Technologies for Lightweight Structures 5(1) (2021), pp. 161-171
Special issue: 5th International MERGE Technologies Conference (IMTC), 1st–2nd December 2021, Chemnitz

Technologies for Lightweight Structures

Designing bended pipes under internal pressure

Martin Herold[1)], Sebastian Iwan[1)], Lothar Kroll[1)]

[1)] Department of Lightweight Structures and Polymer Technology, martin.herold@mb.tu-chemnitz.de, sebastian.iwan@mb.tu-chemnitz.de, slk@mb.tu-chemnitz.de, Technische Universität Chemnitz, Reichenhainer Straße 31/33, 09126 Chemnitz, Germany

Keywords

Bended Pipe Design, Carbon Fiber Braiding Sleeve, Fiber-Plastic Composite, Inverse Margin of Safety, Net Theory

Abstract

There are major benefits, e.g. in the aerospace sector, for lightweight mobile applications, because of integral lightweight design and construction. Integral lightweight design avoids parting points, as they increase the weight and at the same time could cause defects. Pipe technology is a potential application for this issue.

For the design of bended pipes, there are various conventional but only few FEM-based approximation methods that consider fiber plastic composites. This optimization was carried out, especially for high-pressure components with an expected burst pressure of approx. 1,050 bar (approx. 15,200 psi), consisting of liner and multi-layer laminate. Three different optimization methods with adapted material parameters were compared. The net theory was used first. Furthermore, the Tsai–Wu failure criterion was considered. The inter-fiber-failure-criterion of Cuntze has been used for straight pipes. Subsequently, variations in terms of curvature angles, curvature radii, and pipe size for various laminates has been shown in theoretical investigations. The result section provides the inverse reserve factor and an outlook on the expected weight for various fiber combinations.

1 Introduction

In contrast to metals, fiber-reinforced plastics (FRPs) show several critical types of failure due to their anisotropy. Equivalent strain, which has been often used for metals, is not the only criterion for an evaluation of failure. There are breakage criteria for the fiber, the matrix, the interface between fiber and matrix as well as the delamination of individual layers of the composite.

Digital Object Identifier: http://dx.doi.org/10.21935/tls.v5i1.151
www.lightweight-structures.de

Technologies for Lightweight Structures 5(1) (2021), pp. 161-171
Special issue: 5th International MERGE Technologies Conference (IMTC),
1st–2nd December 2021, Chemnitz

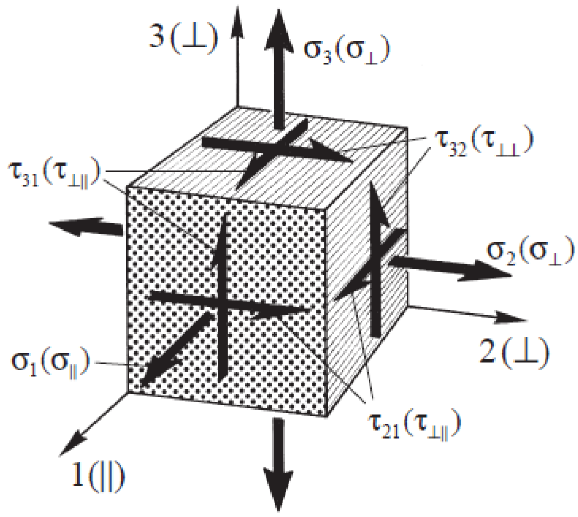

Fig. 1: Spatial strain state of a unidirectional (UD) element and the resulting strain in brackets [1]

FRPs also have differing damage patterns. Failure criteria are divided into first ply failure, gradual failure, and total failure. There are whole ranges of criteria's for both globally and for individual components, which should not been explained in more detail here. A detailed description could be found, for example, in the German book "Konstruieren mit Faser-Kunststoff-Verbunden" (Design with fiber-plastic composites) [1]. In the further course, the Tsai–Wu failure criterion was used for assessment. In some cases, the inter-fiber failure criterion of Cuntze has been used for straight pipes.

2 Materials and methods

2.1 Composition liner, FRP braiding sleeve pipe, matrix VaRTM

The pulled-up pipe consists of different parts. A fitting was arranged at the end of each pipe to ensure a tight connection to other components. In between, there is a multi-material composite consisting of an extruded liner made of PEEK, a braiding sleeve-based fiber-plastic composite made of Tenax® IMS 65 830tex 24K carbon fiber and HexFlow® RTM 6 epoxy resin. VaRTM method applied as injection method.

