Vignaesh Sankaran, Steffen Rittner, Lars Hahn, Chokri Cherif

Development of multiaxial warp knitting technology for production of three-dimensional near net shape shell preforms

Erstveröffentlichung in / First published in:

Textile Research Journal. 2017, 87(10), S. 1226 – 1241 *[Zugriff am: 07.08.2019]*. SAGE journals. ISSN 1746-7748.

DOI: https://doi.org/10.1177/0040517516651102

Textile Research Journal

Original article

Textile Research Journal
2017, Vol. 87(10) 1226–1241

DOI: 10.1177/0040517516651102
journals.sagepub.com/home/trj
SAGE

Development of multiaxial warp knitting technology for production of three-dimensional near net shape shell preforms

Vignaesh Sankaran, Steffen Rittner, Lars Hahn and Chokri Cherif

Abstract

The possibility of direct preforming in the near net shape of final component structure with load- and shape-conforming fiber orientations is highly essential in composite production, not only to reduce costs but also to attain better mechanical properties and form stability. Based on the concept of varying the reinforcement yarn lengths during the feed-in (warp yarn delivery) and segmented doffing, synchronous working numerically controlled warp yarn delivery and doffing machine modules have been newly developed for multiaxial warp knitting machines to create a resource efficient textile process chain by a single-step, large-scale oriented production of load- and form-conforming warp knitted three-dimensional shell preforms with free-form geometrical surfaces. Such customized preforms in the near component net shape offer higher material utilization and increased lightweight potential.

Keywords

three-dimensional shell preforms, warp knitted fabrics, process chain, multiaxial warp knitting technology

Sustainable management of non-renewable resources is a current social need given their scarce availability. Notably, sustainability here means increased energy and resource efficiencies. The multiple possibilities in adapting the characteristics of the fiber composites according to the application requirements offer a great potential for the implementation of resource-saving and energy-efficient lightweight construction solutions, especially in the civil (building and construction), automotive and aviation sectors.[1] These solutions can be particularly more advantageous for components with complex shaped geometries, in which case it is possible to reduce the existing high production costs required for their preforming, which currently requires several sequential, partially automated and manual processing steps.[2,3] In the textile manufacturing sector with a Small and Medium Enterprise (SME) distribution above 90%, the material costs with a share of over 40% constitute the vast majority of the existing total production costs.[4] The material efficient production of textile reinforcements forms one of the main industrial requirements. In this regard, load- and form-conforming fiber orientation is also extremely significant, especially in critical areas subjected to loads. This is highly required in order to avoid the degradation of mechanical properties, where marginal deviation from the yarn course by 10° within a unidirectional layer results in a notable reduction of the tensile strength by approximately 35% and of the stiffness of 20%.[5] As a result, the deviation of the fiber orientations from their determined course in the critical loaded areas needs to be a bare minimum, so as to avoid oversizing of the

Institute for Textile Machinery and High Performance Technology, Technische Universität Dresden, Germany

Corresponding author:
Vignaesh Sankaran, Institute for Textile Machinery and High Performance Technology, Technische Universität Dresden, 01062 Dresden, Germany.
Email: vignaesh.sankaran@tu-dresden.de

components. Hence, the current efforts are aimed in producing textile reinforcements in the near net shape (three dimensions) of the desired final complex geometrical form with a load path aligned reinforcing yarn course. This enables a resource (material and energy) efficient preforming due to the reduction of material needs and the intermediate processing steps during preforming.

In this regard, various research activities have already been focusing on enhancing and further developing the existing technologies, such as braiding, weaving, weft and flat knitting, in order to facilitate a large-scale production of three-dimensional (3D) near net shape shell preforms.[6–10] The limitation of these technologies based on the shaping possibilities and the property needs of the preforms according to the application requirements have already been extensively discussed.[11,12] More significantly, it can be inferred that although a unified technology for the production of both near net shape open-grid and closed-surface textile reinforcements on a single machine is in large scale, it is still not known. The suitability of warp knitting technology for producing complex shaped preforms is well documented.[13,14] Also, in our earlier work the fundamental prerequisites for addressing this problem through this highly productive multiaxial warp knitting (stitch-bonding) technology by means of a novel concept were presented.[15] The technological enhancement based on the concept of varying the reinforcement yarn lengths individually during the feed-in (warp yarn) in this multiaxial warp knitting (stitch-bonding) technology has created an essential basis for producing open-grid textile preforms with mathematically definable geometrical form directly in their final shape. A variable numerically controlled (NC) warp yarn delivery and a segmented mechanical doffing unit for multiaxial warp knitting machines was successfully developed and implemented for this purpose. A significant advantage of this method lies in the reduction of the inhomogeneity when compared to the variable doffing technique that is being solely used, as the doffing force required is very large and leads to undesired anisotropies.

The recently concluded research phase built upon these findings to ensure the production of closed-surface (shell) multiaxial warp knitted textile preforms with more complex geometries and free-form shapes in a reproducible quality as well. In order to achieve this objective, a novel Computer Aided Design (CAD)-based automated textile process chain was developed. Based on the concept of reverse engineering, a viable method that allows the creation of a virtual CAD model for complex geometries, a universal calculation method for computing the required yarn lengths on a virtual CAD model and NC systems for both variable segmented yarn delivery and doffing units has been developed. This paper presents and discusses these new developments based on multiaxial warp knitting (stitch-bonding) technology that allows a one-step production of complex geometrical form-based closed-surface (shell) textile preforms.

Development methodology for the production of near net shape shell preforms

A comprehensive analysis of the previously developed technological process chain for the production of near net shape open-grid preforms was first performed to obtain the new processing prerequisites for a qualitative fabrication of closed-surface (shell) textile preforms. The production of near net shape preforms using the multiaxial warp knitting technology is achieved by locally varying the length of each individual warp yarn across the fabric width. The delivered warp yarn lengths are then doffed by a mechanical doffing system (Figure 1(c)) in a segmented way, so that additional delivered lengths are completely taken up and the warp yarns are held in tension at the knitting (stitch-bonding) unit. The mechanical doffing system has an experimentally determined and set calibrated doffing

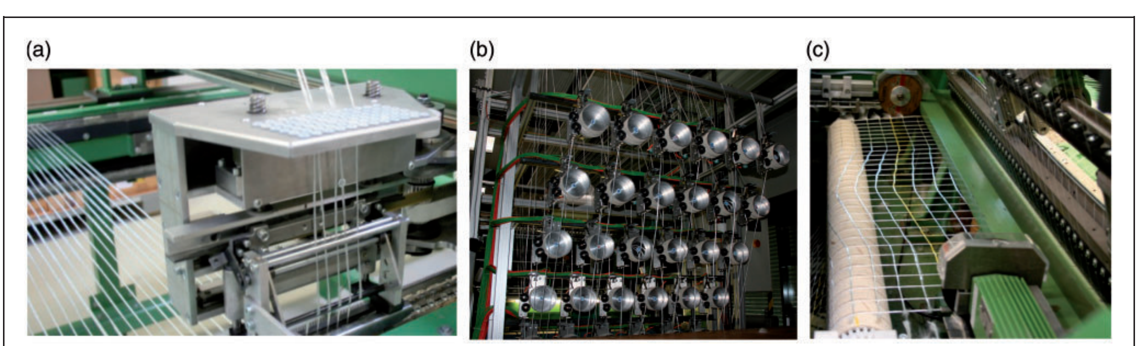

Figure 1. Test setup for system validation.

force of 10 N in each segment to ensure a complete take-up of the delivered warp yarn lengths without any filament breakage. Since the take-up of the delivered warp yarn lengths is decisive in determining the geometrical accuracy of the final preforms, the influence of the exerted doffing force by each segment of the mechanical doffing system for a fixed machine working cycle was first studied.

Experimental study of the mechanical doffing system

In this study, the doffing system was mounted on to the traverse of a tensile testing machine. The warp yarn was then fed through each segment pair in such a way as to recreate the process scenario as in the machine. The linear movement of the traverse represented the fixed machine working cycle and the doffing force was subsequently measured by means of a force measurement sensor. The measured doffing force exerted on the yarn by each doffing segment pair with a low and high contact pressure across the width of the doffing system (outer left, middle and outer right) is summarized in Figure 2.

