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Erstveröffentlichung in / First published in:

Textile Research Journal. 2018, 88(13), S. 1453 – 1465 [Zugriff am: 07.08.2019]. SAGE journals. ISSN 1746-7748.

DOI: https://doi.org/10.1177/0040517516683746

Textile Research Journal

Original article

Textile Research Journal
2018, Vol. 88(13) 1453–1465

DOI: 10.1177/0040517516683746
journals.sagepub.com/home/trj
SAGE

Development of spatially branched woven node structures on the conventional weaving loom

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Abstract

The increasing need of consistent implementation of lightweight constructions in many technical fields makes the manufacture of near net-shaped node structure to be used in textile-reinforced composites a subject of great interest. The manufacture of the node structure is required to provide a strong node point whilst maintaining the circumference of each adjoining strut. Despite a variety of available methods to produce three-dimensional nodal fabric, the required geometry for the complex nodular connection element has not yet been fully achieved. Furthermore, the available methods have limitations. The developed woven concept in this work allows for maintaining the configuration of the node structure and dimensions of the tubes, especially at the node points. As a result, all tubes positioned at node points are fully open; this is accomplished without distorting the surrounding area once the flat woven node structure is removed from the loom and erected into three-dimensional configuration. In order to produce a three-dimensional structure on a conventional weaving machine, the structure must be flattened in an appropriate way. By using a mathematical algorithm, it is possible to graph the flattened structure precisely. The developed weaving concept and relating calculation are applied to create the weaving plan of the spatial nodal structures, which can be produced on a shuttle weaving loom. The developed concept in this paper will provide repeatable manufacturing of complex node structures by using the conventional weaving loom. The struts of node structures manufactured using this method can be woven at any angle and with spatial arrangements.

Keywords

spatial node structure, shuttle weaving loom, Jacquard technique, frame structure

In many technical applications, framework component groups are very important. These structures consist of various interconnected struts. The sections where these struts intersect are referred to as node structures. They represent critical points within a framework. It is important to ensure the connection between the struts without changing the shape of their cross-section. The node configuration determines the basic geometry of the framework and its ability to transfer loads while retaining structural stability. Typical node configurations can be found in the aeronautics, automobile and bridge building industries.[1–4] Due to the high demands regarding rigidity or strength, frameworks are usually constructed from metal or wood. In the connecting sections of the support frameworks, complex nodular elements made from bent metal sheets are used, which often have to be thickened considerably to achieve the required stiffness, strength and to absorb the occurring main loads. This causes

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undesirable mass increases.[5] The increasing necessity to consistently implement lightweight construction concepts in these areas makes requirement-adapted textile node structures very attractive for fiber-reinforced plastic (FRP) components. The use of high-performance fibers, such as glass fiber (GF), carbon fiber (CF) or aramid (AR), allows for the manufacture of fiber-reinforced plastic composites (FRPCs) with comparable mechanical properties at much smaller mass than constructions made from metal materials. Although various methods have been developed for the manufacture of textile three-dimensional (3D) node structures, the required component geometry could not be achieved entirely. An innovative approach is needed that allows the production of complex, single-part node structures in a variety of shapes with compatible geometries.

As proven by the possible textile semi-finished products made from high-performance fibers with profile or tube shapes, weaving has great potential as a manufacturing solution.[6–12] Using the Jacquard technique, profile and tube shapes within the fabric can be designed as needed, giving outstanding structural variety.[13]

The company Sigmatex Ltd has performed research regarding the development of FRP based on stitched multilayer woven fabric. A special focus is placed on a spatially branched node structure. According to this company, this was realized on a weaving machine with an additional Jacquard unit. The node is made from a plain-weave fabric, which is preformed and molded in an additional process step.[14] No variation of the weave pattern is executed.

Fazeli et al.[15] reviewed the most common methods to produce woven node structures. As mentioned above, weaving offers numerous possibilities to realize nodal structures. Generally, these are produced either as planar or as tubular woven fabrics.