The liner material has maximal tensile strength at 23°C of 100MPa (ISO 527), compressive strength is 125MPa (ISO 604) [9]. Increasing the temperature causes decreasing of the strengths in case of polymer chain movement and degradation. The liner is needed for two reasons, diffusion barrier against media and as a core for applying the fiber fabric.

2.2 Net theory

The optimal fiber angle of the net theory for components that are purely exposed to internal pressure is given as 54.7 ° to the main axis. This value results from the ratio of axial to tangential tension of 2:1, the requirement of a balanced angle connection, and the requirement of only two laminate layers.

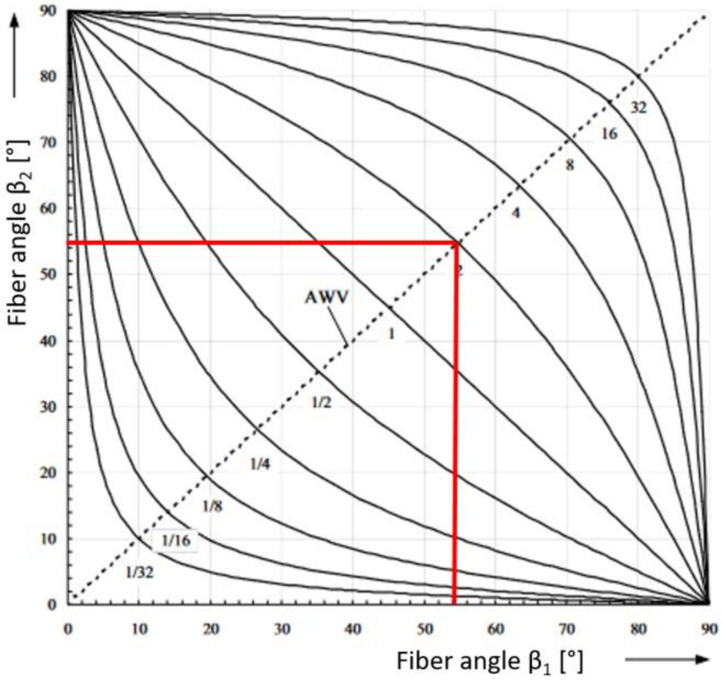

Fig.2: Ideal angle of the net theory for components exposed to internal pressure with two-layer laminate for ratios 1/32 to 32 [1]

In fact, there are other ideal lightweight solutions, which has been described below. This could be seen from the line running through point 2. Design with 0°/90° layers is possible, for example, with circular weaving. However, conventional weaving machines are not available with the required flexibility concerning curvature angles and possibly deviating angles of 0°/90°. Angles of +/- 45° could be easily created in the winding process for straight pipe segments. Ninety degrees windings are technically not possible, because no feed could be produced. Hence, the maximum angle depends on the laying-width of a winding. Depending on the geometry and fiber selection, this angle is between 75° and 88°.

The net theory only provides a few indications for an optimal structure, since the influence of production is not considered. In reality, neither an AWV nor a continuous fiber angle or constant wall thickness could be observed due to the physics of the arch. This is independent of the braiding, weaving, or winding process. In the intrados, a cluster of thicker fibers forms, while in the extrados stretching of the fibers occurs.

2.3 Material model for the consideration of draping effects for bended pipes

The aim of this research was the optimum design of the FRP pipe taking into account the manufacturing process and the locally changing fiber angles. Local fiber angles has been measured optically at a pipe section with an angle of 90°. For this purpose, the pipe was divided into 7 segments (0°, 15°, 30°, 45°, 60°, 75°, 90°) along the pipe and into 16 segments across the cross-section of the pipe (see Fig. 3). The inner side (1) is called Intrados, segment 5 is up and segment 13 is down, 9 is the outside called Extrados.

Technologies for Lightweight Structures 5(1) (2021), pp. 161-171
Special issue: 5th International MERGE Technologies Conference (IMTC),
1st–2nd December 2021, Chemnitz