Result analysis

As can be seen from Figure 2, the measured doffing forces vary largely from the summed set force of 20 N for each segment pair during the linear movement of traverse. Also the doffing force exerted by each segment pair lies below this force and is acyclic. This can be related to the mechanical tolerance of the braking unit for each segment. A further analysis on this doffing system was performed by increasing the contact pressure of each segment pair by suitably setting the adjustable springs available at the edge of the two cylindrical rolls and then measuring the exerted force. The measured force exerted by each segment pair does not show any significant difference with an increased pressure across the width of the doffing system, as can be seen from Figure 3.

System validation

In order to study the influence of the doffing force on the geometrical accuracy of the preform, a subsequent target/actual comparison was performed. Here weft yarns were laid with a fixed distance in the transport chain (Figure 1(a)) prior to the knitting (stitch-bonding) process. Additional warp yarn lengths with factors varying from 1.0 to 1.2 were then delivered using the NC warp yarn delivery unit (Figure 1(b)). The actual weft yarn distances measured after the knitting process were then compared with the theoretical target value. Fifteen warp yarn lengths in the middle of the fabrics were selected for the analysis, as the maximum doffing force is required here (Figure 1(c)).

In Figure 4, the calculated target length to be delivered for each warp yarn (Target Length) and the achieved length (Actual Length) of the corresponding yarn, measured in terms of the distance between two adjacent weft yarns has been tabulated (top) and graphically illustrated (bottom left). From the graphical representation (bottom right) it can be seen that the measured yarn length (Ave. Actual Length) is less than the calculated target length. This aspect can be directly related to the inhomogeneous and insufficient doffing force of the segment due to the mechanical tolerance of the braking unit. The influence of the yarn elongation in the measurement of the system is highly negligible, as the force required to cause an elongation is much higher than the set doffing force of 10 N and can be experimentally validated from yarn tensile tests.

Furthermore, a modified doffing technique with an increased segment surface contact to the fabric was also implemented and experimentally tested (Figure 5(a)). While the doffing technique with a minimal segment surface contact to the knitted textile fabric ensures a damage-free take-up, the transfer of the doffing force required to keep the warp yarn in tension was not sufficient due to the mechanical tolerance of the braking unit, leading to fabric slippage. Hence, the segment surface contact area to the textile fabric was increased, as shown in Figure 5(b), for reducing the slippage to a minimum and thereby ensuring a better doffing force transfer. However, the take-up of the fabric structure and damage-free production of preforms can be realized only at extremely low speeds and it is also highly dependent on the geometrical complexity of the form shape.

The textile production chain here also involved an automated generation of machine parameters with the required yarn length data for the NC warp yarn delivery units. A mathematical model was developed to allow a parametric representation of the final structure geometries. The calculation of the required warp yarn length on the defined parametric surfaces was carried out based on a mixed Secant-Bisection method. However, it is strictly restricted to only simple mathematically definable geometries and is not suited to complex geometries with varying curvatures, free-form shapes or component surfaces where construction data are not available.

Result discussion

The above extensive study about the achievable structural geometry based on the target/actual comparison, machine and processing constraints of the doffing system and the limitations of the process chains

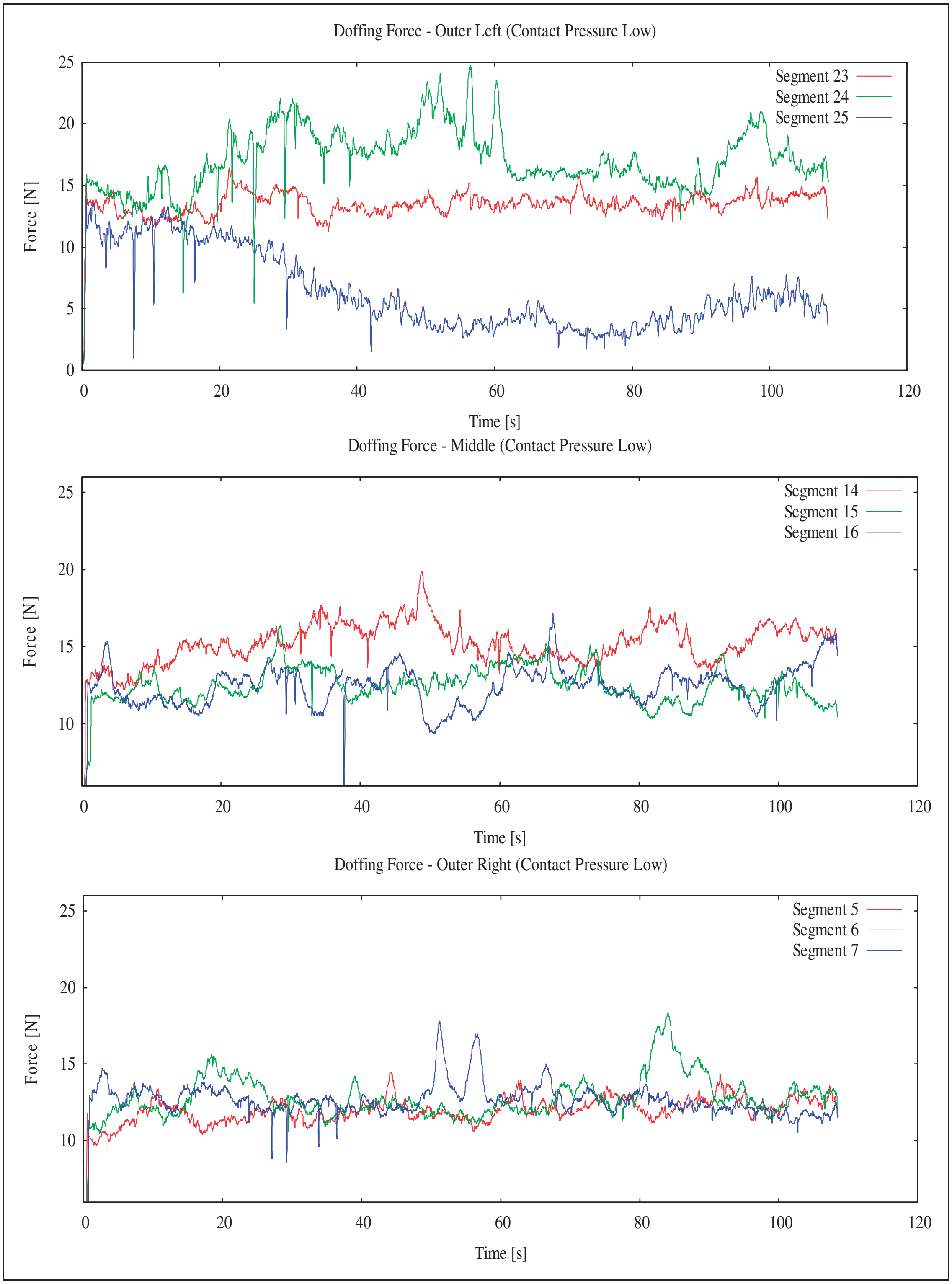

Figure 2. Measured doffing force of a segment pair with low contact pressure.

formed a robust basis for the further development of the technology. Firstly, the process chain was further developed to establish a universal technological process chain based on the concept of reverse engineering, where the complex shaped geometry parts whose design data are not available are scanned through a laser triangulation sensor and their surfaces are recreated from the acquired point cloud data.

Figure 3. Measured doffing force of a segment pair with high contact pressure.

