UNCONVENTIONAL NEAR-NET SHAPE PREFORMS FOR THERMOPLASTIC COMPOSITES

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Summary

For load adapted reinforcement of axial symmetric composite parts preform construction other than that of linear arranged yarns is needed. In seek of appropriate manufacturing technologies the processes of spiral weaving, spiral knitting, and modified warp knitting appear most promising. Focus of this paper is on modified warp knitting. This technology provides a high degree of freedom regarding variable linear and non-linear yarn arrangement within a respective preform layer. However, some technological restrictions apply for the manufacture of axial symmetric preforms which make changes of the predetermined theoretical preform structure unavoidable. Due to the fabric construction of variable oriented warp knits standard test methods cannot be employed to determine their mechanical properties. Testing of consolidated parts is done instead to allow for evaluation of the composite properties. The material combination of carbon filament yarns and polyetheretherketone matrix material is used for improved fracture toughness and temperature resistance of the composites. Hybrid yarns containing both components are developed to achieve short flow paths for the matrix material and thus complete impregnation of the carbon filaments.

Keywords

Variable oriented warp knits, Axial symmetric preform, Modified Malimo system, Hybrid yarn

1 Introduction

Today, the advantages of reinforced warp knitted fabrics are well understood. The most important feature is the almost crimp free introduction of reinforcing yarns into the fabric structure at high production speeds.

For composite applications multi-axial warp knits (MWK) have gained the most importance owing to the flexibility of yarn placement, see [1, 2, 3] for example. Fabrics of this type are composed of multiple layers of oriented yarn. Most common are warp (0°), weft (90°), and bias ($\pm\theta$) yarns held together by chain or tricot stitches through the fabric thickness. Impaled and not impaled warp knitted structures can be distinguished as the two basic types, [4, 5].

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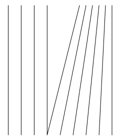
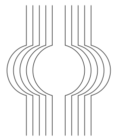
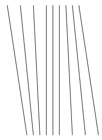
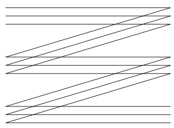
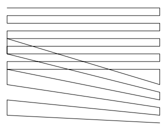
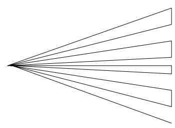
Despite the advantages of warp knitting and the technological advances achieved, only uniform linear arrangement of the reinforcement yarns within a respective layer can be achieved. Local variation of the yarn orientation is not possible. To overcome this limitation, research work was carried out at the Institut für Textil- und Bekleidungstechnik (ITB) at Technische Universität Dresden in Germany. Focus was on modification of the Malimo[1] warp knitting system to allow for local varying reinforcement yarn arrangement. The efforts were carried out in collaboration with the Malimo company starting in 1987. In the end a Malimo system capable of producing variable oriented warp knits (VOWK) was developed. It thus became possible to place warp yarns as well as weft yarns at varying angles within a fabric layer, Table 1. Non-linear yarn arrangement can further be achieved by continuously changing the warp yarn insertion, see [6, 7].

Table 1: Warp and weft yarn arrangements in VOWK fabrics [7, 8]

Warp yarn variation			
Weft yarn variation			

As it is the case for most textile manufacturing technologies the intended use of the modified warp knitting system was for non-technical textiles, [8]. Importance for technical applications was gained resulting from the increasing interest in using textile near-net shape preforms for composite applications. In the following time the system for production of variable oriented warp knits was successfully employed for the production of different kinds of such preforms.

Within a compound research project at Technische Universität Dresden investigations are carried out at the ITB focusing on the manufacture and characterization of near-net shape preforms for failure tolerant high performance composite rotors, [9]. Part of the investigations is the evaluation of different manufacturing technologies for the production of axial symmetric preforms such as spiral weaving, spiral knitting, and modified warp knitting. In this paper the production of preforms via modified warp knitting technology will be described.

To achieve improved failure tolerance of the composite part it was decided to use thermoplastic matrix material rather than a thermoset resin system. The advantages of thermoplastic matrices have been clearly pointed out by several authors, [10, 11, 12]. But the high melt viscosity of thermoplastic materials makes it impractical or impossible to produce composites with current state of technology [10]. In order to eliminate this drawback hybrid yarns are being developed and manufactured at the ITB. This type of yarn material is composed of both reinforcement and matrix component. Manufacturing is done in a commingling process where both components in form of filament yarns are combined into a single yarn. Aim is to achieve a uniform distribution of reinforcement and matrix filaments over the yarn cross section. Following from this short flow paths of the matrix material necessary for complete impregnation of the reinforce-

[1] Malimo® is a registered trademark of the Karl Mayer Textilmaschinenfabrik GmbH

ment filaments become possible. The material combination used is that of carbon (C) and polyetheretherketone (PEEK) to achieve high strength and stiffness as well as high temperature resistance of the final composite part.