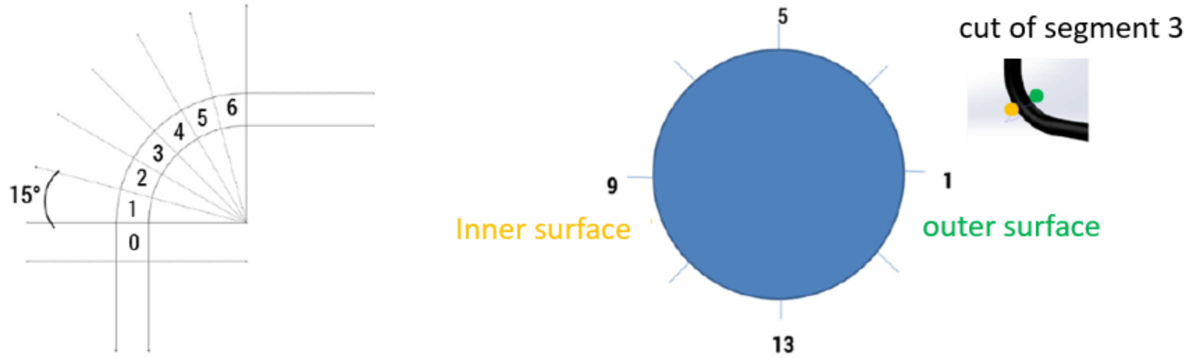

Fig. 2: Axial and tangential segmentation of the bended pipe

Thus, in total112 support points were available along the pipe to discretize the thickness and fiber angle. On this basis, an angle change has been calculated based on the resulting mean value of the fiber orientation in the range 0/5 and 0/13. Similarly, to the thickness changes, these angle changes were available as an inc file for simulation. ANSYS 16.2 has been used as a simulation tool. A parametric model was created using APDL (ANSYS parametric design language). It can implement the desired parameters, such as diameter, curvature radius, pressure, and curvature angle, by entering them in the front range of the inp file. A 4-node shell element, type Shell 181, was used, which includes an option for integrating a laminate structure. The mean element edge length is 2 mm.

After the model has been networked, the respective properties are assigned to the model using simple loop operations. Particularly in the bent area, the angle change has been implemented by creating and assigning 96 sections of a discrete angle change in 15° steps (Fig. 4).

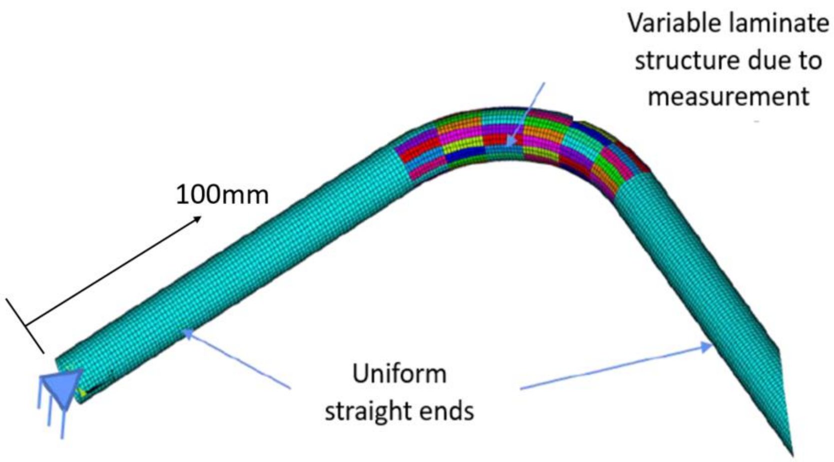

Fig. 3: FEM model for an exemplary 90° bent

The inclusion of changes in wall thickness has also been incorporated into the FEM model. The change in wall thickness also plays a decisive role in the design of metal pipes because of bending.

Various positions are assigned across the segments of the bended pipe. As you can see in Figure 5 the number 1 represents the intrados and the number 9 represents the extrados (see Fig. 5). This arrangement results in 7x16 = 112 variables. The most critical values are at 45° in segment 3.

The highest values were measured on the intrados (position 1). The reason for this is that the fibers accumulate here and the fiber angle increases. This means that there are more fibers. While an accumulation of fibers could be observed in the intrados, thinning of fibers occurs in the extrados (position 9).

