TAILORED FIBRE PLACEMENT OPTIMIZATION TOOL

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Abstract

European aircraft industry demands for reduced development and operating costs. Tailored Fibre Placement (TFP) is a promising technology which contributes to this aim by reducing structural weight at safe design; it exploits considerable reserves in structures made of Carbon Fibre Reinforcement Plastics (CFRP) by placing the carbon fibre rovings according principal stresses. This paper deals with selected results of 4 research projects in the field of TFP the Institute of Composite Structures and Adaptive Systems of DLR is working in. Within the first already finished project the tool TACO (Tailored Composite Design Code), which is a TFP design tool for lightweight aerospace structures, was developed. Three running follow-up projects deal with basic research investigations, improvement of TACO and its industrial application as well as the automatic determination of the roving distributions.

1 Introduction

This paper presents selected results related to the Tailored Fibre Placement (TFP) Technology (cf. Section 2) of 4 research projects (cf. Figure 1) of the Institute of Composite Structures and Adaptive Systems of DLR is working in.

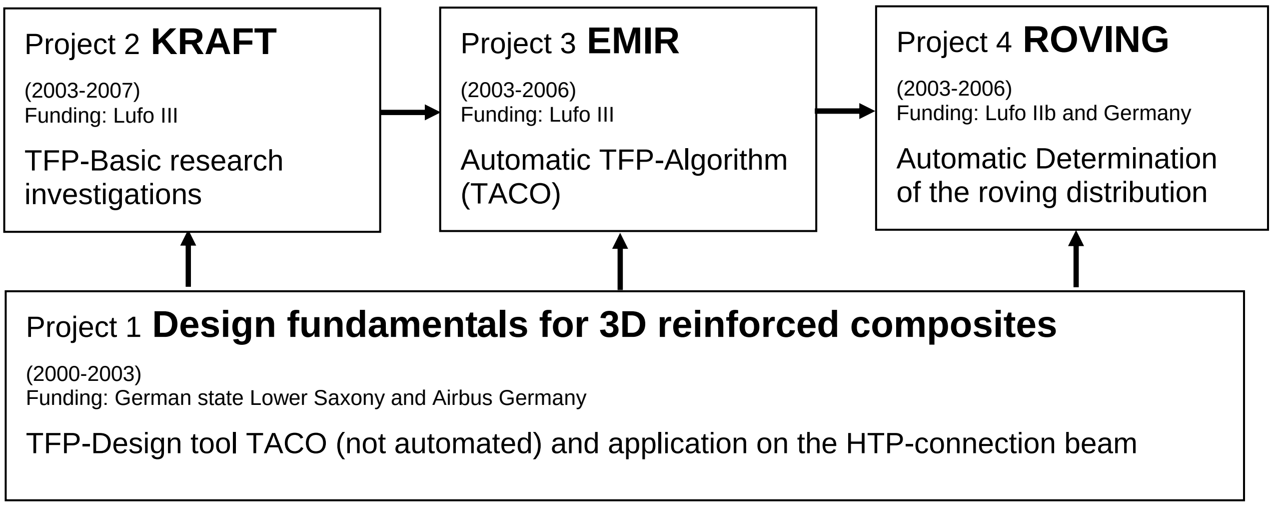

Fig. 1. Interaction of projects related to Tailored Fibre Placement

Figure 1 illustrates the interaction between the projects. It provides information concerning the project title, duration, supporting organization and results related to TFP.

The first project *Design fundamentals for 3D reinforced composites* is finished. The results of the task dealing with TFP were the new TFP optimization tool TACO (cf. Section 4.1) and its application on the HTP-connection beam as typical aerospace structure (cf. Section 4.2). The simulation results were compared with testing results also performed within the projects. The success of this project resulted in the three follow-up projects KRAFT, EMIR and ROVING.

The objectives of the project *KRAFT* are basic research investigations. The TFP method is studied on small structures using the tool TACO. Finally, some optimized structures will be manufactured and tested. Expected results are the validation of TACO simulations and design recommendations.

EMIR is a large national project and TFP is one workpackage. The objective of its TFP task is the automatization of the TFP-optimization tool TACO and its improvement to be applicable for the industrial day-to-day design process. This work is already finished.

The last project *ROVING* aimed to develop a tool which reads the optimized results from TACO and generates a drawing of the distributed rovings for the manufacturing process. Because this task is more challenging than expected, only concepts and test tools were developed.

Figure 2 illustrates each contribution of these research projects to the industrial development of a TFP structure. KRAFT provides design guidelines for an improved design process. EMIR allows the TFP optimization using TACO. ROVING delivers the last step to the manufacturing. It generates a drawing of the optimized roving distribution which is the basis for the stitching machine in the manufacturing process.