Unfortunately, the production of nodal structures from planar woven fabrics requires post-processing efforts to remove the excess fabric, which results in the loss of a large amount of the material. In addition, the alignment of the yarns in the main axis of the individual tube profiles or in the direction of force flow between the involved components is not achievable.[16–19]

Nodal structures as tubular woven fabrics offer a convenient transition in the node area without requiring further manufacturing steps. However, the tube profiles can only be arranged in the production direction, which is disadvantageous, as it causes a lack of construction possibilities of the node structures.[20,21] This limits application possibilities of such components as frame structures in lightweight construction.

Methodology for weaving node structures

In order to overcome the above mentioned limitations of common methods, Fazeli et al.[15] recently developed a weave concept for manufacturing node structures. Within this work, the node structures were produced on a shuttle weaving loom by flattening and weaving them as multi-surface woven fabrics in one piece. In order to flatten the 3D node structure into a two-dimensional (2D) node schematic, the 3D model was cut open along the particular edge/s of the structure. The resulting gaps in the flattened model were filled with floating yarns in the weave process. The shape of the gaps depends on the arrangement of the tubes in the required nodal and can be determined mathematically. Pulling floating warp yarns after completing the weaving process contracts the area and joins the two cutting edges in the final structure. These process steps are illustrated in Figure 1 by the example of the T-node structure.[15]

The developed woven node structures using this method consist of several intersecting tubes. The position of the individual tubes in relation to each other can be varied at any angle. The production method of node structures allows for high quality, especially in the node area where the tubes intersect. Furthermore, the individual tubes have the same alignment of the yarns in their main axis, which leads to a homogeneous structure. Since all tubes in the structure are produced seamlessly, there is no excess fabric to be removed and it makes this method fundamentally material efficient. This weaving concept allows the reproducible manufacturing of node structures. The advantages of the developed concept in comparison to the conventional method are illustrated in Figure 2.

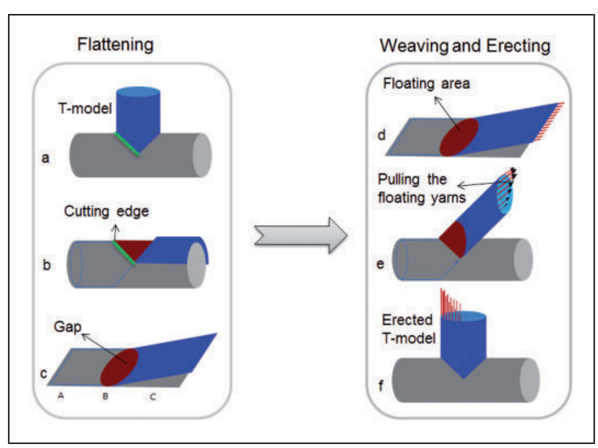


Figure 1. Schematic flattening and erection of the T-structure: (a) T-model; (b) folded T-model with gap; (c) flattening schematic with floating yarns; (d) and (e) erection process of the T-model; (f) erected T-model.[15]

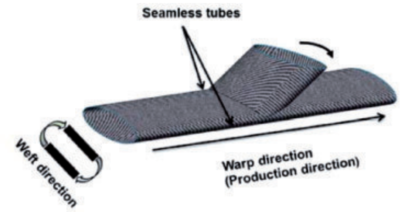
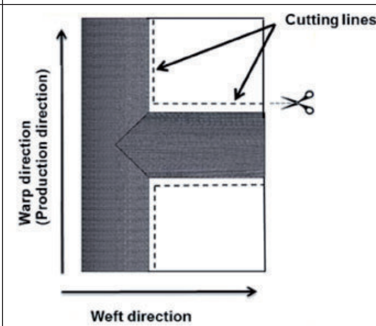
	Positioning the T-Structure
Variant A (Used in this work) **Advantages:** • Structural homogeneity, • Seamless tubes, • Excellent three dimensionality, • Material efficiency	
Variant B (conventional method) **Restrictions:** • Structural inhomogeneity, • Post-processing are required to remove the excess fabric , • Low material efficiency	

Figure 2. Advantages of the developed concept in comparison to the conventional method.