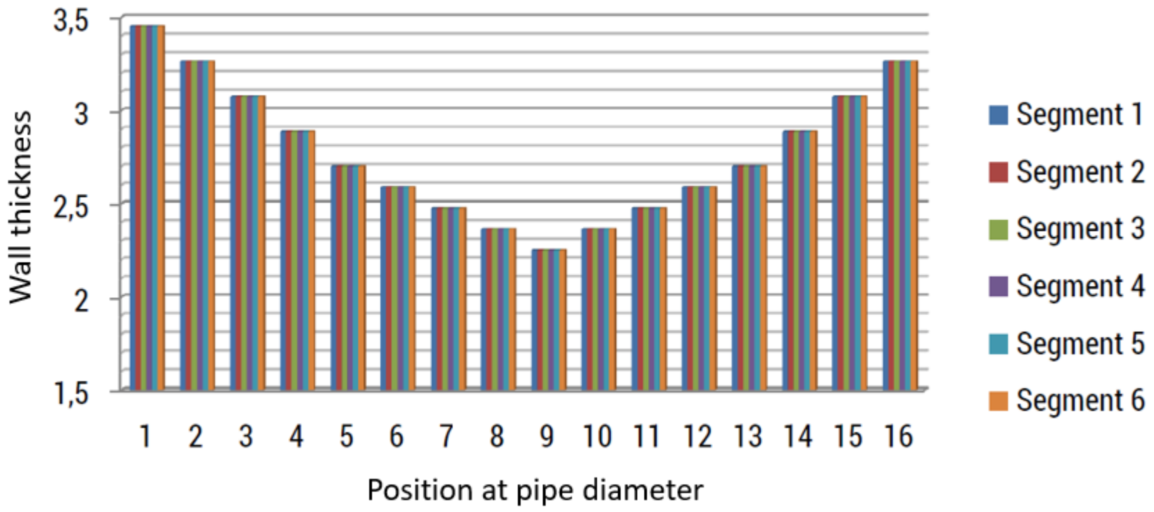

Fig. 5: Segmental change in wall thickness for a 3-layer laminate

2.4 Inverse margin of safety

The inverse margin of safety (1/RF) is well known in the field of FRP [8]. It describes the failure of parts resulting from physically based failure hypotheses of fiber-composites. There are various hypotheses for describing component failure in the field of FRP.

1/RF = 0 component is unloaded

1/RF<1 component is safe against the failure hypothesis

1/RF>1 component is uncertain against the hypothesis. The FRP cannot bear the burden [8].

2.5 Determination of material parameters

To determine the material parameters, several plates (each 0,13 m^2) with different structures, e.g. unidirectional but also application-oriented structures, have been produced to determine the material parameters. For identifying the characteristic values, tests were carried out at 0° (II, x-direction), 90° (T, y), and 45° to the preferred direction of the plates based on DIN EN ISO 527-5. In order to determine the shear parameters of the UD layer, additional shear tests according to DIN EN ISO 14129 were carried out.

A Zwick Z100 machine has been used for tensile testing. For validation of the UD characteristic values, plates with the fiber orientations +/- 35°, +/- 54°, and +/- 60° have been produced from the braided structures (see Fig. 6). The characteristic values of the individual layer, in particular the shear modulus and the shear strength, have been adapted and validated based on the test results.

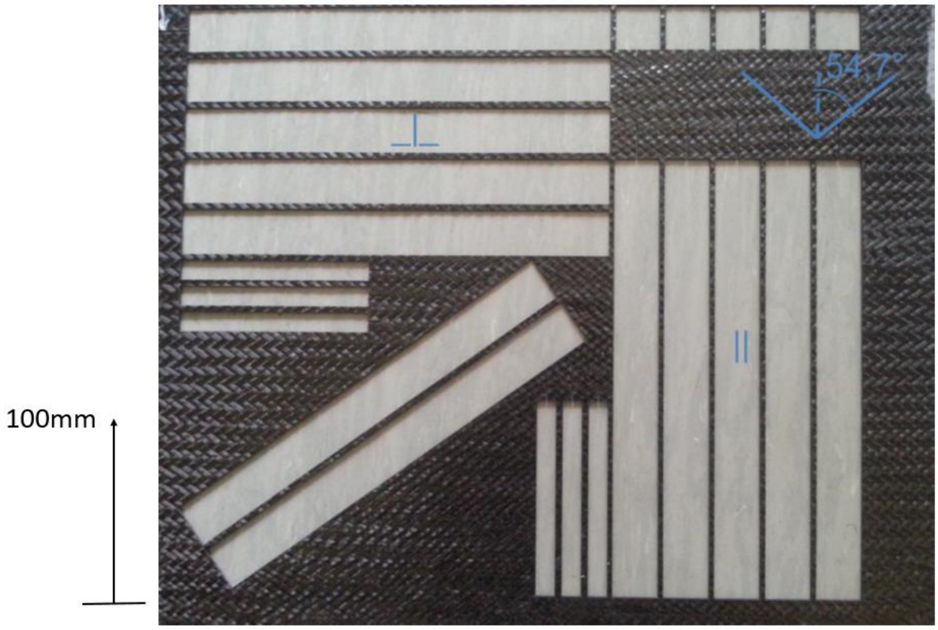

Fig. 4: Sample plate for determining the mechanical parameters for the UD-layer- results

The material characteristics could be seen in Table 1. Based on these material parameters, as well as the FEM model and the failure hypotheses, various optimizations to minimize the inverse margin of safety by varying the shear strengths, material model, etc. are possible. These should determine the optimal braiding angle depending on the theories.

