**Dieses Dokument ist eine Zweitveröffentlichung (Verlagsversion) /
This is a self-archiving document (published version):**

Monireh Fazeli, Martin Kern, Gerald Hoffmann, Chokri Cherif

Development of three-dimensional profiled woven fabrics on narrow fabric looms

Erstveröffentlichung in / First published in:

Textile Research Journal. 2016, 86(12), S. 1328 – 1340 [Zugriff am: 07.08.2019]. SAGE journals. ISSN 1746-7748.

DOI: <https://doi.org/10.1177/0040517515606361>

Diese Version ist verfügbar / This version is available on:

<https://nbn-resolving.org/urn:nbn:de:bsz:14-qucosa2-354190>

„Dieser Beitrag ist mit Zustimmung des Rechteinhabers aufgrund einer (DFGgeförderten) Allianz- bzw. Nationallizenz frei zugänglich.“

This publication is openly accessible with the permission of the copyright owner. The permission is granted within a nationwide license, supported by the German Research Foundation (abbr. in German DFG).

www.nationallizenzen.de/

Development of three-dimensional profiled woven fabrics on narrow fabric looms

Monireh Fazeli, Martin Kern, Gerald Hoffmann and Chokri Cherif

Textile Research Journal
2016, Vol. 86(12) 1328–1340
© The Author(s) 2015
Reprints and permissions:
sagepub.co.uk/journalsPermissions.nav
DOI: 10.1177/0040517515606361
trj.sagepub.com

Abstract

Three-dimensional (3D) profiled woven fabrics with varying cross-sections along the component parts are needed in a number of industrial applications. One of the main advantages of the ribbon loom weaving technique is the ability to produce highly diverse structures with open or closed edges. The realization of 3D profiled woven fabrics that satisfy the requirements is directly connected to the ability to process high-performance fibers in the weft direction. The processing of high-performance yarns in the weft direction with low fiber damage will open new application areas for shuttle weaving machines. By employing modified mechanical loom elements, the variety of producible structures can be increased significantly.

Keywords

three-dimensional profiled woven fabrics, shuttle weaving technique, Jacquard technique, shuttle ribbon loom

Lightweight structures constitute an eminently important solution to the conservation of limited resources of energy in aeronautics and vehicle engineering. Nowadays fiber-reinforced plastic composites (FRPCs) are regarded as the new era of lightweight structures and they have wide application in various industries.^{1–3} In order to enhance the existing lightweight construction principles in automotive and aircraft engineering, the requirements for the production of complex-structure profiles need to be fulfilled.^{4–7} Profiles, especially those made from high-performance fiber materials with complex geometries, such as lightweight and safety-relevant structural components, are of great interest to the mentioned industries.⁸ Typical applications include stringers and floor frames in airplanes, car body frame parts such as A-, B-, or C-pillars, and frame parts for machine engineering constructions.⁹

The semi-finished products needed for the realization of such structures are most productively manufactured by direct performing.¹⁰ Direct preforming requires the creation of profile geometries during the fabric formation process.

To achieve complex-geometric profiles made from high-performance fibers, several methods are used:

winding, braiding, warp knitting, multilayered flat knitting, and weaving. Due to the disadvantages listed below, the application of these methods in the market has so far been limited.

- Winding: the lack of fiber reinforcement in the direction of wall thickness, due to process limitations, restricts the application range to the resulting risk of delamination, especially under high bending loads of the components. Components with concave curves cannot be realized.^{11,12}
- Braiding: high investment and preparations (e.g. core manufacture, set-up times) costs have been inhibiting the flexible production of a variety of products.^{13,14}

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

Corresponding author:

Monireh Fazeli, Institute of Textile Machinery and High Performance Material Technology, Technische Universität Dresden, 01062 Dresden, Germany.