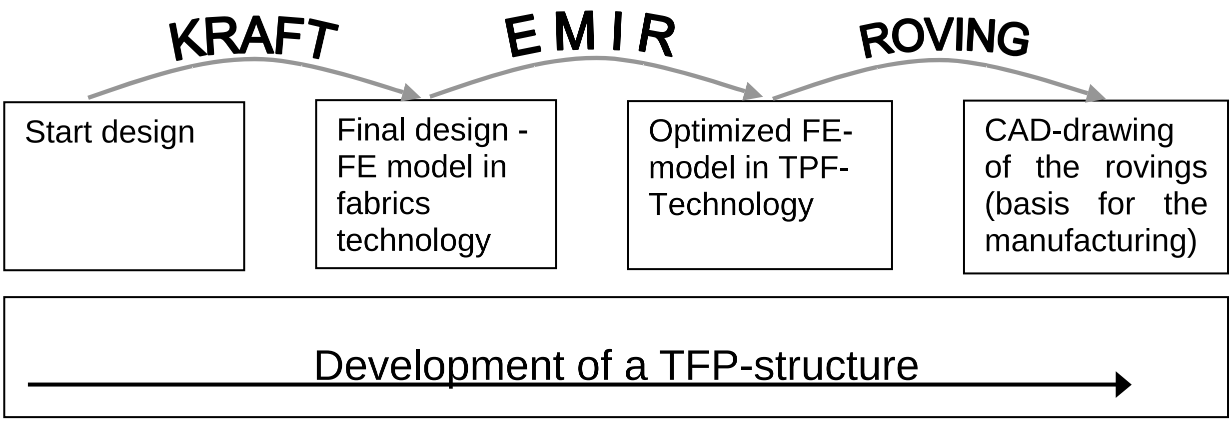

Fig. 2. Contribution of the research projects to the development of a TFP structure

2 Tailored Fibre Placement Technology

Tailored **F**ibre **P**lacement (TFP) is a textile process for the production of fibre reinforced structures. Using TFP the carbon fibre rovings may be placed on a base material in almost any desired orientation, thus deploying calculated optimum fibre quantities and orientations for optimal performance. In common composite structures the anisotropic material properties are usually not fully exploited.

In Figure 3 it is illustrated how the relative strength of a composite layer depends on the angle α between the fibre (within that layer) and the load direction. In this simple example, only axial tension and compression is considered. If the direction of the load is only 10 degrees off the fibre direction, its load-carrying capacity is reduced by 80%. It is thus plausible that the weight of composite structures could be significantly reduced if the fibres were fully exploited. In the simple example from Figure 3 the optimal fibre orientation would be at α =0. However, in a real structure under different loading conditions there may exist different solutions for each load case. It is therefore expected that the optimization potential is especially high, if only a few load cases need to be considered.

Stress concentration at notches, edges and cut-outs are critical in view of the material failure behaviour in a structure. While in isotropic structures only a shape optimization is possible to reduce local stress concentrations, in orthotropic and composite structures an orientation of the fibres appropriate to the local stress condition can be used as an additional local design variable for strength and stiffness optimization.

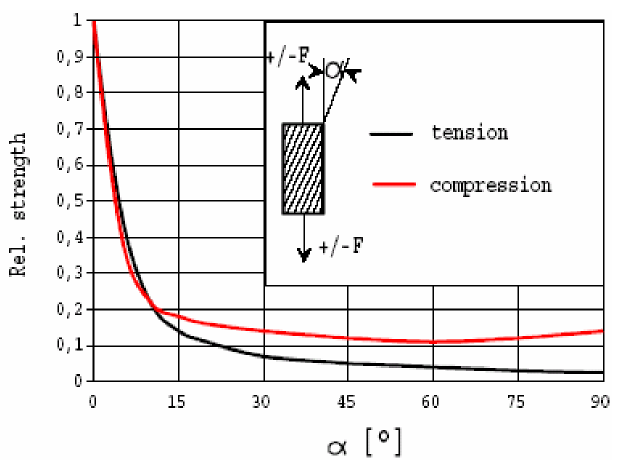

Fig. 3. Dependence of relative strength and angle between fibre direction and load direction [1]

Different approaches to optimize composite structures are known, such as energy methods [13], the load path method [7, 15] and the Computer Aided Internal Optimization (CAIO) [9, 10, 14]. In the CAIO method, a procedure to optimize fibre arrangement in composite structures, the fibres of a loaded structure are locally aligned to the principal directions of the stresses. Since stress distribution and fibre orientation are coupled, an iterative procedure is necessary to align fibre orientation in the principle direction of the stress. As result of this procedure the shear stress and the corresponding failure response is reduced.