These recreated surfaces are then stored as a CAD model and form the basis of the calculation of the yarn course. In order to overcome the process constraints of the mechanical doffing system related to the resulting inhomogeneous doffing force transfer during the fabric take-up, the existing mechanical control through the braking unit for the transfer of doffing force to the fabric is replaced with a numerical control

Warp yarn distance	32.80															
Yarn delivery factor	1.02	1.05	1.07	1.1	1.12	1.15	1.17	1.2	1.2	1.17	1.15	1.12	1.1	1.07	1.06	1.02
Target Length	33.46	34.45	35.10	36.09	36.74	37.72	38.38	39.36	39.36	38.38	37.72	36.74	36.09	35.10	34.45	33.46
Ave. actual length	33.68	33.67	33.77	33.81	33.83	33.87	33.89	33.92	33.92	33.89	33.87	33.83	33.81	33.77	33.67	33.68

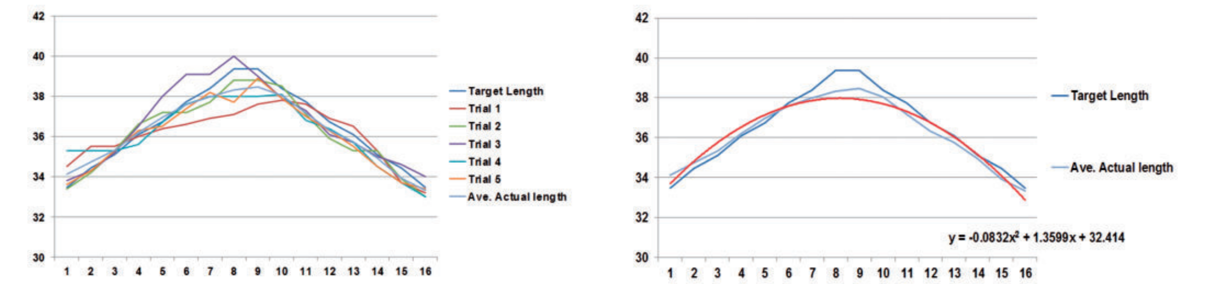

Figure 4. Validation of the system by target/actual comparison.

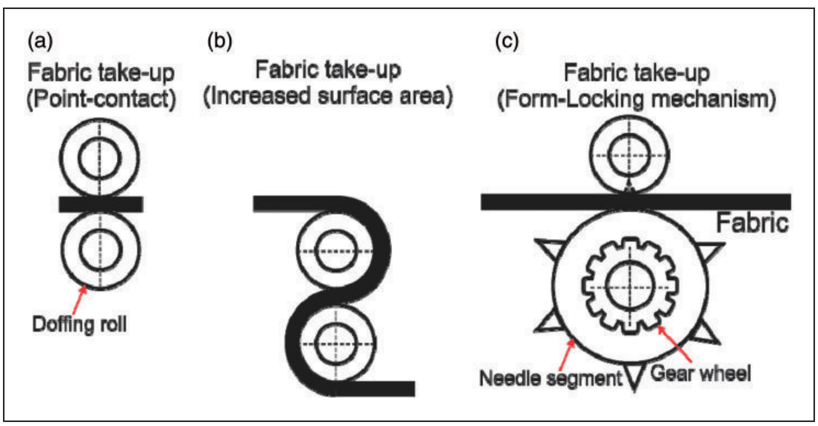

Figure 5. Doffing methods for fabric take-up.

by means of servo drives. This allows for an accurate and digitally controllable doffing force transfer required for the take-up of delivered additional warp yarn lengths. Moreover, the doffing technique is also further enhanced with a needle segment unit specifically for the production of closed-surface fabrics (shell preforms) so that the transfer of the doffing force can be significantly increased with only a minimal surface contact to the fabric and also ensures a negligible fabric slippage. In addition to this modified doffing technique, the experimental analyses have also shown that an ideal transfer of the doffing force for the delivered warp yarn take-up can only be ensured when the cutting of the weft yarns from the transport chain, that is, fabric let-off, takes place during the knitting (stitch-bonding) process, similar to the biaxial stitch-bonding machines. Hence, a suitable cutting methodology was also developed, taking the existing machine space, design and its ergonomics into consideration.

Development of a universal textile process chain

Computational model and method

Research activities related to direct preforming technologies have been focusing on the creation of a simulation model for computer aided manufacturing. The producible textile constructions required for the final geometry are determined by computation of the yarn lengths based on their courses and processing constraints.[16–18] The computed lengths can then be transformed into the machine data, thereby significantly reducing the change time required for the production of different structures. A universal computational principle based on profile segmentation and yarn distribution enables one to calculate the optimal yarn length. In an iterative process the geometrical and technological limits are also taken into consideration for determining the producibility of the textile. Here, the scanned CAD model of a free-form surface geometry is taken as reference for the calculation. The weft and warp yarn directions can be selected according to the required load case scenarios.

Figure 6(a) illustrates a sample structure selected for computational and validation purposes, while Figure 6(b) shows the defined yarn directions. After the directions are defined, the inner edge of the component along the warp direction is chosen and divided into equidistant points. The distance between the points represents the length between the weft yarns as laid in the transport chain (see Figure 7). The distance between the points, that is, minimum weft yarn distribution, was chosen as 1.89 mm on the basis of the machine gauge E14. The total length of the curve along the inner edge for the selected sample is 470 mm and the total number of weft yarns required to be distributed across the component geometry in order to represent a closed surface amounts to 243. Figure 7 represents a total of 30 distributed weft yarns (every eighth weft yarn) (n_{SF}) for illustrational purposes.

Subsequently, the component geometry is divided into segments according to their curvature along the divided points of the inner edge, and these serve as weft yarns. The segmentation process occurs in such a way that the distance between any two points within

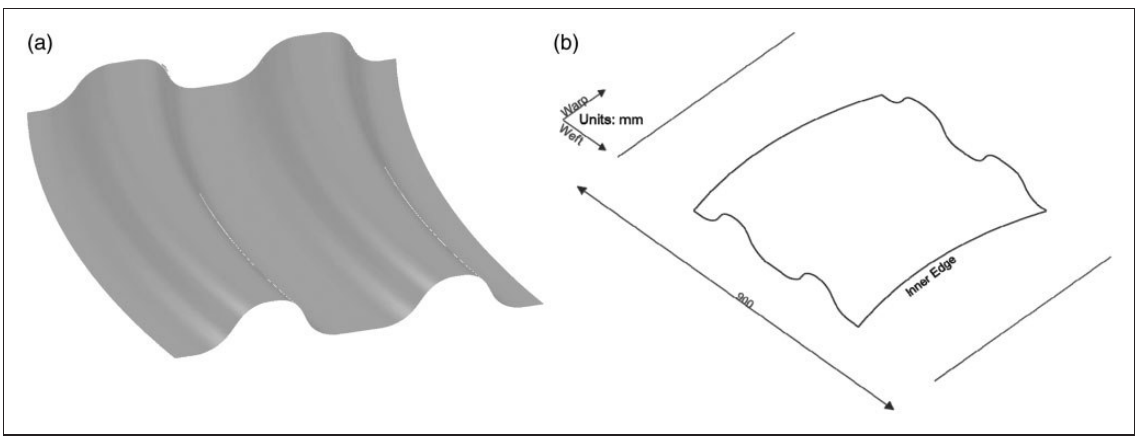

Figure 6. Sample structure: (a) reference Computer Aided Design model; (b) defined yarn orientations.

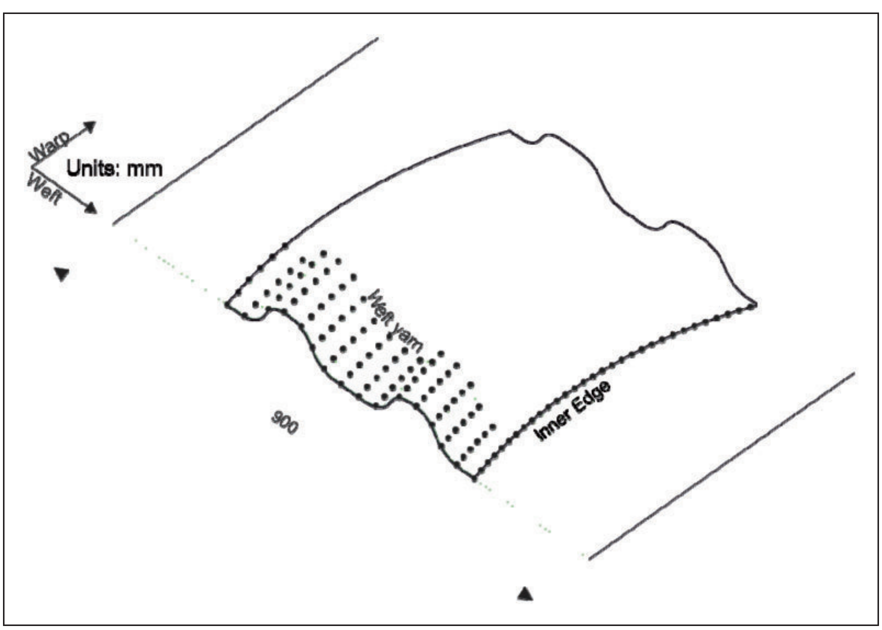

Figure 7. Weft yarn distribution through segmentation.