Email: Monireh.Fazeli_Zoghalchali@tu-dresden.de

- Warp knitting: the production of three-dimensional (3D) net-shape preforms only allows limited application of this fabric formation process.^{15–17}
- Multilayered flat knitting method: this method offers a possibility for the near-net-shaped production of preforms. However, no establishment of the basic knitting technique at the market is currently known.^{18,19}

In comparison to the above-mentioned methods, the high flexibility of weaving creates an outstanding advantage for the manufacture of complex structures. Patterns and product parameters can be varied without obstructions. On conventional machines, a diversity of structures can be realized without special devices or alterations.^{3,7,8,10}

Figure 1. Profile geometry shuttle ribbon woven fabric.

Figure 2. ITM's narrow shuttle loom set up.

Shuttle ribbon weaving is the fabric formation method with particularly high potential for a cost-effective, automated, and reproducible manufacture of semi-finished products made from high-performance fibers

Figure 3. Side-view of the machine during weave formation process.

Number of layers	Name of the elements	Structure elements (SE)
1-Layer	1L (Open)	
2-Layers	2La (Open)	
	2Lb (Closed)	
3-Layers	3La (open)	
	3Lb (Closed)	
4-Layers	4La (Open)	
	4Lb (Closed)	

Figure 4. Structure elements.

Figure 5. Woven structure with three structure sections.

Figure 6. Schematics of the system for possible three-dimensional profiled woven structures. (Color online only.).

Figure 7. Structure combination chart.

and with varying cross-sections along the length of the component, as illustrated in Figure 1.

Due to the continuous insertion and circulation of the weft thread, the created fabrics can be closed and highly complex. Woven fabrics are characterized by type of weave pattern, that is, the arrangement of warp and weft yarns to one another. Generally, woven fabrics can be categorized as single-layer and multi-surface structures. A complex weave pattern is a flat fabric weave pattern with multi-surfaces as exemplified by tubular structures.

The weave pattern design represents the basis for the realization of both simple and complex structures on a

narrow shuttle loom. In order to produce the above-mentioned profile structures, complex multilayered woven fabrics have to be developed. In addition to the developed weaving and structure techniques that minimize processing effort, all aspects of weave and pattern design for single or multilayer fabrics have to be taken into consideration. To realize the complex weave patterns on a narrow shuttle loom, shedding necessarily has to be performed using the Jacquard technique. Only this type of shedding ensures pattern diversity and flexibility.

In this research we describe the fundamental design approach concerning complex weave patterns for complex structures. One of the main focuses is to show how the weft sequences play a significant role in developing complex 3D woven structures. A guide line is developed for the structure development, and a basis is established for even more complex woven fabric structures to be used in high-tech applications. Figure 2 and Figure 3 shows the ITM's modern narrow shuttle weaving loom (MAGEBA) set up.

Development of a system for producing possible three-dimensional profiled structures on a narrow shuttle loom

Within the research, the different capabilities of the shuttle loom technology to create 3D profiled woven fabrics are developed systematically. Using the Jacquard technique with its extraordinary technological possibilities regarding the variety of weave patterns, simple or very complex patterns can be realized, making this method fundamentally suitable for the

+						
	No new Structure		No new Structure		No new Structure	

Figure 8. Structures with three sections.

+				
	No new Structure			

Figure 9. Structures with four sections.

development of 3D profiled woven fabrics. A complex weave pattern is a flat fabric weave pattern with a multi-surface (e.g. tubular) structure. Narrow shuttle weaving has a particularly high potential for the realization of innovative and complex 3D profiled woven fabrics. The aim of developing a system is to give an overview of the different possible 3D woven

structures on the narrow shuttle loom and also to use the results in order to address more complex 3D woven structures.

The system is based on the combination of different structure elements (SEs). All possible open and closed (tube) woven SEs on the narrow shuttle loom that consist of one, two, three, and four layers are shown in

Figure 10. Three-dimensional profiled woven structures.¹⁹

Figure 11. Three-dimensional model of a circle-to-double-T profile.

Figure 4. The reason for choosing the maximum of four layers is that this number of layers allows a display of the entire system. The principle can also be used for structures with more than four layers.

The whole system is a combination of these SEs in two, three, and four structure sections (SSs). Each section is based on one SE from Figure 4. Figure 5 shows an example of woven structure with three SSs.