Using an optimization criterion in combination with FEM calculation results provides a very efficient optimization method leading to a curvilinear fibre pattern in contrast to the constant fibre direction of traditional design [4-6, 8-16]. The application of such a procedure allows an optimized design for a specific composite light-weight-component. It aims to fully exploit the uniaxial material properties, leads to a local reinforcement and a more efficient load transfer and improves the fracture behaviour. Main area of application is uniaxial loaded laminate structures with a limited number of load cases. A typical application is an open-hole plate under unidirectional tensile loading.

Material models and appropriate properties of the textile fibre composites are of critical importance for a successful application. In [12, 17] it is pointed out how the manufacturing process affects the material properties. For example, in [12] the influence of stitching on fracture behaviour is considered in TFP structures. A challenging problem in the analysis of the anisotropic mechanical properties of composites has been the development of adequate failure criteria. A strength model for 3D fiber-reinforced plastics consisting of unidirectional layers with a high in-plane fiber density and additional reinforcements perpendicular to the layers with a significantly lower fiber density is presented in [19].

3 Material properties

The material stiffness and strengths are reduced due to the increased fibre waviness. In addition, the carbon rovings are slightly damaged by the needle threads during the manufacturing process. This leads locally to spatially varying material properties. In a first ply failure analysis this is usually taken into account by a global reduction of the basic material strength values.

Comparing TFP material properties to prepreg material properties, one can in a first step assume that TFP exhibits similar stiffness but smaller material strength values.

The reduction factor depends on the kind of material (fibre and resin) and the manufacturing process. The compressive strength, for instance, which had the most significant influence on fracture for the geometries considered, can be between 40% and 70% of prepreg compressive strength. Recently even higher values were achieved by Hightex [1]. Still, it is difficult to get reliable material strengths values for the simulation of structures made in TFP technology.

For the optimization of the HTP connection beam (cf. Section 4.2) the following material strengths were taken:

- In a first approach the best known TFP material strengths values (e.g. the compressive strength is 70% of prepreg compressive strength) were assumed in order to find the load carrying capacity limits of the HTP connection beam made in TFP technology.
- After testing of the optimized HTP connection beam the computed maximum loads at first ply failure and maximum test loads were equalized and realized material strength values were estimated.

Within the other projects a similar procedure is foreseen.

4 Project 1: Design fundamentals for 3D reinforced composites

Partners within the project were Airbus Germany, DLR and IFL of the Technical University Braunschweig. The main objective was the development of design rules for 3D reinforced composites. In the workpackage to TFP the TFP optimization tool TACO was developed and applied on the HTP connection beam a part of the A340-300.

4.1 TFP optimisation tool TACO

4.4.1 General

The tool TACO (Tailored Composite Design Code) was developed to optimize complex composite structures and it is embedded in the MSC PATRAN / NASTRAN environment. It is used to optimize the fibre orientations of structures made of Carbon Fibre Reinforcement Plastics (CFRP).

An optimization criterion instead of a mathematical optimization is used, because in the mathematical approach the number of design variables becomes too large. As optimization criterion the two-dimensional CAIO formulation was adapted. The tool changes the fibre orientations within a user-defined layer of a finite-element (FE) model such that the fibres are as closely aligned to the direction of the principal stresses as possible. For failure analysis the so called Simple Parabolic Criterion (SPC) was implemented (cf. Section 4.4.4), which is able to distinguish between fibre fracture and inter fibre fracture as different failure modes.

4.4.2 Optimization Concept

Before the optimization procedure starts, a linear plane stress analysis of the structure is carried out. Based on a two-dimensional stress state, the two orthogonal principal directions of the stress

$$\begin{aligned} n^1 &= (\cos\phi, \sin\phi) \\ n^2 &= (-\sin\phi, \cos\phi) \end{aligned} \tag{1}$$

- expressed by an angle - can be computed from

$$\tan(2\phi) = \frac{2\tau_{xy}}{\sigma_x - \sigma_y} \tag{2}$$

The two principal stresses are given by

$$\begin{aligned} \sigma_1 &= \frac{\sigma_x + \sigma_y}{2} + \frac{\sigma_x - \sigma_y}{2}\cos 2\phi + \tau_{xy}\sin 2\phi \\ \sigma_2 &= \frac{\sigma_x + \sigma_y}{2} - \frac{\sigma_x - \sigma_y}{2}\cos 2\phi - \tau_{xy}\sin 2\phi \end{aligned} \tag{3}$$

The two principal stresses must be compared to decide in which of the two principal directions the fibres should be aligned.

In a simplified method to design TFP structures one starts with a plane stress analysis for a given structure with an arbitrary isotropic material. According to the isotropic stress analysis the fibres are aligned to the direction of principal stresses. In such an approach the coupling of stress state and anisotropy is neglected.