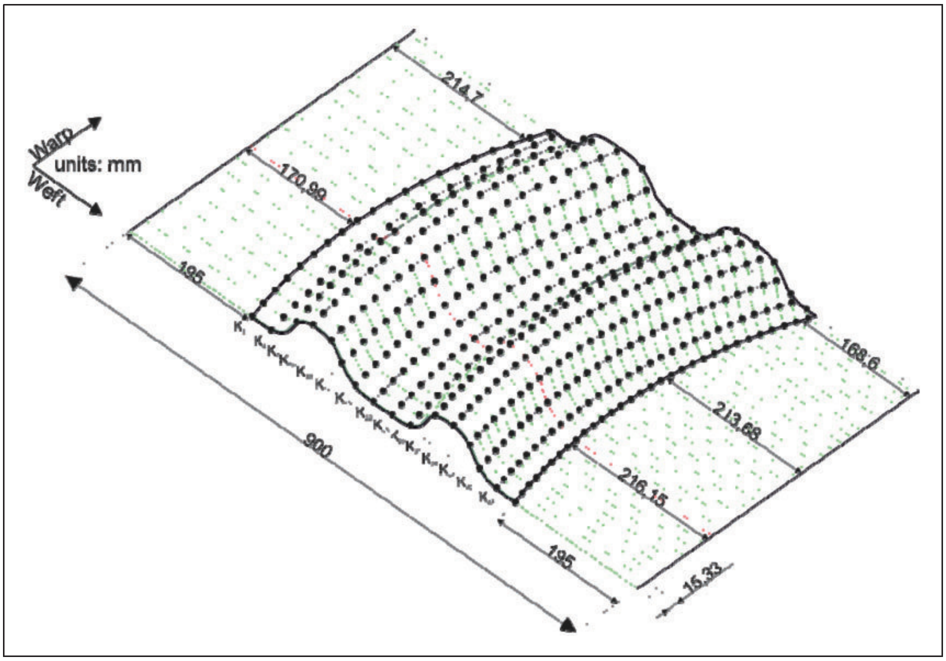

Figure 8. Warp and weft yarn distribution for calculation of yarn lengths.

two consecutive weft yarn segments at no point of time exceeds twice the smallest distance, that is, 3.78 mm in this case, based on the permissible additional warp yarn length that can be taken up as allowed by the doffing system design. Each weft yarn segment is then divided into a further equal number of points across the surface width. These points along each segment represent the fixed warp yarn distribution.

The warp yarn distribution here was chosen in accordance with the machine gauge F7 with one full and two empty feeds. This corresponds to a distance of 10.89 mm between the yarns. The total number of warp yarns distributed across the sample width of 480 mm is 45. After the segmentation is carried out for the whole structure, the total length of each warp yarn is calculated by adding the distance between the same corresponding points in each of the weft yarn segments. Figure 8 shows the weft and warp yarn distributions. Every third warp yarn (n_{KF}) is illustrated in the figure for representational purpose. The final calculated warp yarn lengths for the sample structure are provided in Table 1. The rows of the table represent the weft yarns that are to be processed, while the columns represent the total warp yarn lengths that need to be delivered by each NC warp yarn delivery unit for these weft yarn sets. Since each NC warp yarn delivery unit will carry a total of three warp yarns (e.g. warp yarn bunch 1–3, 4–6, etc.), their delivery lengths remain the same. These values are stored in ASCII file format and are used as input for the generation of machine control data.

Development of a NC doffing system

Doffing principle. In order to ensure an efficient control and transfer of doffing force for the take-up of the delivered warp yarn lengths, the mechanical construction design and the doffing control methods were modified. Doffing methods that include frictional force transfer for fabric take-up with a point contact (Figure 5(a)) or with an increased contact area (Figure 5(b)) have already been found to be insufficient, as experimentally determined. Also, experimental results have shown that the increase of doffing force by means of increased contact area leads to fiber damages.

Various doffing methods involving force transfer and form-lock mechanisms and their advantages have been extensively reviewed.[19] One of the doffing methods involving a form-locking mechanism with a point contact is doffing rolls with a needle segment (Figure 5(c)). The major disadvantage of such form-locking mechanisms when compared to the force transfer mechanism is the linking and the delinking of form-locking elements (such as the needle) to the fabric before and after the doffing, resulting normally in extensive fiber damages. However, recent machine developments, especially in the field of multiaxial warp knitting technology, have shown that these fiber damages in principle can be significantly reduced through suitable design of the needle geometry and penetration methods.[20] One of the major advantages offered by the form-locking mechanism, though, is that the force transfer by means of form-locking elements can be efficiently implemented

Table 1. Calculated warp yarn lengths (in mm) for the sample structure

$n_{SF}\backslash n_{KF}$	1	4	7	10	13	16	19	22	25	28	31	34	37	40	43
1	23.09	21.47	20.32	19.64	18.56	17.32	17.32	22.38	21.47	20.32	19.64	18.56	17.32	16.45	15.39
9	23.09	21.47	20.32	19.64	18.56	17.32	17.32	22.38	21.47	20.32	19.64	18.56	17.32	16.45	15.39
17	23.09	21.47	20.32	19.64	18.56	17.32	17.32	22.38	21.47	20.32	19.64	18.56	17.32	16.45	15.39
25	23.09	21.47	20.32	19.64	18.56	17.32	17.32	22.38	21.47	20.32	19.64	18.56	17.32	16.45	15.39
33	23.09	21.47	20.32	19.64	18.56	17.32	17.32	22.38	21.47	20.32	19.64	18.56	17.32	16.45	15.39
41	23.09	21.47	20.32	19.64	18.56	17.32	17.32	22.38	21.47	20.32	19.64	18.56	17.32	16.45	15.39
49	23.09	21.47	20.32	19.64	18.56	17.32	17.32	22.38	21.47	20.32	19.64	18.56	17.32	16.45	15.39
57	23.09	21.47	20.32	19.64	18.56	17.32	17.32	22.38	21.47	20.32	19.64	18.56	17.32	16.45	15.39
65	23.09	21.47	20.32	19.64	18.56	17.32	17.32	22.38	21.47	20.32	19.64	18.56	17.32	16.45	15.39
73	23.09	21.47	20.32	19.64	18.56	17.32	17.32	22.38	21.47	20.32	19.64	18.56	17.32	16.45	15.39
81	23.09	21.47	20.32	19.64	18.56	17.32	17.32	22.38	21.47	20.32	19.64	18.56	17.32	16.45	15.39
89	23.09	21.47	20.32	19.64	18.56	17.32	17.32	22.38	21.47	20.32	19.64	18.56	17.32	16.45	15.39
97	23.09	21.47	20.32	19.64	18.56	17.32	17.32	22.38	21.47	20.32	19.64	18.56	17.32	16.45	15.39
105	23.09	21.47	20.32	19.64	18.56	17.32	17.32	22.38	21.47	20.32	19.64	18.56	17.32	16.45	15.39
113	23.09	21.47	20.32	19.64	18.56	17.32	17.32	22.38	21.47	20.32	19.64	18.56	17.32	16.45	15.39
121	23.09	21.47	20.32	19.64	18.56	17.32	17.32	22.38	21.47	20.32	19.64	18.56	17.32	16.45	15.39
129	23.09	21.47	20.32	19.64	18.56	17.32	17.32	22.38	21.47	20.32	19.64	18.56	17.32	16.45	15.39
137	23.09	21.47	20.32	19.64	18.56	17.32	17.32	22.38	21.47	20.32	19.64	18.56	17.32	16.45	15.39
145	23.09	21.47	20.32	19.64	18.56	17.32	17.32	22.38	21.47	20.32	19.64	18.56	17.32	16.45	15.39
153	23.09	21.47	20.32	19.64	18.56	17.32	17.32	22.38	21.47	20.32	19.64	18.56	17.32	16.45	15.39
161	23.09	21.47	20.32	19.64	18.56	17.32	17.32	22.38	21.47	20.32	19.64	18.56	17.32	16.45	15.39
169	23.09	21.47	20.32	19.64	18.56	17.32	17.32	22.38	21.47	20.32	19.64	18.56	17.32	16.45	15.39
177	23.09	21.47	20.32	19.64	18.56	17.32	17.32	22.38	21.47	20.32	19.64	18.56	17.32	16.45	15.39
185	23.09	21.47	20.32	19.64	18.56	17.32	17.32	22.38	21.47	20.32	19.64	18.56	17.32	16.45	15.39
193	23.09	21.47	20.32	19.64	18.56	17.32	17.32	22.38	21.47	20.32	19.64	18.56	17.32	16.45	15.39
201	23.09	21.47	20.32	19.64	18.56	17.32	17.32	22.38	21.47	20.32	19.64	18.56	17.32	16.45	15.39
209	23.09	21.47	20.32	19.64	18.56	17.32	17.32	22.38	21.47	20.32	19.64	18.56	17.32	16.45	15.39
217	23.09	21.47	20.32	19.64	18.56	17.32	17.32	22.38	21.47	20.32	19.64	18.56	17.32	16.45	15.39
225	23.09	21.47	20.32	19.64	18.56	17.32	17.32	22.38	21.47	20.32	19.64	18.56	17.32	16.45	15.39
233	23.09	21.47	20.32	19.64	18.56	17.32	17.32	22.38	21.47	20.32	19.64	18.56	17.32	16.45	15.39

