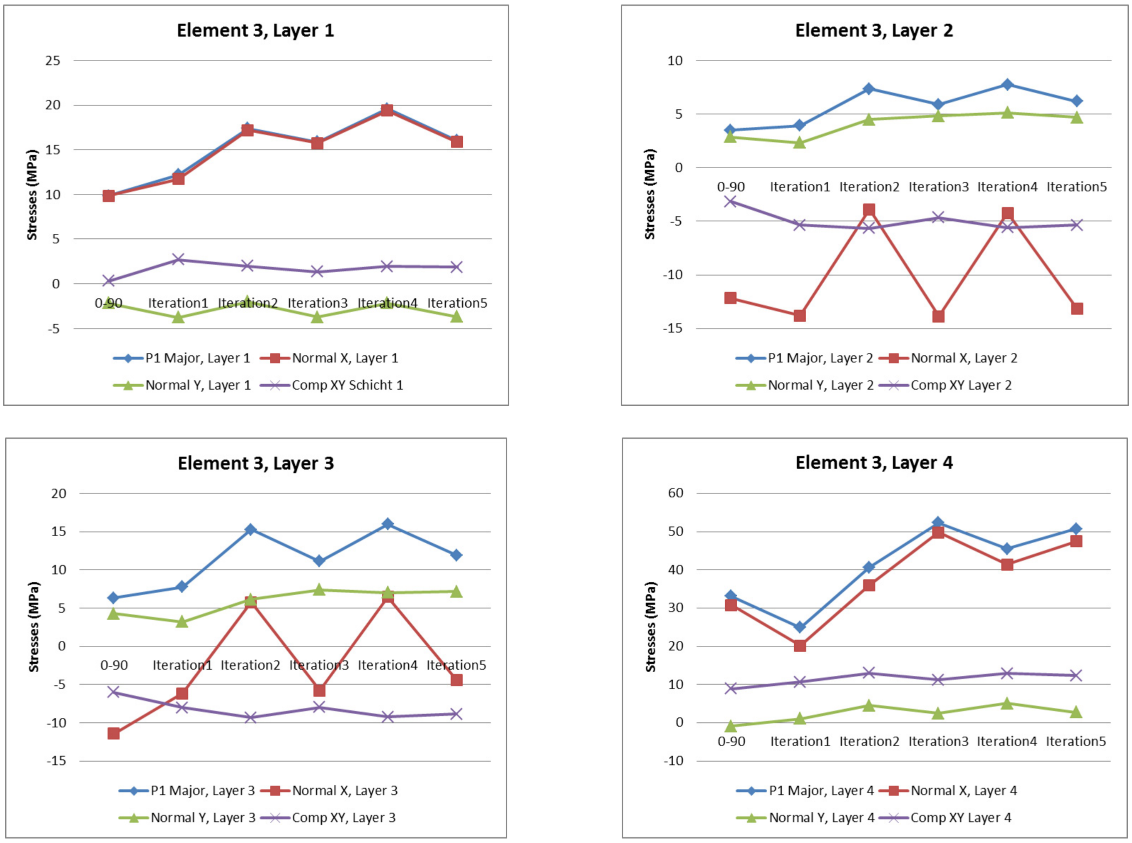

Figure 10: Composite stresses in element 3, layerwise inspection

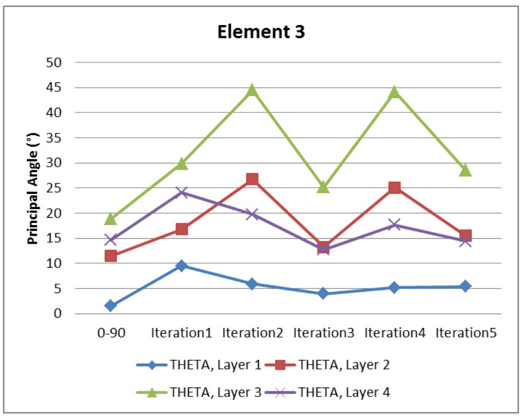

Figure 11: Principal angle for element 3

Conclusions and Outlook

The application of principal stress optimisation criterion has been applied to a complex structure, wherein principal stress information is determined for one layer and the information is applied to a predefined stacking sequence of $(0/90)_S$ laminate with constant ply thickness. The aim to reduce composite shear stresses can be achieved in most parts of the structure with this procedure. Observer elements show these conclusions. In complex loaded elements stress fluctuations over the coupling iterations could be observed and convergence could not be achieved with the semi-consistent approach.

Also an increasing global failure level could be shown during the optimisation procedure because of the non-idealised orientation of the fibres of the plies referenced to the first layer.

An engineering approach by defining a $(0/90)_S$ laminate is detrimental for the full reduction of shear stresses in the laminate. Principal stresses vary across the thickness especially in multiaxially loaded areas. Therefore a layerwise changing vector information has to be applied to fully adjust fibre orientation to ply based acting stresses. Further it seems that a high potential for increasing the lightweight degree is a coupled optimisation of tailored fibre placement and thickness adjusting of the layer.

In this work the optimisation is based on a semi-consistent approach. Currently the authors work on a full consistent scheme where the stress state and fibre orientation are coupled in the local integration. Therefore the above stated problems occurring by using the semi-consistent approach should be solved with the full consistent optimisation strategy for TFP.

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