In order to fully exploit the fibres, they are aligned in the direction of the principal stress. However, fibre orientation and stress state are coupled: as the fibre orientation changes, so does the stress state. Thus, another linear plane stress analysis of the structure must be carried out and afterwards it must be checked whether the fibres need to be re-aligned. If so, the process of re-aligning and checking is repeated until convergence is reached. For the test cases considered in this paper, this only took a few iterations. As a result of this procedure the shear stresses, defined in a material system, becomes small and the stress and strain states becomes collinear. Thus, an approach similar to the described one is given by using the strain field instead of the stress field. A generalized method valid for anisotropic and nonlinear materials can be obtained by a corresponding energy approach.

4.4.3 Main Subroutines in TACO

TACO is written in Patran Command Language (PCL) and contains four main subroutines or session files (Properties, Results, Optimization, Failure). A schematic view of the tool and the optimization procedure is given in Figure 4. Properties are attached to the elements to define fibre orientation for any element. If a FE-model with an appropriate property definition exists and if results of a first stress calculation are given, the optimization procedure can be started. To get all information and settings in a consistent way the sub-routines must be applied in a defined sequence. Applying the subroutines in the described iterative way, results for optimized fibre orientation, stress and strength-analysis are given as result-case in the Patran database.

4.4.4 Failure Criterion

In order to optimize the load-carrying capacity of a structure, a criterion for the onset of fracture must be chosen. There are different criteria for the determination of fracture of composite materials. A good overview can be found in Cuntze et al. [3]. For the failure analysis of a TFP-layer, it is recommended to distinguish between Fibre Fracture (FF) and Inter Fibre Fracture (IFF) as different failure modes (cf. [3, 19]). In the following, these criteria, which are implemented in TACO, are discussed.

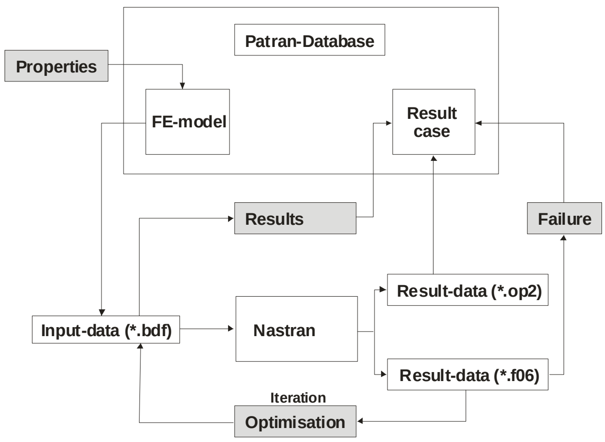

Fig. 4. TACO overview

For FF an appropriate criterion is the simple maximum stress criterion:

$$\left| \frac{\sigma_{\parallel}}{R_{\parallel}^{(+,-)}} \right| = 1 \qquad (4)$$

$\sigma_{\parallel}$ is the stress and $R_{\parallel}^{(+,-)}$ are the strengths of a unidirectional layer for tensile (+) and compressive (-) loads in fibre direction, respectively. For IFF of unidirectional composite layers the Simple Parabolic Criterion (SPC) has been developed and experimentally verified by Cuntze et al. [3]. The fracture hypothesis of Mohr for brittle materials is used as a basis. Therefore the criterion is formulated solely in stresses and strengths of the fracture plane (cf. Figure 5):

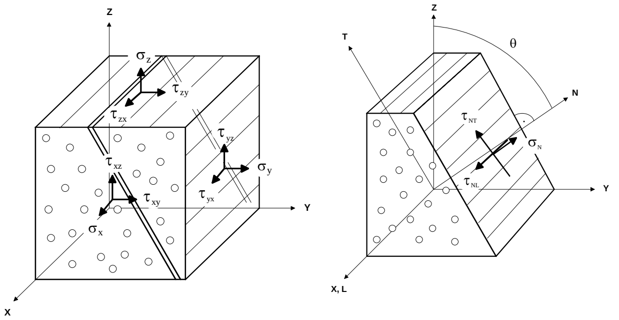

Fig. 5. Components of the stress tensor and stresses in the fracture plane of an unidirectional composite layer

$$\sigma_N \ge 0: \quad \sqrt{\left(1-p^{(+)}\right)^2\left(\frac{\sigma_N}{R_N^{(+)}}\right)^2+\left(\frac{\tau_{NT}}{R_{NT}}\right)^2+\left(\frac{\tau_{NL}}{R_{NL}}\right)^2}+p^{(+)}\frac{\sigma_N}{R_N^{(+)}}=1 \qquad (5)$$

$$\sigma_N < 0: \quad \sqrt{\left(p^{(-)}\right)^2\left(\frac{\sigma_N}{R_y^{(-)}}\right)^2+\left(\frac{\tau_{NT}}{R_{NT}}\right)^2+\left(\frac{\tau_{NL}}{R_{NL}}\right)^2}+p^{(-)}\frac{\sigma_N}{R_y^{(-)}}=1 \qquad (6)$$