2 Machine Description

The technology for producing variable oriented warp knits is based on the classic Malimo system with cross weft yarn insertion, see [13]. The machine at the ITB was modified in a way so that brittle high performance yarns can be processed with little damage. However, inevitable damage to the reinforcement filaments is done resulting from the knitting needles piercing through the yarn layers. To allow for variable weft yarn and warp yarn insertion the Malimo system has been modified as following described. More detailed descriptions of the modified Malimo system can be found in [6, 7, 8] for example.

On the modified machine a maximum of three warp yarn systems can be used in contrast to a single system in case of classical Malimo technique. The yarns within two of the warp systems can be variably introduced into the fabric structure, Figure 1. Both systems can be superimposed. Variation is possible for single yarns or sets of yarns, respectively, over the entire working width of the machine. Individual variation can be achieved for a number of up to twenty yarns. Action for the yarn variation is generated by digital controlled stepping motors to which the yarn guides of a respective system are connected via toothed belt. To account for non uniform yarn consumption the yarns are fed from bobbins in a creel rather than from a beam. For the third warp yarn system only linear arrangement in machine direction is possible. These yarns are usually fed from a beam.

For variable weft yarn arrangement a second insertion mechanism is introduced whereas for classical Malimo technique a single cross weft yarn insertion system is used. Thus the incorporation of linear weft yarns at varying angles becomes possible, see Table 1. A yarn carriage is used, capable of handling single yarns as well as yarn sets. The carriage motion is computer controlled along the two independent axes x_4 and y_4, see Figure 1. Both weft insertion systems can be used separately or in combination.

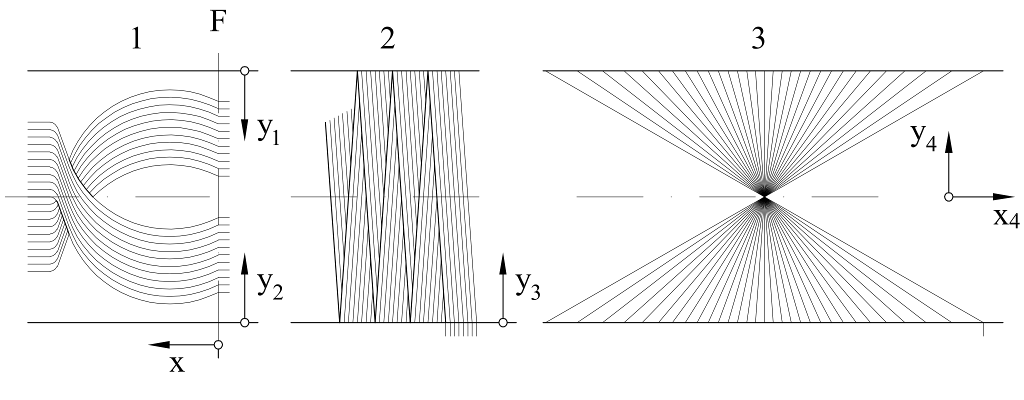


Figure 1: Warp and weft yarn insertion on modified Malimo system (1–variable warp insertion, 2–cross weft insertion, 3–variable weft introduction, F–fabric formation line)

For production of the axial symmetric preforms a total of four yarn layers is employed. Following a single preform is composed of two layers of variably introduced warp yarns and two layers of weft yarns. The yarns of only one weft yarn layer are arranged at varying angles whereas the second weft layer represents cross inserted yarns. The latter are necessary to insure for stitch formation over the entire machine width namely in that areas where intermittently neither warp nor weft yarns are incorporated into the fabric structure. To achieve minimal derivations from the predetermined preform structure (see Section 3) low yarn count PEEK filament yarns are used instead of C/PEEK hybrid yarns.

3 Preform Design and Characterization

For the design of the preform structure stresses induced by centrifugal forces in a thin disc are considered. Consequently a preform comprising oriented yarns in radial and circumferal[2] direction was derived. In order to determine the stress distribution in a polar orthotropic disc analytical calculations were carried out at the Institut für Leichtbau und Kunststofftechnik (ILK)[3] [14]. In contrast to isotropic material behavior it was found that the maximum tangential stresses occur in the vicinity of the outer rim of the disc. For the radial stresses almost similar behavior to isotropic materials was found. Following from the calculations a theoretical preform structure as shown in Figure 2 was derived.