The following steps are followed for the systematic development of the structure.

Step 1: SEs from one layer to four layers are defined.

Step 2: All possible combinations with two SSs based on SEs are developed.

Step 3: All possible combinations with three SSs based on SEs are developed (the final structures from Step

Figure 12. Arrangement of the woven sections and their cross-section.

Figure 13. Theoretical layer structure of the double-T profile.

2 will be added to SEs to create structures with three SSs).

Step 4: All possible combinations with four SSs based on SEs are developed (the final structures from Step 3 will be added to SEs to create structures with four SSs). These steps are shown in Figure 6.

To add up the SEs and systematically create further structures, the chart shown in Figure 7 will be used. In this chart the structures in the horizontal row with orange color will be added to the structures in the violet column, thus creating new structures.

To understand the principle of the chart, the following points have to be considered.

- The violet column (the SE column) will be identical in all charts.
- The orange row will be replaced with the new structures from the result columns (white columns) of the previous chart. This means that if the previous chart has seven result columns, the orange row will

be replaced seven times. Thus, all possible combinations will be included in the results.

- At first all structures with one section will be placed in the orange row. Then they will be replaced with the structures with two sections and finally with the structures with three sections. Based on this procedure, all possible SE combinations from one to four sections will be created systematically.

In Figures 8 and 9 some of these charts and the related woven structure (Figure 10) are shown.

All resulting structures from the developed system are 3D profiled woven fabrics with constant cross-sections (with open and closed elements) along the length of the component. The next part will explain the development of 3D profiled woven fabrics with a cross-section changing along the length of the component.

Developing circle-to-double-T structures

The circle-to-double-T structure represents a link between two different cross-sections (circle and

Figure 14. Interlacing schematic of the warp yarns in top and bottom fabrics.

Figure 15. Interlacing schematic for the bridge (section 2).

double-T cross-sections). It is characterized by a continuous transfer between the two cross-sections. It is produced either with a continuous tube in the center of the profile or with a cavity beginning in the circular

profile and ending in the profile. The theoretical appearance of this structure is illustrated in Figure 11.

The warp density of the circle-to-double-T profile is 446 yarns per 15 cm fabric width (29.73 yarns/cm) and

Figure 16. Schematic course of the first four weft insertions.

Figure 17. Schematic course of the mirrored weft insertions.

the weft density is 32 yarns/cm. The structure has a component length of 250–300 mm. The number of wefts inserted into the structure depends on the production design, on the weaving pattern, and, thus, also on the take-off. The shape of these structures will be influenced significantly by the weft sequence, that is, the order of weft insertion between warp layers.

For a profile supposed to change from a tubular cross-section into a double-T beam (Figure 11), a segmentation of the whole structure into several sections is advantageous.

The first three sections (in the C-C cross-section) make up the double-T profile with a closed central bridge and two collapsible margin areas (see Figure 12.). The margin areas (sections 1 and 3) are separated into a top and a bottom woven fabric. The two margin areas must not be connected. Neither must the structure be cut after the weaving process. The central bridge is connected through all warp layers, which makes it as thick as the top and bottom fabric of a margin area combined.

Because of the high warp density (29.73 yarns/cm) weaving sections 1 and 3 as two fabric layers and section 2 as one fabric layer increases the friction between warp yarns during the shedding process, which leads to high yarn damages, unclear shed formation, and

inhomogeneity in the structure. To reduce the yarn damages during the shedding process and still retain the same warp density, the structure is woven based on four fabric layers with a plain weave pattern that are connected through partial interlacing between layers.

This means that the fold-out fabric layers required in margin areas (sections 1 and 3) will be referred to as the top and bottom fabrics. The top fabric is realized by a partial interlacing of the first and second fabric layers. The bottom fabric is created by means of a partial interlacing between the third and fourth fabric layers. Figure 14 shows a schematic illustration of the interlacing principle.