$p^{(+,-)}$ represents gradients of the fracture body defined by Equations (5) and (6). Cuntze et al. [3] developed the following strength model for unidirectional layers using basic strengths of the layer with respect to the material axes:

$$R_N^{(+)} = R_y^{(+)} = R_z^{(+)} \qquad (7)$$

$$R_{NL} = R_{xy} = R_{xz} \qquad (8)$$

$$R_{NT} = \frac{R_y^{(-)}}{1+\sqrt{1+2p^{(-)}}} \qquad (9)$$

The criteria mentioned above were developed for unidirectional layers in a three dimensional stress state. The failure criteria for the plane stress, which are implemented in TACO, are a simplified case of the 3D case described above.

4.2 Application on the HTP connection beam

TACO was applied to optimize a preliminary version of the horizontal tail plane (HTP)-connection beam of an Airbus A340 airplane (cf. Figure 6 and 7) of which experimental data was available. The HTP-beam was subjected to three independent load cases: tension, combined tension/compression and bending. Three specimens were manufactured at Airbus Germany (plant Stade) according to the optimized solution (cf. Figure 8) obtained by TACO and were tested for all three different load cases [2]. The experimental results were compared to the TACO predictions. The results for the optimized HTP-beams were also compared to the results for the conventional composite beams made of fabrics that had been tested earlier.

In a first approach the combined load case tension and bending was considered. Due to the non-symmetric load case bending the optimized fibre orientations are also non-symmetric. The load-carrying capacity could not be increased. In a second approach the structure was optimized for the load case tension only. This concept led to a reasonable solution for which manufacturability could be ensured.

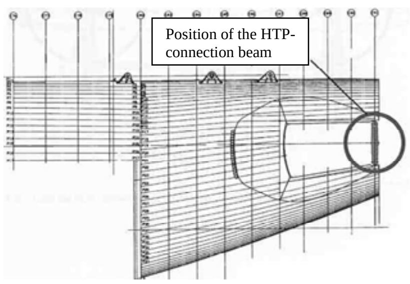

Fig. 6. Position of the HTP connection beam within Section 19 of the fuselage [2]

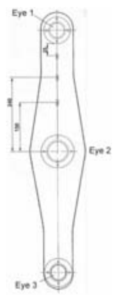

Fig. 7. HTP connection beam

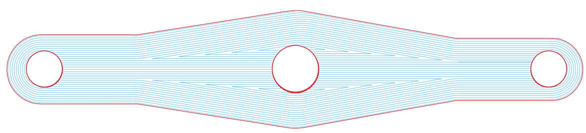

Fig. 8. Rovings of the HTP connection beam, optimized for the load case tension [20]

After TACO had suggested an optimal fibre orientation, the HTP connection beam was manufactured three times. Each test structure was tested according to one of the three load cases. The test results were compared to test results for a conventional HTP connection beam made of fabrics that had been tested earlier. For the load case bending the load carrying capacity was 8% worse, however, for the other load cases there was a significant improvement of about 60 % for tension and 79 % for compression. More detailed results are published in [20].

Based on these results it can be concluded that the optimization criterion that was chosen is not suitable for structures which are subjected to too many different load cases. However, TFP promises reserve capacities and significant weight reduction for structures which are subjected to a smaller number of load cases.

5 Project 2: KRAFT

5.1 General

This project, which is co-ordinated by DLR, is linked to the project CORUBA led by Airbus. The main objective of KRAFT is the improvement of the understanding and the application of the TFP technology within the industrial process and to derive design recommendations. There are still a lot of questions which are of high interest to be investigated. Some examples are:

- What are the limits of the TFP technology?
- What kind of structures or load cases are most suitable for TFP?
- Which modeling strategies or numerical methods are most appropriate (e.g. for the load introduction)?

This paper deals with project objectives and selected results achieved so far.

5.2 Selected results

5.2.1 Structures considered

Figure 9 presents the type of structures the investigations are performed on. Load cases considered are tension, compression and shear.