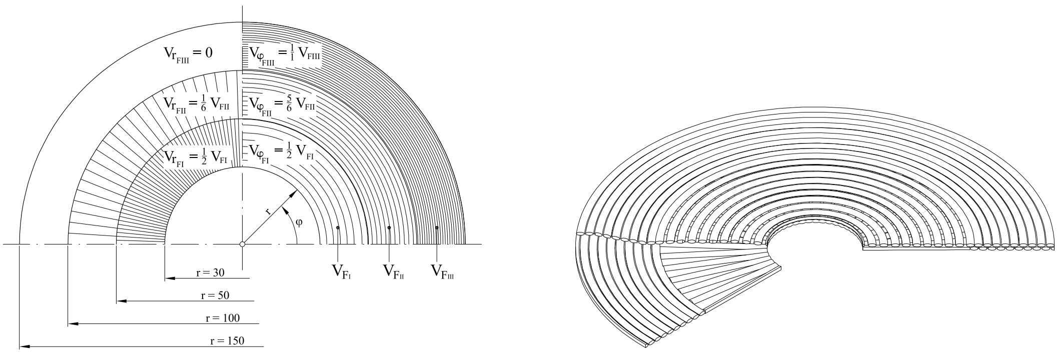


Figure 2: Theoretical preform structure

From the figure can be seen that the fiber volume in circumferal direction increases towards the outer rim of the disc whereas that in radial direction decreases. It should be noted that the fiber volume fraction of reinforcement filaments in the composite part is preadjusted to 60% resulting from the use of C/PEEK hybrid yarns, see [12]. Thus in the following it is rather referred to the relative fiber volume in a respective direction.

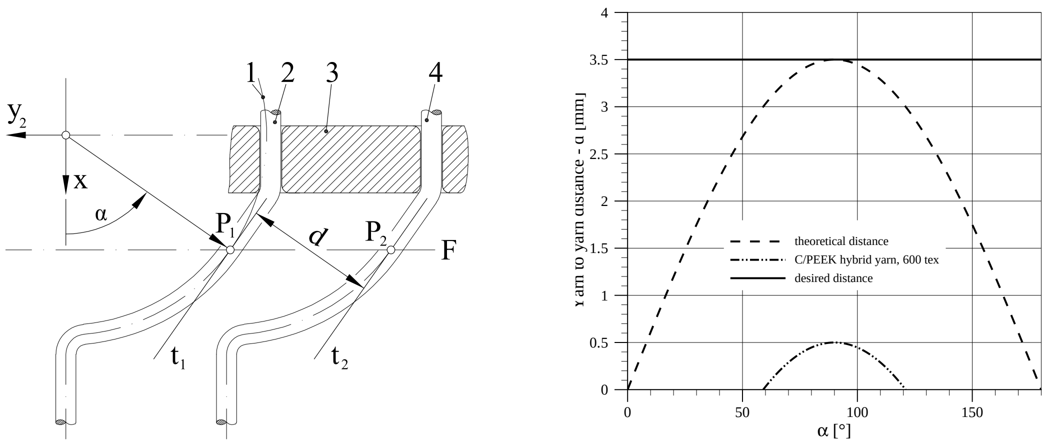
For preform production by modified warp knitting some changes of the theoretical preform structure become necessary due to technological restrictions that apply during the manufacturing process. The most noticeable deviation in the preform design is the warp yarn arrangement in circumferal direction. Due to the fact that the warp yarns are introduced in machine direction a closed circular arrangement of these yarns cannot be achieved, see Table 1. Furthermore, resulting from the variation of yarn sets the distance of two adjacent yarns varies depending on the angle at which they are incorporated into the fabric structure. Figure 3 illustrates the variation of the yarn to yarn distance within a warp yarn set.

From Figure 4 it becomes obvious that warp yarn introduction is done for a constant diameter. In order to achieve yarn arrangement over the entire disc radius it was decided to superimpose both warp yarn systems before they are arranged into a left and right semicircle, respectively.

Second, weft yarn arrangement in radial direction is possible over the entire machine width only, see Figure 1. The yarns are feed from a single bobbin as described in Section 2. At half of the machine width the yarns cross each other which is leading to increased layer thickness. This fact is neglected in the further considerations since this

[2] also referred to as tangential

[3] Institute of Lightweight Construction and Plastics Technology at Dresden University of Technology



1	Predetermined yarn path	**2**	Warp yarn
3	Warp yarn carriage	**4**	Adjacent warp yarn
d	Distance between t_1 and t_2	**F**	Fabric formation line
t_1	Tangent on **2** in P_1	t_2	Tangent on **4** in P_2
x	Machine direction	y_2	Transverse machine direction

Figure 3: Distance between two adjacent warp yarns

part of the preform will be cut out after consolidation. From Figure 1 becomes clear that continuous weft yarn arrangement in radial direction cannot be achieved. The yarns are rather formed in two symmetrical triangular shaped areas. Accounting the fact that in this case with both systems for warp and weft insertion, respectively, homogeneous yarn arrangement cannot be achieved, the actual preform structure was derived. Figure 4 shows the structure of the actual preform as described. Instead of closed preform layers such of disc segment shape are being used.