Table 1: Material properties Tenax IMS65 E23 24K 830 tex / Epoxy 50% FVG

Property	***Value***	***Property***	***Value***
Ex	167000 MPa	R1(+)	2774 MPa
Ey	9500 MPa	R1(-)	-1507 MPa
Ez	9500 MPa	R2(+)	77 MPa
Gxy	4500 MPa	R2(-)	-190 MPa
Gyz	3653.8 MPa	R3(+)	77 MPa
Gxz	4500 MPa	R3(-)	-190 MPa
nuxy	0.3	R12	55 MPa
nuyz	0.3	R23	48 MPa
nuxz	0.3	R21	55 MPa

The stiffness Ex in fiber direction and across Ey and Ez are completely different compared to metals. This material property could also be seen with sliding modulus Gxy and Gyz. The Poisson's ratio could be calculated due to the elasticity law. The strengths R are different in tensile strength R1(+) and compressive strength R1(-). The composite does have higher strengths compared to classical steel alloys. The shear strengths R12, R23, and R21 are lower.

It is obvious that by including the adapted shear parameters and the braided structure, significant deviations in 1/RF could be observed, especially deviations from the minimum.

Technologies for Lightweight Structures 5(1) (2021), pp. 161-171
Special issue: 5th International MERGE Technologies Conference (IMTC),
1st–2nd December 2021, Chemnitz

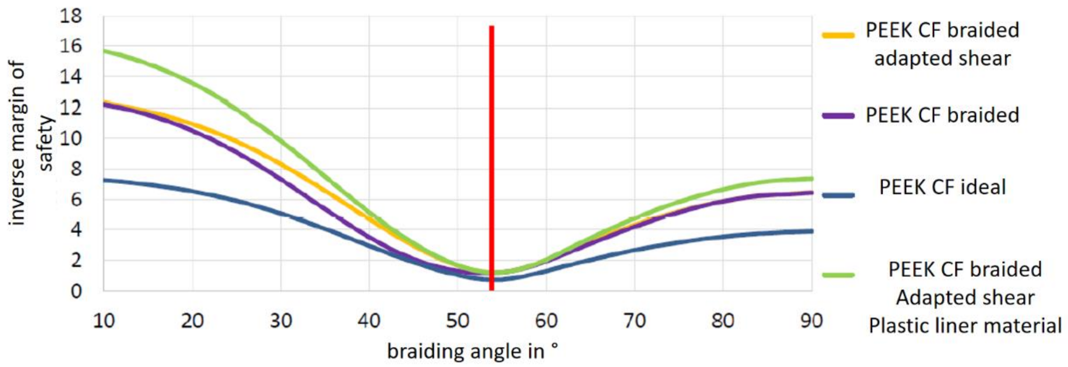

Fig. 5: Inverse margin of safety at several braiding angles

The fiber angle has been optimized for various layups, taking changes in wall thickness and fiber angle of the 90° bent pipe into account. Irrespective of the variation of material models and parameters, all models have a local minimum at ϑ=53.7° in adaptive angle, deviating to 54,7° in net theory. One degree could be classified as a minimum in this condition.

In the first case (Fig. 7), optimization was carried out with a constant angle. This means that the fiber angle ϑ applies equally to + ϑ and - ϑ. The goal is the minimum load for FRP as well as the liner. The optimal fiber angle for this case is 53.7° in the straight area (nominal angle). It can be seen that a deviation of 5°, e.g. the case of production, leads to a doubling of the inverse margin of safety.

The aim of further optimization (Fig. 8) is to achieve an ideal combination of braiding angles across several layers. In the second case, two independent angles ϑ1 and ϑ2 have been assumed, with ϑ1 representing a laminate layer made of + ϑ1 and –ϑ1.