The interlacing of the 16 warp yarns is not performed simultaneously, but divided into four sequences. Each sequence contains four warp yarns. In the first sequence (Interlacing 1 in Figure 18), a warp rising of the first yarn in the second warp layer occurs (warp yarn # 2), as well as a sinking of the first warp yarn in the first layer (warp yarn # 1). Thus, the first two warp yarns of the repeat interlace the top fabric. In the bottom fabric, warp yarns 3 and 4 are repeating the same process. All other yarns of the 16-warp weaving structure chart create a non-interlaced four-layered plain weave pattern during the first

Figure 18. Weaving pattern diagram of the left-hand margin area (section 1).

sequence. According to the interlacing sequences pattern in Figure 18, interlacing 1 happens during the first four weft insertions and the remaining four weft insertions continue to create a simple four-layer plain weave.

Figure 19. Weaving pattern diagram of the right-hand margin area (section 3).

As shown in Figure 13, section 2 is to be considered as one fabric layer. The entire structure, however, is made up of a four-layered woven fabric (four layers of plain weave), which are combined into a single layer by partially interlacing. The interlacing between

Figure 20. Weaving pattern diagram of the closed bridge (section 2).

the fabric layers is done according to a certain weaving pattern (Figure 20).

Each of the margin areas (sections 1 and 3) of the double-T beam consists of two unconnected woven fabrics, which can be erected independently after

Figure 21. Altered weft sequence for the circle profile (tube), starting from the weft insertion into the second layer.

production. As the weft insertion on the ribbon loom is performed by means of bobbins, there is always a closed selvage, which requires further considerations regarding the weft sequence process for the production of the structure. The result is a weft sequence leading to the desired double-T profile structure. This structure is shown in Figure 16.

It has to be considered that the weft sequence in the outer margins does not run from the top into the bottom layers, as this would create a closed selvage preventing the margin areas from folding out.

As illustrated in Figure 16, the three areas are not connected uniformly. There are three crossing points at the left transfer, while there are four of them at the right transfer point. To create a symmetrical and stable structure, the weft sequence 1–4 shown above is mirrored as wefts 5–8 (see Figure 17).

The courses of the weft insertions are illustrated for the first eight wefts. The course of the weft insertions for the interlacing patterns also follows the same principle.

Figures 18, 19 and 20 the weave pattern of sections 1–3.

In order to create a profile transition into a tubular shape in the structure, an open part has to be created in addition to the closed central bridge (section 2). This centrally open part differs from the preceding closed part only in terms of interlacing.

For the open section, the margin areas (sections 1 and 3) can be used as a basis. The interlacing is performed according to the same principle, as illustrated in Figure 14.

The weave pattern diagrams that have already been established for the two outer sections can be used in a variation. Only the weft sequence of the existing margin weave pattern diagrams has to be adapted to the center.

The distinct feature of the structure is the fluent transition from the double-T to the tube, as illustrated by the developed computer-aided design (CAD) model (see Figure 11). By means of a Stäubli Jacquard software program, the responsible heddles for each section are defined and the developed weaving pattern diagrams for each section are entered directly into the software. To simplify control programming of the Stäubli GmbH-produced Jacquard machine, the four sections are regarded as straight sections for the time being and entered. The fluent transition of sections 1 and 3 into sections 2 and 4 (Figure 12.), respectively, is realized by

Figure 22. Selvages at the beginning of the structure (a) and shortly before the transition to the circle profile (b).

Figure 23. Narrow woven circle-to-double-T profile.

a step-by-step adoption of the weaving patterns of the central section from the inside out.

First test weavings of the structure showed that the selvages of the tube were relatively weak and loose, as they are only connected twice per side in a weft cycle of eight wefts. This results in instability of the structure at the transitions from top to bottom fabric. For this reason, section 5 is inserted. The weft sequence used in the center to the end of the margin bridges is changed from the point onward where only the tubular fabric is to be produced. The interlacing points remain unchanged.