independent of the material and required fabric constructions. This advantage of the form-locking mechanism together with recent developments in needle constructions forms a better doffing alternative using point contact for the production of near net shape closed fabrics.

Mechanical hardware construction design. The doffing segment (Figure 9) consists of two parallel mounted rolls and is designed in such a way that the bottom roll can be actively driven with the top roll being passive and driven through friction. The bottom roll consists of 15 active mounted needle segments designed to take three warp yarns each. The width of a needle segment is 22 mm and there are two rows of needles mounted on it. The segment has a diameter of 150 mm. The needle has a conical form with a bottom diameter of 1.63 mm and is separated by a distance of 10.96 mm in the working direction. This ensures that a minimal penetration of the fabric is guaranteed. Each needle segment is attached to a servomotor, with the tooth belt having a gear ratio of 100:30, and can be independently controlled.

Conversely, the top roll is mounted with 15 passive segments. Each passive segment has a diameter of 84 mm. The segments have two rows of grooves along their outer surface arranged in such a way that the needle from the bottom segment passes into them during the rotation. This arrangement is particularly advantageous. Beside the force transfer on the weft yarns by the form-lock element, namely the needle, frictional force transfer also takes place on the warp

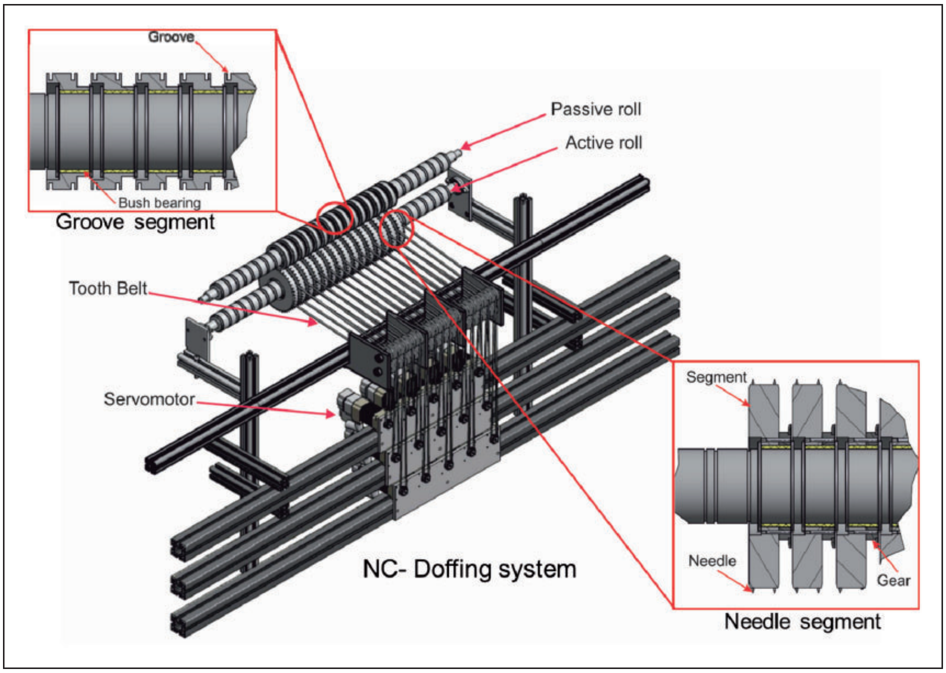

Figure 9. Mechanical design of the numerically controlled (NC) doffing system.

yarn due to the point contact ensured by the two segments.

Control system design. In order to numerically control the doffing system, a synchronous servo drive of type 1FK7022-5AK71-1DA0 with a maximum torque of 1.6 Nm from the company Siemens AG, Germany, was selected. The control system for doffing purposes is designed in such a way that the maximum possible force is exerted on the knitted fabrics and the warp yarns in particular, so that the yarns are held in tension at the knitting unit. This method can qualitatively ensure that all the delivered additional warp yarn lengths are efficiently taken-up without the need to have an additional digital control system. Also, from the design side, only a torque-controlled system is required in order to ensure that the desired doffing force to be exerted is achieved. In order to calculate the required torque for the system design (Figure 10) and its control, the same previous value of 10 N was considered to be the maximum required doffing force for a single warp yarn in each segment.

In the case of three warp yarns, the maximum force, $F_{Z\max}$ is calculated as 30 N. Based on the maximum force and the mechanical design of the segment and the transfer ratio, the required moment M_R for the servo drive control is calculated as given below. The radius of the needle segment, r_1, is 75 mm, while the radius of the attached gear wheel segment, r_2, is 39.9 mm. The gear ratio between the needle segment and servo drive is selected as 100:33. The required control torque for a maximum doffing force, $F_{Z\max}$ can be calculated by the following equation

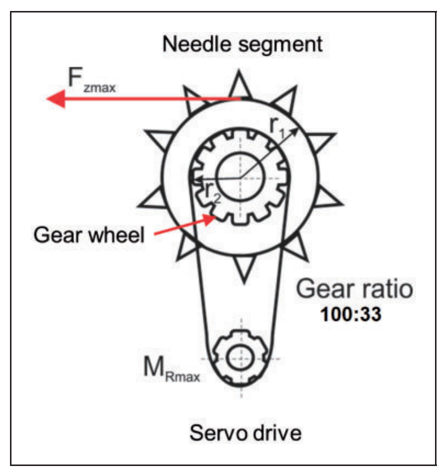

Figure 10. System design for a torque controlled segment.

$$M_{R\max} = \left(\frac{F_{Z\max}}{r_2} * r_1\right) * r_2 * 0.33$$

The required control torque for the designed system was thus calculated to be 0.7425 Nm. The physical