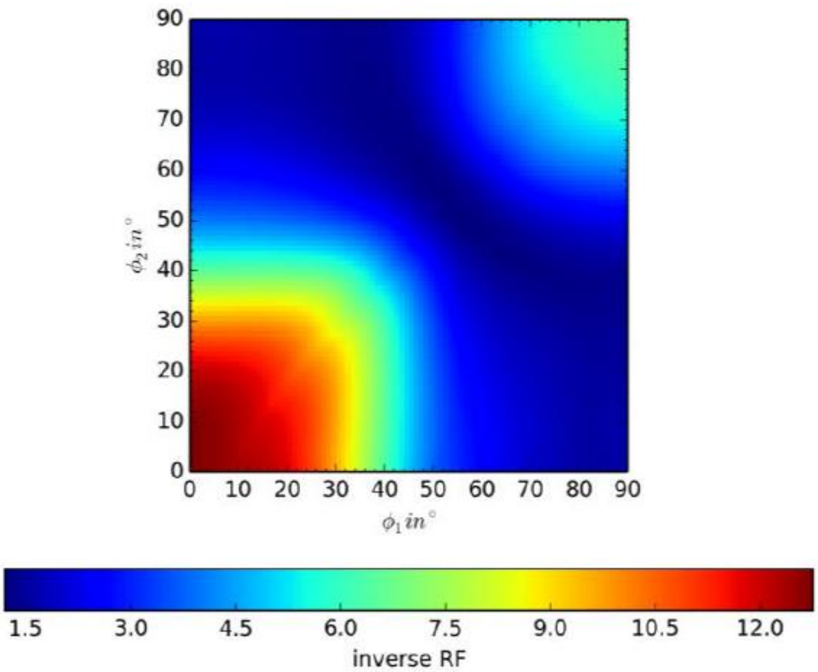

Fig. 8: Carpet plot inverse margin of safety and fiber angle when optimizing for two angles (2-D optimization)

Hence, a braided layer, each consisting of + ϑ and –ϑ, consists of two UD layers with half the thickness, which adhere ideally. It is most likely that the shear failure between the layers + ϑ and –ϑ is of no importance for the subsequent failure, as there is a firm textile bond. To determine the optimal multilayer structure with different angle combinations, the load on the liner has to be considered. The liner only contributes little to the overall rigidity of the component. However, within the composite, it is the partner with the highest possible strain (45% according to ISO 527 [8]). The maximum tensile strength at room temperature is 100 MPa (ISO 527); the compressive strength is 125MPa (ISO 604). These values decrease sharply under the influence of temperature.

Contour lines (Fig.9) have been used for better representation. These lines describe the equal range within the set limits, which the values have not yet reached. The specified total layer thickness is 2 mm, i.e. one of the four individual layers is 0.5 mm thick. The ideal design point is a laminate structure of [+/- 59°, +/- 49°]. The inverse margin of safety is 1.2. The component, therefore, fails at the specified thickness of 2mm.

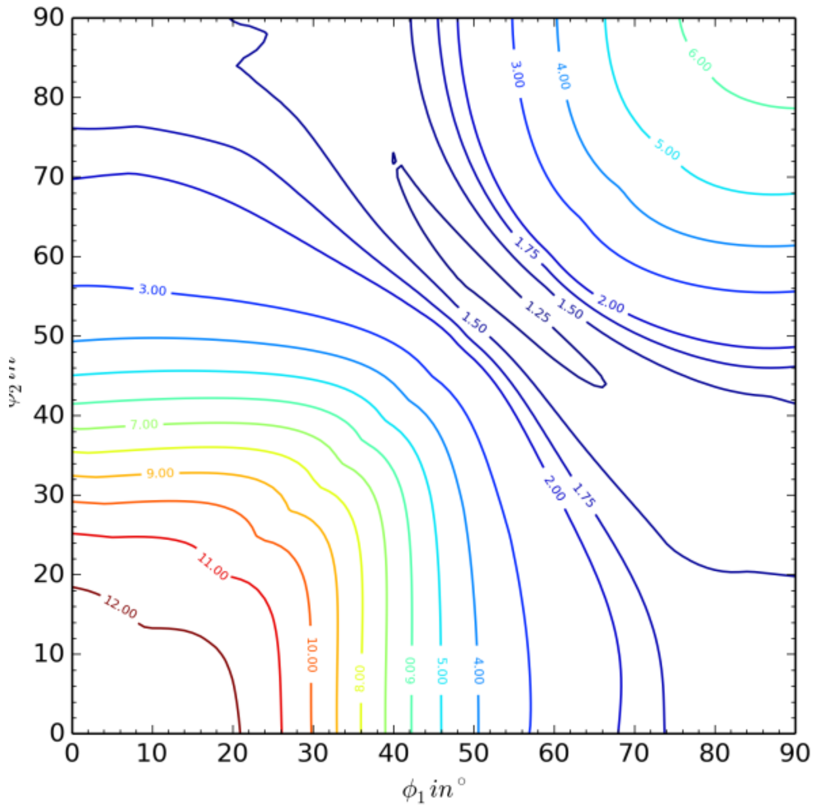

Fig. 9: Contour lines inverse margin of safety and fiber angle when optimizing for two angles (2-D optimization)