Preferred solution for the circle-to-double-T profile

The developed preferred solution for the circle-to-double-T profile is distinguished by the fact that the increase of the number of margin hooks is continuously performed after every second weft insertion. Thus, 143 warp yarns (from hook number 2 to 144 and from hook number 305 to 447) (excluding margin wires) per margin, and 160 warp yarns (from hook number 145 to 304) for the central bridge are available. This results in bridge

width of about 5 cm. Figure 22 shows the woven margins at the beginning (Figure 22(a)) and shortly before the transition into a tubular shape (Figure 22(b)).

A weft repeat of 286 wefts results from the number of warp yarns per margin and from the prerequisite that hooks are integrated only after every second weft. This repeat is necessary to realize the complete transition. As the weft repeat in this variant is longer than in the first, while the weft number remains constant at 352 wefts, the first weft for the transition is lowered to 33/352.

This means that at weft 33 hooks 144 and 305 are integrated into the center, while hooks 143 and 306 are integrated at weft 35, etc.

The woven profile exhibits a uniform ratio of central and margin sections. When erecting the margin areas, neither creases nor gaps or similar problems occur. The result of the circle-to-double-T profile in polyester is shown in Figures 23 and 24.

Based on the results using PET, the woven functional model is realized with carbon filament yarn of 800 tex fineness. The model woven in this manner has the same weaving pattern as the polyester fabric. In order to keep the fabric width constant, aramid fibers are used as selvage thread. With the aramid fibers as an expander system, the fabric width can be kept relatively constant despite the complex weave pattern (see Figure 25).

The carbon circle-to-double-T profile does not exhibit gaps or wrinkles after erection (Figure 26). This profile can be used in airplanes and car bodies as a connection part between two profiles with different cross-sections.

Conclusion and outlook

The developed weaving principle shows the high potential and flexibility of the weaving process considering the weft sequences for manufacturing a diversity of the complex 3D woven structures.

Figure 24. Circle side (a) and double-T side of the profile (b).

Figure 25. Circle-to-double-T profile woven fabric, non-erected.

Figure 26. Erected circle-to-double-T profile.

The starting point of this publication was the aim of producing complex, 3D narrow woven fabrics in a circle-to-double-T profile on a shuttle loom weaving machine, using systematic weave pattern development and shuttle loom technology. To produce the circle-to-double-T structure at the best possible quality and lowest yarn damages, different patterns with different sequences of wefts were investigated. Finally, the best weft sequence was chosen and the circle-to-double-T profile was woven successfully.

Furthermore, the different capabilities of the shuttle loom technology for the creation of 3D profiled woven fabrics were systematically developed. By means of a systematic weaving pattern, the various possibilities from simple to complex 3D fabric structures were presented. To develop this system of 3D woven fabric, SEs were developed and combined.

To produce the 3D woven fabrics from a variety of weave pattern diagrams, the working width can be subdivided into several sections also depending on the number of hooks of the Jacquard. An individual weave pattern can be set for each section. The practical feasibility of the developed 3D profiled narrow fabrics makes the manufacturing of different complex preforms possible.

The developed weaving principle (considering the weft sequences) in this paper shows the high potential and flexibility of the weaving process to manufacture complex preform structures.

Another development potential of the shuttle loom technology is further research into the possibilities of nodal elements curved in several directions. To produce such nodes on a shuttle loom, suitable settings and required machine modifications have to be explored, and new machine elements have to be developed.

The results presented in this paper can be transformed to the broad shuttle loom even though some investigation is necessary to ensure a clean shedding process, such as modification of the warp yarn drawing map and setting the heddles at different heights.

The combination of the suggested variants for a broader range of structural diversity in narrow woven textiles offers enormous research potential. The resulting possibilities have to be specified further in future 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 article presents selected results of the IGF research projects 16957 BR of the Forschungsvereinigung Forschungskuratorium Textil e. V., Reinhardtstr. 12–14, 10117 Berlin and is funded through the AIF within the program for supporting the “Industrielle Gemeinschaftsforschung (IGF)” from funds of the Federal Ministry of Economics and Technology (BMWi) by a resolution of the German Bundestag.