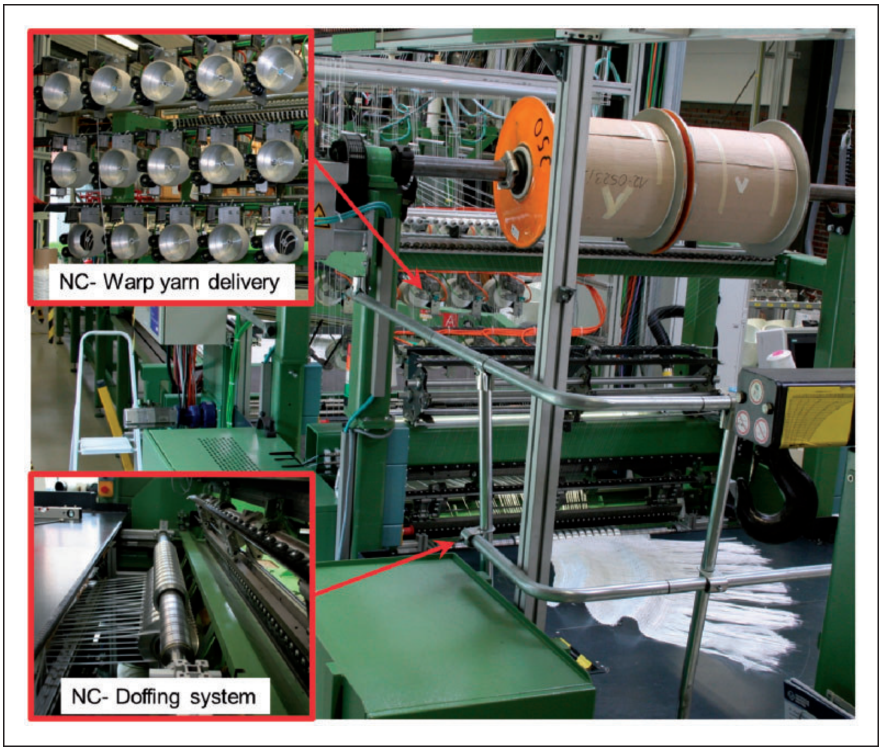

Figure 11. MALIMO 14024 with integrated numerically controlled (NC) warp yarn delivery and doffing system.

Table 2. Machine specifications of the MALIMO 14024 multiaxial warp knitting machine

MALIMO 14024 Multiaxial warp knitting machine		
Specifications		Range
1	Working width	Up to 1270 mm
2	Machine gauge	7F/10F/12F/14F
3	Stitch length	0.5–5 mm
4	Working speed	Up to 1400 min^{-1}

design of the new doffing system has already been summarized in Figure 9.

Realization of the modified working cycle

The newly developed NC doffing system along with the NC warp yarn delivery unit was integrated in the multiaxial warp knitting machine MALIMO 14024 from KARL MAYER Technische Textilien GmbH, Germany, as shown in Figure 11. The technical specification of the machine is illustrated in Table 2. Modifications were also made to the NC warp yarn delivery unit so that a set of three warp yarns could be fed in. Changes were also made to the yarn feed-in in such a way that warp yarn groups can be delivered with minimal deflection into the knitting (stitch-bonding) unit for producing closed-surface fabrics (shell preforms).

The modified working cycle was then realized in which additional warp yarn lengths were delivered by varying the speed of the NC warp yarn delivery unit. The speed of the warp yarn delivery unit was synchronized to the machine by means of an encoder. The doffing unit was set with the required doffing force and the torque control ensures that the set force is maintained throughout the working cycle.

Experimental study. In order to study the modified working cycle, each doffing segment unit was set with a doffing force of 30, 25 and 22 N in each cycle and a constant pattern of additional warp yarns lengths was delivered with a factor ranging between 1.0 and 1.3 to the normal length. This factor range was chosen on the basis of experimental evaluation, as the best doffing results were achieved when varying the delivery length within this range across the working width of the fabric in a single machine working cycle. Also, a constant set stitch length of 2 mm was selected here. The warp yarn tension was then measured before the knitting (stitch-bonding) unit, as shown in Figure 12.

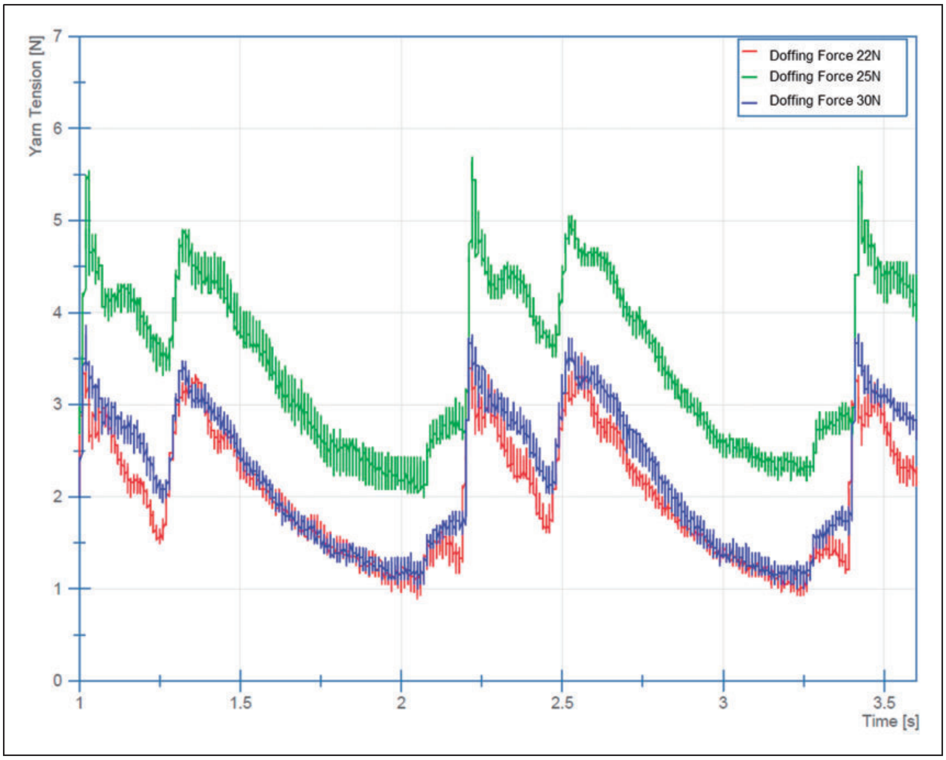

Figure 12. Measured warp yarn tension for various set doffing forces.

Result discussion. Contrary to the calculated maximum required doffing force of 30 N, a set doffing force of 25 N results in a maximum warp yarn tension of around 5 N. A set maximum doffing force of 30 N leads to fiber damages, as visually observed, that can be related to the excessive force applied by the form-lock element leading to fiber damages. This in turn results in fabric slippage, leading to insufficient doffing force transfer. On the other hand, the set doffing force of 22 N is also not sufficient to keep the warp yarn in tension. Furthermore, it can be observed that the achievable warp yarn tension is lower than the desired yarn tension of 10 N per yarn. This is due to the fact that a significant amount of force is lost for the fabric take-up that is formed between the doffing system and the knitting unit.

Although the doffing system has been placed as close as possible to the knitting unit, an immediate placement directly next to the knitting unit is not possible due to the existing machine design. Also, the cutting of weft yarns, that is, fabric let-off from the transport chain directly at the knitting unit, is also not possible. The cutting of the weft yarns on both sides during the knitting cycle leads to a better doffing force transfer on to the warp yarns. However, it also results in fabric deformation arising due to the deviation of yarn courses and thereby hindering the fabric take-up. Hence, the weft yarns were cut off from the transport chain during the knitting cycle only on one side. The cutting of weft yarns on the other side was carried out at the doffing unit, so as to ensure that the yarn courses do not exhibit large deviations. Figure 13 shows the cutting unit implemented directly at the knitting unit.

Implementation and validation of the process chain

Sample production. The feasibility of the process chain was demonstrated on the basis of a sample production of a near net shape preform representing a complex shaped doubly curved surface with an outer planar dimension of 500 mm × 470 mm a (e.g. a Stringer component, as used in aircraft structures). The generated machine data for the calculated warp yarn lengths (as in Table 1) using the computational model was then directly transferred to the controller of the warp yarn delivery and doffing unit using a Transmission Control Protocol/Internet Protocol (TCP/IP) interface.