The third case (Fig. 10) is based on optimization with two layers of the same fiber structure of 0.7 mm and a further layer with a different fiber structure of 0.7 mm, i.e. [+/- ϑ1, +/- ϑ1, +/- ϑ2]. The inverse margin of safety is minimal at [+/- 55°, +/- 55°, +/- 52°]. The inverse margin of safety is approx. 0.85 along a line from [+/- 45°, +/- 45°, +/- 90°] to [+/- 67°, +/- 67°, +/- 33°]. The liner tension is also minimal.

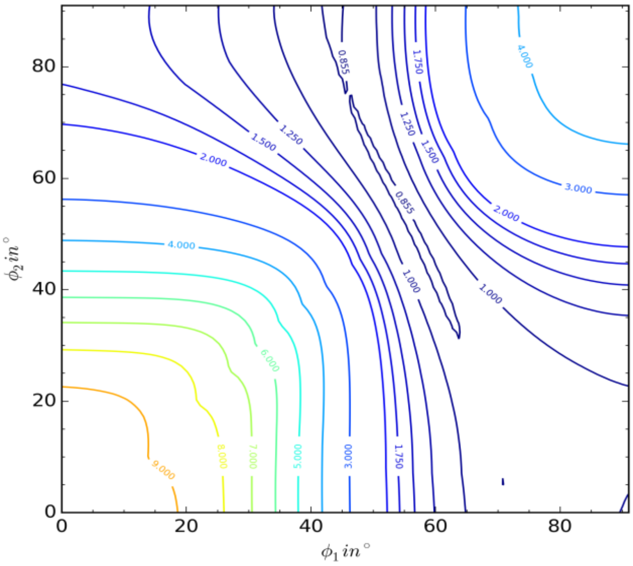

Fig. 10: Contour lines (right) inverse margin of safety and fiber angle when optimizing for CFK 2+1 angle (2.5-D optimization)

3 Discussion and conclusion

With help of an adjustment from the global fiber angle, because of drapery in the bending section, and the adapted wall thickness a new simulation model for designing pipes in case of internal pressure. There are several optimal points within which a possible structure could be found in a technologically meaningful way based on material and technology-related criteria. The fiber angle tolerance of the used pipes may be one criterion. Individual components would inevitably fail if, for example, it were not possible to lay the braided sleeve within a narrower limit of +/- 3°. According to the net theory and 1D optimization, it does not result in the optimal lightweight laminate. A safe process window (compare Fig. 11) is producible with conventional braiding machines. The expanded process window is also producible with braiding machines and adaptive braiding configurations. Within this, a close connection to the braiding manufacturer is helpful.

Technologies for Lightweight Structures 5(1) (2021), pp. 161-171
Special issue: 5th International MERGE Technologies Conference (IMTC),
1st–2nd December 2021, Chemnitz