References

- Gessler A and Schouten M. Textiltechnik für Luftfahrt - Lessons learnt-. In: *cluster-treff neue werkstoffe*. Naila, Germany 2 October, 2007.
- Berthold U. Vom Faserverbund zum Metall zum Faserverbund -Werkstoffsubstitution im Flugwesen-. In: *abschlussveranstaltung WIS-WSP-WT*. Dresden, Germany 3 December, 2009.
- Torun A. *Advanced manufacturing technology for 3D profiled woven preforms*. PhD Thesis, Technische Universität Dresden, Germany, 2011.
- Hu J. *3-D fibrous assemblies, properties, applications and modelling of three-dimensional textile structures*, 1st ed. Hong Kong: Woodhead Publishing, 2008, pp.34–60.
- Mountasir A, Hoffmann G, Cherif Ch, et al. Mechanical properties of thermoplastic composite based on high stiffened 3D multi-layered woven fabrics. In: *14th world textile conference (AUTEX 2014)*, Bursa, Turkey, 26–28 May 2014.
- Mountasir A, Hoffmann G and Cherif Ch. Development of multilayered woven panels with integrated stiffeners in transverse and longitudinal directions for thermoplastic lightweight applications. *Text Res J*. Epub ahead of print September 2013. DOI: 10.1177/0040517512474367.
- Islam A. 3D Woven structures and an overview of manufacturing technologies. In: *4th world conference on 3D fabrics and their applications*, Aachen, Germany, 10–11 September 2012.
- Chen X, Taylor L and Tsai L. An overview on fabrication of three-dimensional woven textile preforms for composites. *Text Res J*. January 2011; DOI: 10.1177/0040517510392471.
- Stig F. *3D-woven reinforcement in composites*. PhD Thesis, KTH Stockholm, Sweden, 2012.
- Bhattacharay S and Koranne M. Novel method of weaving three dimensional shapes. *Int J Cloth Sci Technol* 2012; 24: 56–63.
- Kiesselbach G. Pressurized GRP pipes for hydroelectric plants. *3R Int* 2009; 48: 255–262.
- Reinicke R, Hauptert F and Friedrich K. Neue Herstellungsverfahren für thermoplastische Verbundwerkstoff-Gleitlager. In: *VDI-werkstofftag 13 jahrestagung*. Ulm, Germany, 10–11 June 1997, Vol. 1331, pp.235–242.
- Milwich M and Planck H. Possibilities and limits of braiding technology. In: *1. denkendorfer faserverbundwerkstoff-kolloquium*. Dekendorf, Germany 11–12 December, 1990.
- Erber A, Birkefeld K and Drechsler K. The influence of braiding configuration on damage tolerance of drive shafts. In: *SEICO, SAMPE Europe 30th international jubilee conference*, Paris, France, 23–25 March 2009, pp.364–371.
- Hufnagl E, Arnold R, Ridzewski J, et al. Entwicklung innovativer Multixialgewirke zur Kunststoffverstrückung: impulse für die Faserverbundtechnologie. In: *10th nationales symposium SAMPE Deutschland*, Dresden, Germany, 12–13 February 2004, pp.11.1–11.12.
- Gries Th and Klopp K. *Füge- und oberflächentechnologien für textilien: Verfahren und anwendungen*. Berlin: Springer, 2007.
- Hufenbach W. *Textile verbundbauweisen und fertigungstechnologien für leichtbaustrukturen des maschinen- und fahrzeugbaus*. Dresden: Technische Universität Dresden, 2007.
- Abounaim Md. *Process development for the manufacturing of flat knitted innovative 3D spacer fabrics for high performance composite applications*. PhD Thesis, Technische Universität Dresden, Germany, 2009.
- Cebulla H. *Formgerechte zwei- und dreidimensionale mehrlagengestricke mit biaxialer verstärkung: entwicklung von maschine, technologie und produkten*. PhD Thesis, Technische Universität Dresden, Germany, 2006.
- Fazeli M. *Technological development and weave design of 3D narrow weaves on a shuttle loom*. Faculty of Mechanical Engineering. Master's Thesis, Technische Universität Dresden, Germany, 2010.