The inner most warp yarn set of 43–46 had the minimum calculated total length of 467.79 mm. The outer most warp yarn set of 1–3 had the maximum calculated total length of 738.88 mm. The outermost yarn varies

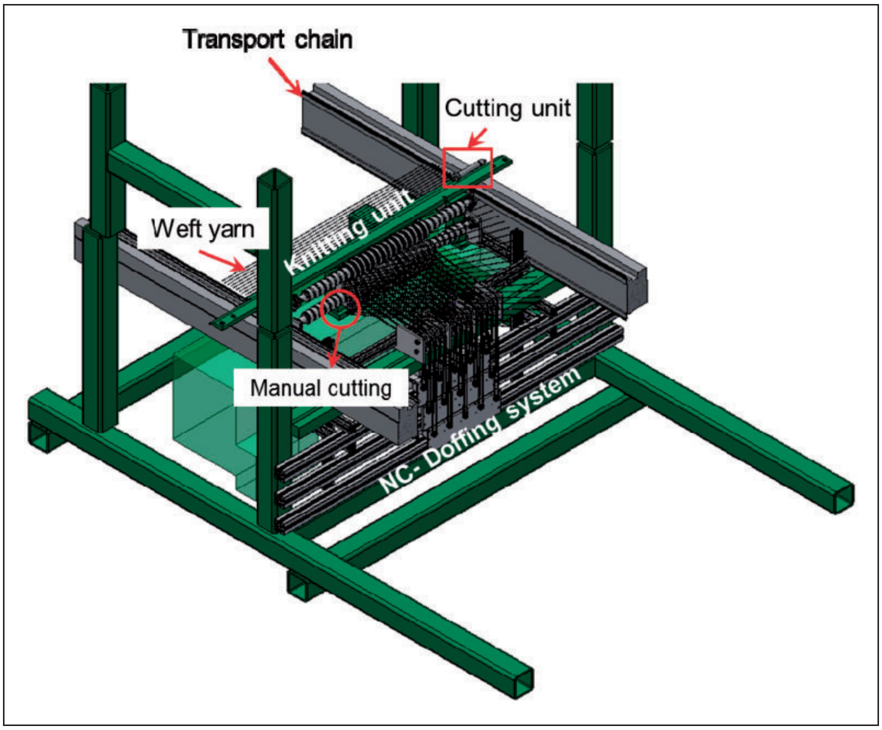

Figure 13. Schematics of the integrated doffing system and the cutting methodology.

Table 3. Production parameter for the sample structures

Warp yarn	EC glass fiber rovings 1200 tex	Carbon fiber rovings 800 tex
Weft yarn	AR glass fiber rovings 640 tex	Carbon fiber rovings 1600 tex
Sewing thread	PES Sabac 24 tex	PES Sabac 24 tex
Machine speed	50 min^{-1}	50 min^{-1}
Stitch length	2 mm	2 mm
Weft feed	3 Full	3 Full
Bonding	Tricot closed	Tricot closed

with a factor of 1.57 to the innermost yarn. These computed warp yarn lengths for the yarn delivery are then converted to the length factors and are used as control data for the NC warp yarn delivery units. In the case of the doffing unit, a factor of 1.0 was used to set a uniform doffing force of 25 N. The doffing forces beyond the set force for each doffing unit can be varied by entering the absolute value.

Both glass and carbon fiber were selected for the production of sample structures. Table 3 presents the production parameters of the sample and the Figure 14 shows the produced sample structures.

System validation. A target/actual comparison for the validation of the process chain to determine the accuracy of the yarn delivery and doffing system is not possible online for the produced closed-surface (shell) sample structure, unlike the open-grid preforms. Automated computation of the warp yarn lengths in their final geometrical shape is highly dependent on the complexity of the curvature and accuracy of the measurement system. The development of such an automated validation system is currently in progress. Hence, a manual validation of the system accuracy was performed by first stretching the warp and weft yarns of the near net shape sample flat onto a surface plane and then measuring the absolute length of the outermost and innermost warp yarn. The measured total length of the innermost warp yarn was 465.6 mm, while the outermost warp yarn was found to be 707.79 mm long. The measured length ratio factor is 1.52 and this varies with the calculated factor by 0.05.

In order to demonstrate the flexibility of the production chain, further preform samples such as hemispherical cross-section and free-form surface geometry of a car impact protection part were also produced (Figure 15). Although the above samples were produced with an increased weft density, some applications might demand an increased warp yarn density as well. In such cases, the number of warp yarns can be increased by suitable constructional design modifications to the NC warp yarn delivery and doffing unit in order to carry more yarns. With this new technological development, it is now possible to produce resource efficient two- or three-layered textile-reinforced structures with

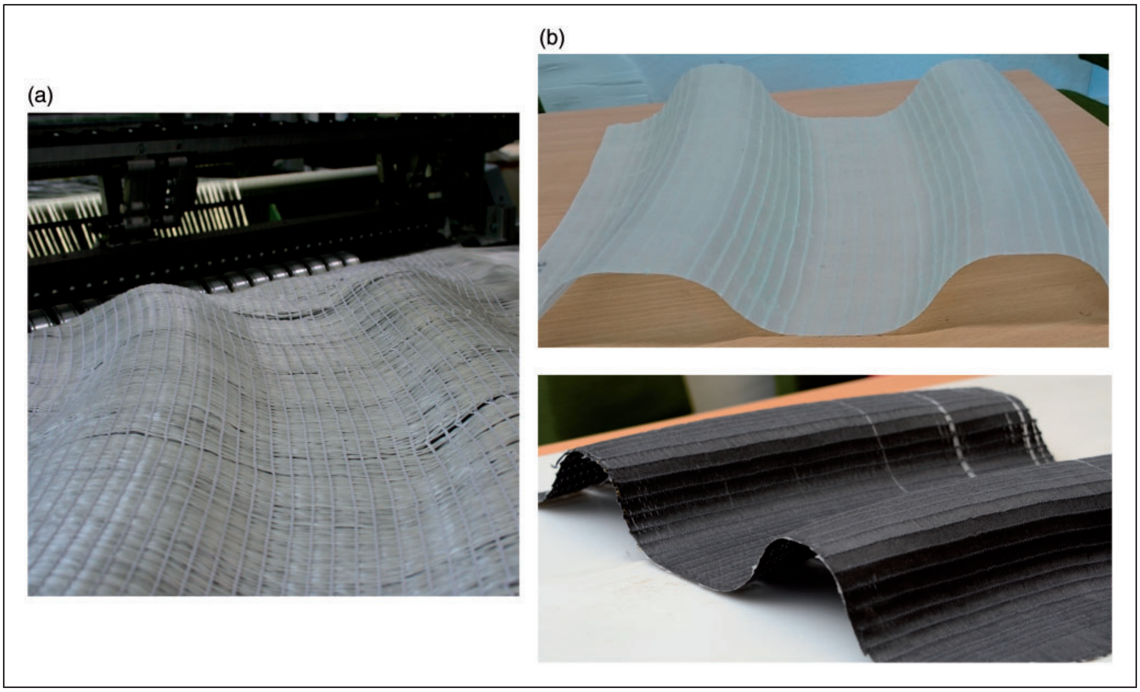

Figure 14. Produced sample structure: (a) dry preform; (b) finished structure.