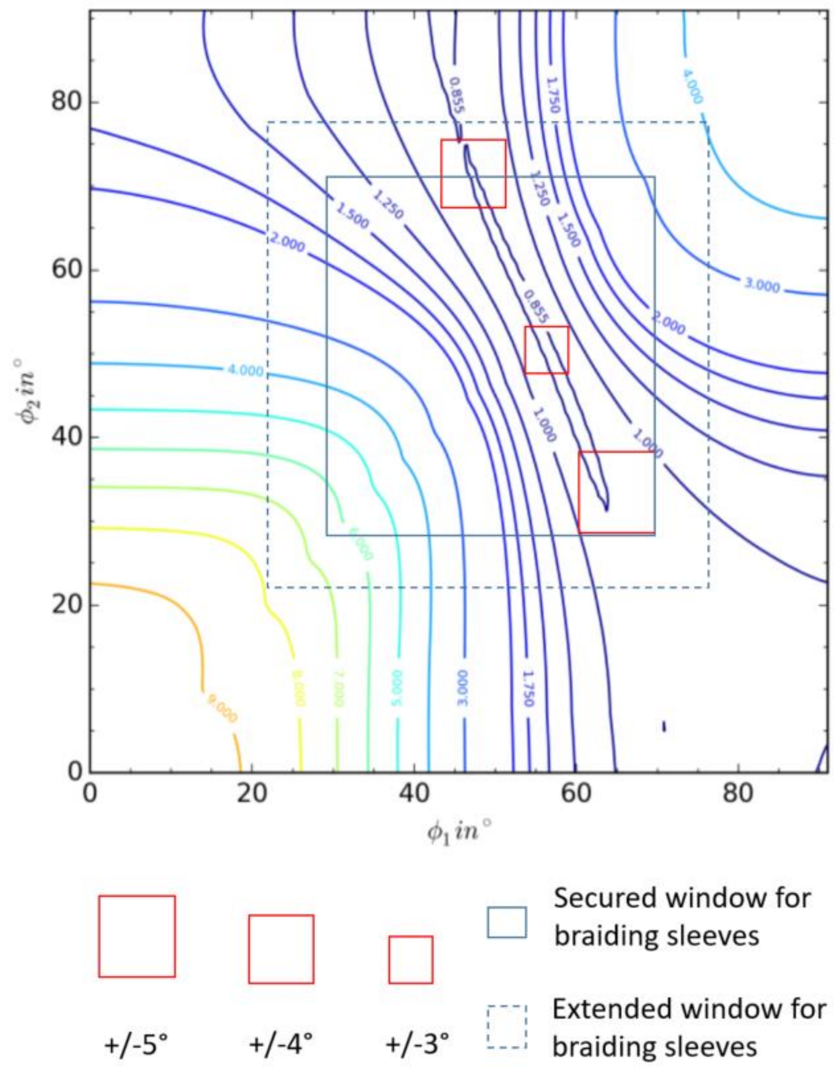

Fig. 11 Contour lines 2.5 D with fiber-angle-tolerance

The investigations show that a safe design of bended fiber plastic pipes under internal pressure load is possible. Both, the tolerable stress in the liner, as well as the inverse margin of safety, have been taken into account. The fiber angle and the change in wall thickness because of the draping in the pipe bent were adjusted. Any parameters could be changed with the help of the developed design tool. This includes internal pressure, diameter and angle of curvature between 0° and 180° as well as bending radius. Braiding sleeves are used, for example, which is manufactured using automated braiding sleeve technology (cf. ABRAST IMTC 2019. The calculation tool could also be used for other technologies, such as winding, braiding or bending.

References

[1] Schürmann, H.: Konstruieren mit Faser-Kunststoff-Verbunden. Berlin/Heidelberg: Springer Verlag, 2007. ISBN 3-540-40283-7.

[2] Puck, A.: Festigkeitsanalyse von Faser-Matrix-Laminaten Modelle für die Praxis. München/Wien: Hanser, 1996. ISBN 3-446-18194-6.

[3] Kroll, L.; Müller, S.: Failure Theories for Composites in Calculation of Anisotropic Composite Materials. TU-Chemnitz, Chemnitz: 2018.

[4] Cuntze R.G.; Freund, A.: The predictive capability of failure mode concept-based strength criteria for multidirectional laminates. Composites Science and Technology, 64 (2004), pp.343–377. doi: 10.1016/S0266-3538(03)00218-5

[5] DIN EN ISO 527-5: Kunststoffe – Bestimmung der Zugeigenschaften – Teil 5: Prüfbedingungen für unidirektional faserverstärkte Kunststoffverbundwerkstoffe (ISO 527-5:2009), 2009.

[6] DIN EN ISO 14129: Faserverstärkte Kunststoffe - Zugversuch an 45°-Laminaten zur Bestimmung der Schubspannungs-/Schubverformungs-Kurve des Schubmoduls in der Lagenebene (ISO 14129:1997), 1997.

[7] Teijin Carbon.: Tenax ™ Filamentgarn IMS 65, 2021. https://www.teijincarbon.com/de/produkte/tenaxr-kohlenstofffaser/tenaxr-filamentgarn?r=1. (accessed 26 January 2022).

[8] Hexcel Corp.: HexFlow® Infusion Resins, 2021. https://www.hexcel.com/Products/Prepregs-and-Resins/HexFlow-Infusion-Resins-for-Aerospace. (accessed 26 January 2022).

[9] Academic, 2000-2021: Academic dictionaries and encyclopedias: Reservefaktor, 2022. https://de-academic.com/dic.nsf/dewiki/1175977. (accessed 26 January 2022).

[10] VICTREX® PEEK™ high performance polymers: Materialdatenblatt VICTREX® PEEKTM 450G903 BLACK, ©Victrex plc Revision Mar 2010, Lancashire, UK, 2010.