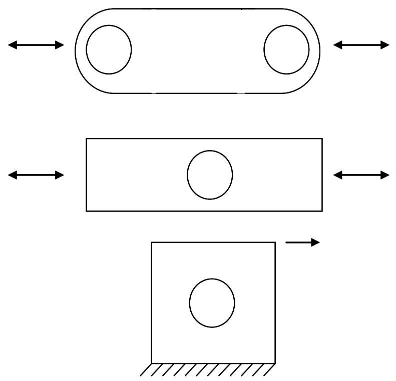

Fig. 9. Types of structures investigated

5.2.2 Principal directions

During the TFP optimization process within TACO the fibre orientation of each finite element is modified according to the direction of the principal stresses. Figure 10 and 11 show exemplary two possibilities investigated at a simple structure loaded by tension.

In Figure 10 the fibres were modified to the principal direction belonging to the largest positive principal stress, independent if the other principal stress is negative with a larger absolute value. In Figure 11 the fibres were modified to the principal direction belonging to the principal stress with the larger absolute value, independent of the sign. It is evident that the procedure used in Figure 11 leads to a fibre distribution, which is difficult to produce. Therefore the optimisation according the signum value of the principal stresses, which results are shown in Figure 10, is favoured.

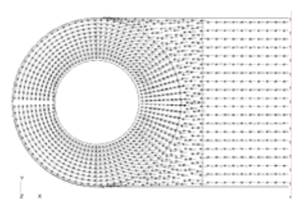

Fig. 10. Optimisation according the signum value of the principal stresses

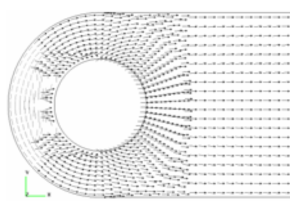

Fig. 11. Optimisation according the absolute value of the principal stresses

5.2.3 Load introduction

Having a closer look at Figure 10 one can see that the principal stresses are not running in parallel to the whole of the structure. One explanation is that the load is introduced within a linear calculation using a rigid body which is connected to the structure by MPCs (Multiple Point Constraints). This procedure leads to unrealistic stresses in the area of loading. The fibre distribution in Figure 13 was obtained using a nonlinear contact-calculation and corresponds to a more realistic modeling. The results demonstrate that a nonlinear contact calculation is required for an accurate optimisation.

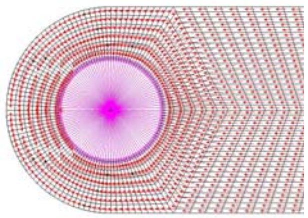

Fig. 12. Linear calculation

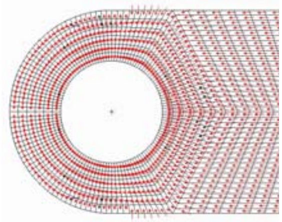

Fig. 13. Non-linear calculation

6 Project 3: EMIR

EMIR is a national research project led by Airbus Germany. The main objective is the design and manufacturing of a fuselage demonstrator made of CFRP sandwich structure. One task within that project deals with Tailored Fibre Placement technology. It aims to make the TFP design tool TACO applicable for the day-to-day industrial deign process. In addition, the improved tool TACO shall be applied on a typical aerospace structure which is suitable to be manufactured in TFP technology.

6.1 Improvement of TACO

The basic version of TFP optimisation tool TACO was developed within the project *Design fundamentals for 3D reinforced composites* (cf. Section 4). Although TACO was successfully applied on the HTP connection beam, it was not programmed efficiently and its handling was not very user-friendly. Within that project TACO was improved concerning the following aspects:

- Reduction of computation time due to improved programming
- Increase of user-comfort (graphical user interface and automation)
- Programming of inter-faces for external tools like ROVING (cf. Section 7)

The improved TACO version is easy to use and allows an efficient application within the industrial design process. Figures 14 and 15 show exemplary optimised results applying the improved TACO version on a structure with a whole loaded by tension. Figure 14 shows the optimised fibre orientations and Figure 15 the distribution of the material efforts.