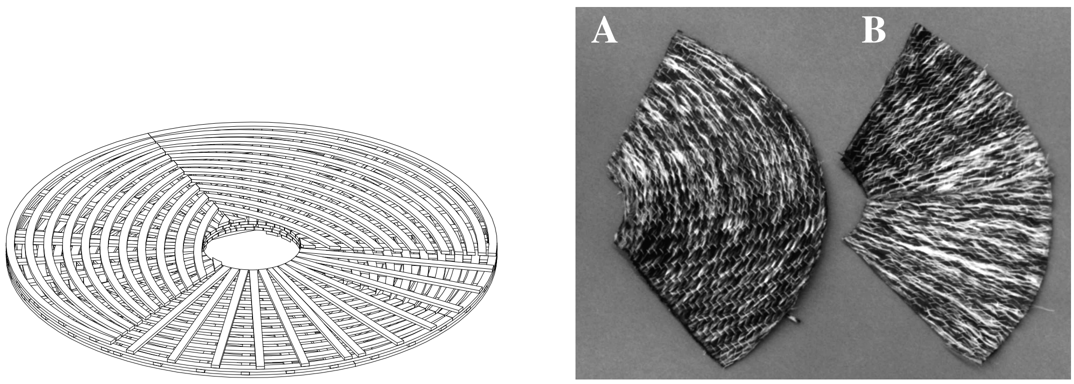


Figure 4: Actual preform structure obtained from modified warp knitting

On the left side a preform composed of multiple segments is shown. On the right side a single segment in top view (A) as well as bottom view(B) is presented. From these figures the yarn arrangement in tangential and radial direction can clearly be seen, respectively.

Determination of the preform properties by standard testing methods is difficult because of the preform structure. Following from this testing of the composite parts becomes necessary for preform evaluation. Consolidation and testing is done at the ILK. Autoclave processing is used to manufacture the composite parts. For composite testing determination of the burst rotary speed is carried out. To allow for a comparison of the test results, two additional reinforcement structures are included in the investigations.

The two considered structures are weft inserted warp knits (WIWK) and plain woven (PW) fabrics in form of symmetric quasi isotropic stacks. The results gained from testing are presented in Figure 5.

Var.	Stacking	Note
V1	$[0^\circ_2/60^\circ_2/120^\circ_2]_s$	WIWK
V2	$[0^\circ_2/60^\circ_2/120^\circ_2]_s$	WIWK - stitched
V3	$[0^\circ/60^\circ/120^\circ]_s$	PW
V4	$[0^\circ/60^\circ/120^\circ]_s$	PW - stitched
V5	$[T/R/T^a]_s$	VOWK

[a] Tangential/Radial/Tangential

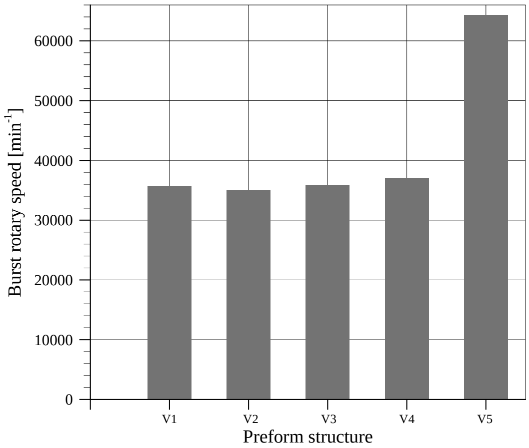


Figure 5: Measured burst rotary speeds of the different composite discs [15]

This figure reveals that the burst rotary speed determined for the VOWK composite discs is almost twice as high as that of the discs reinforced by quasi isotropic WIWK and PW fabrics, respectively. Thus the advantages of a polar orthotropic preform construction can very well be proven for a state of stress induced by centrifugal forces.

4 Conclusions and Future Work

The modified Malimo system showed to be suitable for the production of axial symmetric preform structures for reinforcement of composite discs. The advantages of polar orthotropic VOWK preforms over quasi isotropic preform construction could well be illustrated by the burst rotary tests carried out. Full potential of the modified Malimo system is developed when both, warp yarn variation and variable weft yarn insertion are used. Despite this some derivations from the theoretical preform structure had to be made due to technological restrictions regarding the yarn variation. Critical for commercial application is the economic efficiency of the technology as investigated in [16].

Future work to being carried out will focus on the comparison of VOWK preform with spiral woven fabrics (SW) as well as with biaxial reinforced weft knitted spiral fabrics (BRWKS). Further the development of a geometrical model for VOWK of arbitrary construction remains to be considered.

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