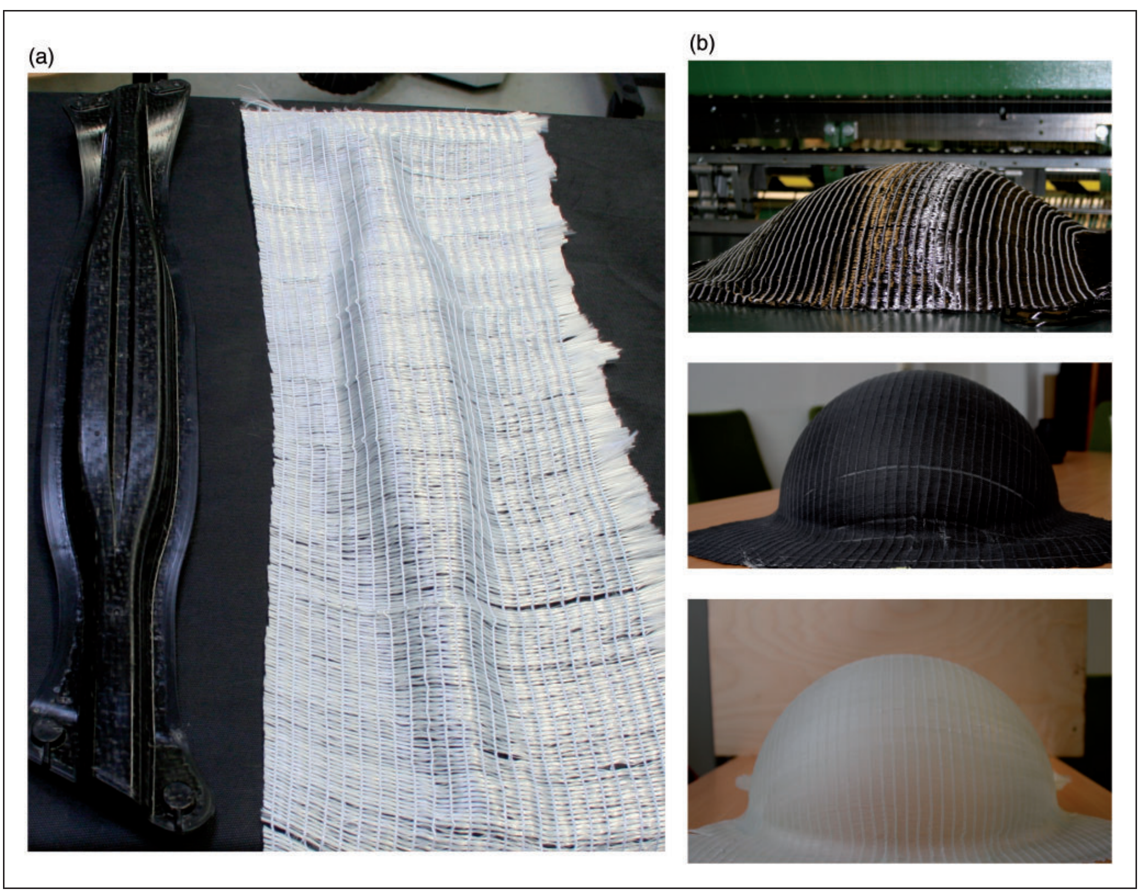

Figure 15. Produced preform samples: car impact protection part (a) and hemispherical cross-section preform and structure (b).

form- and load-conforming yarn courses in accordance with the application demands.

Conclusion and outlook

The focal point of this research work was to achieve a universal process chain for manufacturing 3D near net shape warp knitted preforms (open grid and closed surface) with complex geometries. The development of a geometrical model has enabled the calculation of the yarn course for free-form surfaces, thereby closing the loop from design to production. The creation of this technological process chain has resulted in a better understanding of the processing behavior for the materials used, the calculation methods and the technological requirements. The integration of NC warp yarn delivery and doffing units together with the realization of a modified working cycle has ensured that a fundamental large-scale technological possibility based on multiaxial warp knitting exists for the production of textile preforms in near component contours. The major advantage of this development in comparison to other textile technologies using similar systems, for example, weaving, is that both open- and close-surface near net shape preforms can be produced on the same machine. The technological possibility for producing preforms in the final component shape with negligible fiber undulation offers a highly significant potential for a complete utilization of the fiber substance and thereby fulfilling an essential lightweight requirement of semi-finished products for high-performance composites. Also with the development of a NC system will also be possible in the future to create a direct interface to the structural simulation where the stresses occurring in the textile preforms in accordance with the final structural requirements can be studied and the required form- and load-conforming yarns courses determined, thereby reducing the trial-and-error costs. The validation of the technology and textile process chain was demonstrated by the production of sample patterns. With this development, the multiaxial warp knitting based technology together with NC warp yarn delivery and doffing unit offers a viable solution for energy-efficient production of textile preforms with minimal material requirements suited for complex demands and large-scale manufacturing. This novel unified technology for producing both open-grid and closed-surface (shell) near net shape textile preforms opens up multiple application possibilities for reinforcing components in complex spatial composites with a mineral- or a plastic-based matrix, wooden composites or elastomers. Furthermore, these developed methods are modular and can also be transferred to other textile technologies, such as leno weaving or multilayer knitting.

Acknowledgement

We would like to thank Mr Martin Waldmann, Mr Ralf Muehle and Mr Florian Josten for their active support in this research work.

Declaration of conflicting interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The authors disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This work was supported by the German Research Foundation at the Technische Universität Dresden (grant number DFG CH 174/20-2).

References

1. Cherif Ch, Sankaran V and Ruder T. Multi-material design and textile constructions for lightweight structures. In: *14th world textile conference AUTEX 2014*, Bursa, Turkey, 26–28 May 2014, p.22.
2. Alagirusamy R, Fangueiro R, Ogale V, et al. Hybrid yarns and textile preforming for thermoplastic composites. *Text Progr* 2006; 38: 1–71.
3. Hu J. *3-D fibrous assemblies: Properties, applications and modeling of three-dimensional textile structures*. Manchester: Textile Institute, 2008.
4. Eisenhauer C, Borchert B and Hoeck W. Advancements in the development and testing of highly-drapeable tailored textiles. In: *proceedings of the 8th Aachen-Dresden international textile conference*, Dresden, 27–28 November 2014.
5. AVK-Industrievereinigung. *Handbuch faserverbundkunststoffe/composites. Grundlagen, verarbeitung, anwendung*. Wiesbaden: Springer Fachmedien, 2013.
6. Bilisik K. Three-dimensional braiding for composites: a review. *Text Res J* 2013; 83: 1414–1436.
7. Buesgen A. Woven 3-dimensional shapes – updates and future prospects for new weaving techniques. *Melliand Eng* 1999; 6: 130–132.
8. Golra O, Tariq J, Ehsan N, et al. Strategy for introducing 3D fiber reinforced composites weaving technology. *Proc Technol* 2012; 1: 211–216.
9. Spickenheuer A, Schulz M, Gliesche K, et al. Using tailored fibre placement technology for stress adapted design of composite structures. *Plast Rubber Compos* 2008; 37: 227–232.
10. Bruer SM, Powell N and Smith G. Three dimensionally knit spacer fabrics: a review of production techniques and applications. *J Text Apparel Technol Manag* 2005; 4: 1–30.
11. Sankaran V, Younes A, Engler T, et al. A novel processing solution for the production of spatial three-dimensional stitch-bonded fabrics. *Text Res J* 2012; 82: 1531–1544.
12. Sankaran V, Rittner S and Cherif Ch. Development of novel technological process chain for the production of

3D stitch bonded fabrics. In: *14th world textile conference AUTEX*, Bursa, Turkey, 26–28 May 2014, p.91.
13. Naveen V, Padaki R, Alagirusamy, et al. Knitted preforms for composite applications. *J Ind Text* 2006; 35: 295–321.
14. Rao RMGKV, Alagirusamy R and Nagar A. Mechanical properties of glass composites based on knitted performs with inlays. *Ind J Text Fibre Res* 2000; 25: 121–129.
15. Sankaran V and Cherif Ch. New machine concept for producing 3-D stitch-bonded fabrics. *Fibres Text East Eur* 2013; 21: 92–96.
16. Cherif Ch, Krzywinski S, Diestel O, et al. Development of a process chain for the realization of multilayer weft knitted fabrics showing complex 2D/3D geometries for composite applications. *Text Res J* 2012; 82: 1195–1210.
17. Buesgen A, Finsterbusch K and Birghan A. Simulation of composite properties reinforced by 3D shaped woven fabrics. In: *12th European conference on composite materials (ECCM)*, Biaritz, France, 29 August–1 September 2006, http://www.shape3.de/publications/ECCM%202007%20Simulation%203D%20Fabric%20Reinforcements.pdf (2006, accessed 25 November 2015).
18. Sankaran V, Ruder T, Rittner S, et al. A multiaxial warp knitting based yarn path manipulation technology for the production of bionic-inspired multifunctional textile reinforcements in lightweight composites. *J Ind Text*, Epub ahead of print 20 October 2014. doi:10.1177/1528083714555778.
19. Schulz Chr. *Entwicklung einer technologie für die herstellung textiler halbzeuge für thermoplastische verbundwerkstoffe auf basis der mehrlagenflachstricktechnik*. PhD Thesis, Technische Universität Dresden, Germany, 2002.
20. Hausding J and Maertin J. Warp-knitted semi-finished products and warp-knitting technologies. In: Cherif Ch (ed.) *Textile materials for lightweight constructions*. Berlin Heidelberg: Springer, 2016.