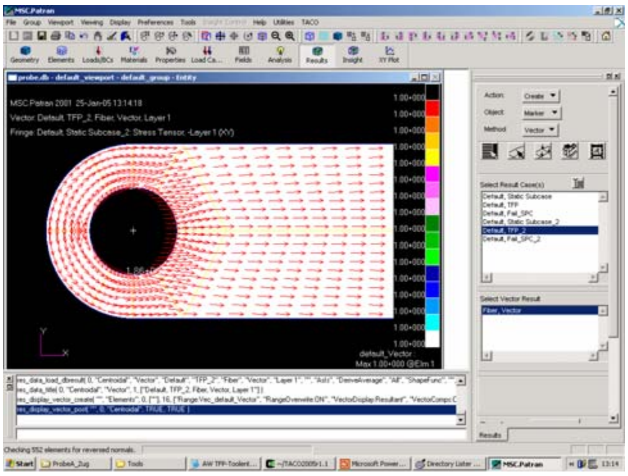

Fig. 14. Fibre orientations after the optimisation

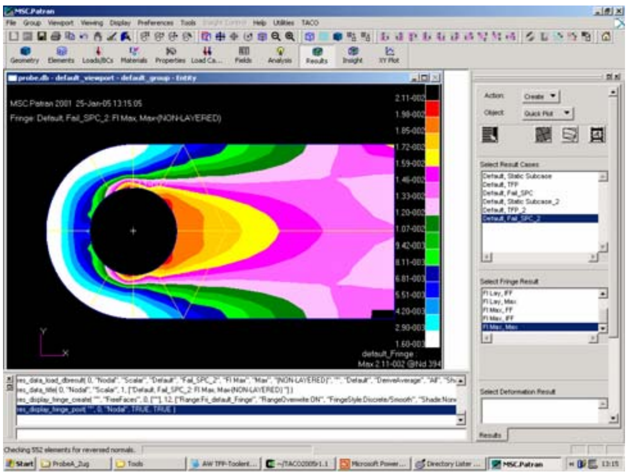

Fig. 15. Distribution of the material efforts after the optimisation

7 Project 4: ROVING

The objective of the project ROVING was to develop a tool which generates automatically a continuous and easy to manufacture distribution of the rovings out of the optimized TACO calculation. The results shall be a DXF-file, which builds the basis for the stitching machine. Such a tool shall also fulfill the following requirements:

- independent of the structural part
- works automatically

In addition, the following manufacturing dependent conditions shall be considered:

- preferably constant roving density
- minimal number of start points and end points in one TFP layer
- no distinct curvature of the fibres

During the project the commercial tool TECPLOT was taken as basis (cf. Figure 16). TECPLOT contains already routines which calculate and visualize stream lines. In addition, it allows the automation and the output of DXF-files. Based on TECPLOT different concepts were developed and tested. However, during the project it became clear that this task is more challenging than expected, so the different concepts developed were evaluated. This experience builds the foundation for further steps which have to be done in a follow-up project.

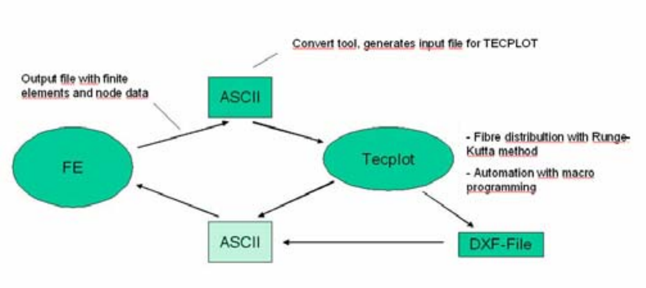

Fig. 16. Principal concept of the planned tool ROVING

8 Concluding remarks

This paper presents results related to the Tailored Fibre Placement (TFP) Technology of 4 research projects accomplished at the Institute of Composite Structures and Adaptive Systems of DLR.

The main result is the TFP design tool TACO (Tailored Composite Design Code), which was developed for the optimization of lightweight aerospace structures. It changes the fibre orientations within a selected layer of a composite Finite Element model. For a given load case, the fibres are aligned as closely as possible to the direction of the principal stresses. In this way, the shear stresses in the structure are minimized and thus its load-carrying capacity is increased. The final version of TACO is a user-friendly tool applicable in the industrial day-to-day design process.

TACO was successfully applied to optimize a preliminary version of the HTP connection beam - a part of the Airbus A340-500/600 fuselage structure - in TFP technology. The optimized HTP connection beam was manufactured and tested. The test results were compared to test results for a conventional HTP connection beam made of fabrics that had been tested earlier. For the critical load case bending the load carrying capacity was 8% worse, however, for the other load cases there was a significant improvement of about 60 % for tension and 79 % for compression.

The running project KRAFT investigates basic research questions of the TFP technology. It aims to improve the understanding and the application of the TFP technology within the industrial process and will derive design recommendations.

The finished project ROVING aimed to develop a tool which generates automatically a continuous and easy to manufacture distribution of the rovings out of the optimized TACO calculation. During the project different concepts were developed, tested and evaluated. They build the foundation for further steps which have to be done in a follow-up project.

It can be concluded that the TFP technology promises reserve capacities and significant weight reduction for structures which are subjected to a smaller number of load cases.

9 Acknowledgements

The tool TACO was developed within the project *Design fundamentals for 3D reinforced composites* which was funded by the German state Lower Saxony and Airbus Germany. The follow-up research activities on Tailored Fibre Placement within the projects *KRAFT*, *EMIR* and *ROVING* are supported by BMBF and Airbus Germany. All support is gratefully acknowledged.

References

[1] Hightex Verstärkungsstrukturen GmbH, "Explanation of the TFP technology", *http://www.hightex-dresden.de/*.

[2] U. Kütemeier, P.J. Jörn, A.S. Herrmann, "Reverse Engineering für eine Bauteilfertigung in Tailored Fibre Placement-Bauweise", *DGLR-Tagung*, Munich, 17-20 November, 2003.

[3] R. G. Cuntze, R. Deska, B. Szelinski, R. Jeltsch-Fricker, S. Meckbach, D. Huybrechts, J. Kopp, L. Kroll, S. Gollwitzer, R. Rackwitz, „Neue Bruch-kriterien und Festigkeitsnachweise für unidirek-tionalen Faserkunststoffverbund unter mehrachsiger Beanspruchung - Modellbildung und Experimente", *Fortschrittsberichte VDI 5*, 506, VDI Verlag, Düsseldorf, 1997.

[4] P. J. Crothers, K. Drechsler, D. Feltin, I. Herszberg, T. Kruckenberg, "Tailored fibre placement to minimise stress concentrations", *Composites Part A* 28A, 28(7), 619-625, 1997.

[5] P. J. Crothers, K. Drechsler, D. Feltin, I. Herszberg, M. Bannister, "The design and application of Tailored Fibre Placement", *11. International Conference on Composite Materials*, Gold Coast, Australia, 1997.

[6] K. Gliesche, T. Hübner, H. Orawetz, "Application of the tailored fibre placement (TFP) process for a local reinforcement on an "open-hole" tension plate from carbon/epoxy laminates", *Composites Science and Technology*, 63(1), 81-88, 2003.

[7] D. W. Kelly, M. W. Tosh, "Interpreting load paths and stress trajectories in elasticity", *Engineering Computation*, 17(2), 117-135, 2000.

[8] R. Li, D. Kelly, A. Crosky, "Strength improvement by fibre steering around a pin loaded hole", *Composite Structures*, 57(1-4), 377-383, 2002.

[9] C. Mattheck, A. Baumgartner, R. Kriechbaum, F. Walther, "Computational methods for the understanding of biological optimization", *Computational Materials Science*, 1(3), 302-312, 1993.

[10] C. Mattheck, "Design in Nature", *Interdisciplinary Science Reviews*, 19(4), 298-314, 1994.

[11] P. Mattheij, K. Gliesche, D. Feltin, "Tailored Fiber Placement-Mechanical Properties and Application", *Journal of Reinforced Plastics and Composites*, 17(9), 1998.

[12] P. Mattheij, K. Gliesche, D. Feltin, "3D reinforced stitched carbon/epoxy laminates made by tailored fibre placement", *Composites Part A*, 31(6), 571-581, 2000.

[13] P. Pederson, "Optimal Orientation of Anisotropic Materials, Optimal Distribution of Anisotropic Materials, Optimal Shape Design with Anisotropic Materials, Optimal Design for a Class of Nonlinear Elasticity ", G.I.N. Rozvany (ed.), *Optimization of Large Structural Systems*, Vol. 2, 649-681, 1993.

[14] R. Kriechbaum, J. Schäfer, C. Mattheck, "CAIO (Computer aided internal optimization) A powerful method to optimize fiber arrangement in composite materials", *1st European Conf. on Smart Structures and Materials*, Glasgow, 281-284, 1992.

[15] M. W. Tosh, D. W. Kelly, "On the design, manufacture and testing of trajectorial fibre steering for carbon fibre composite laminates", *Composites Part A*, 31(10), 1047-1060, 2000.

[16] M. W. Tosh, D. W. Kelly, "Fibre steering for a composite C-beam", *Composite Structures*, 53(2), 133-141, 2001.

[17] C. Weimer, T. Preller, W. Mitschang, K. Drechsler, "Approach to net-shape preforming using textile technologies. Part I+II: edges and holes", *Composites Part A*, 31(11), 1261-1277, 2000.

[18] K. Rohwer, R.Rolfes, "Calculating 3D stresses in layered composite plates and shells. Mechanics of *Composite Materials*" 1998;34: 491–500.

[19] J. Juhasz, R. Rolfes, K. Rohwer, „A new strength model for application of a physically based failure criterion to orthogonal 3D fiber reinforced plastics", *Composites Science and Technology* 61 (2001) 1821–1832

[20] Rolfes R., Tessmer J., Degenhardt R., Temmen H., Bürmann P., Juhasz J., "New Design Tools for Lightweight Aerospace Structures", Proceedings of the *Seventh International Conference on Computational Structures Technology*, Lisbon, Portugal, 7-9 September, 2004