Fazeli et al.[15] applied the illustrated concept in Figure 1 for the development of a node structure with the examples of a T and an X node structure. Yet, in these structures all tubes are located in one plane. The above illustrated concept can be further developed for manufacturing of spatially branched node structures. However, the flattening process of the spatial structures poses a special challenge. To further expedite consistent lightweight construction in automobile and mechanical engineering, this work will develop a fabric formation concept for the production of load-adjusted spatial nodal structures from high-performance filament yarns in integral construction, exemplified by the LI-node and W-node. To develop weave patterns for the LI-node and W-node, software tools (DesignScope Victor, EAT GmbH) were used and the fabrics were developed on a modern narrow shuttle loom by Mageba Textilmaschinen GmbH & Co. KG (Figure 3).

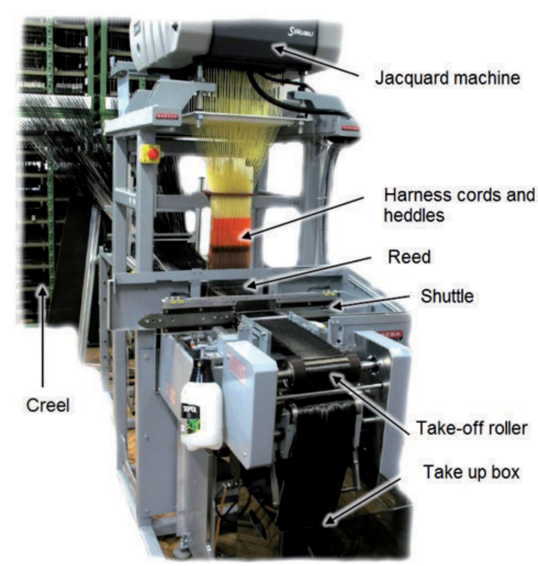


Figure 3. Narrow shuttle loom set up.

Developing and manufacturing spatial node structures

Node structures are distinguished by a network of several dense or hollow-profile elements connected in one or more places. These elements can be arranged in any desirable angle to one another, creating a planar or spatially complex structure. The spots in which at least two such elements are connected are called nodes. A node structure whose central axes are located on the same plane is referred to as a planar structure. If the central axes are located on more than one plane, the node structures are referred to as spatial. A node structure whose central axes are located on three different planes is defined as a complex spatially branched node structure.

Figure 4 shows samples of complex spatial node structures, for example, a fitting connector. Potential applications for such node structures include joints and attachment fittings for truss structures, spacecraft structures, thermal planes, mechanical housings and bushings. This paper describes a weaving method for manufacturing spatially branched node structures on a conventional weaving loom based on carbon yarn exemplified by the LI structure and the W structure. The goal is reducing the production run time and limiting the wastage of the surrounding fabric.

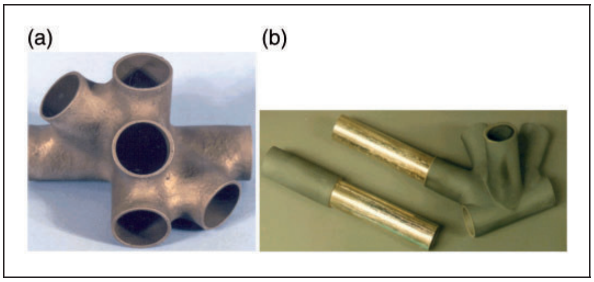


Figure 4. (a) Multi-inlet fitting for a truss node. (b) Cast fitting brazed to a Gr/Al tube.[22]

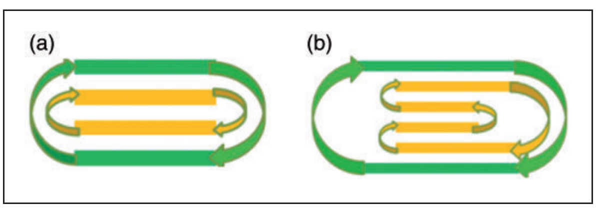


Figure 5. The sub tube runs within the main tube. (b) The folded sub tube runs within the main tube. (Color online only.)

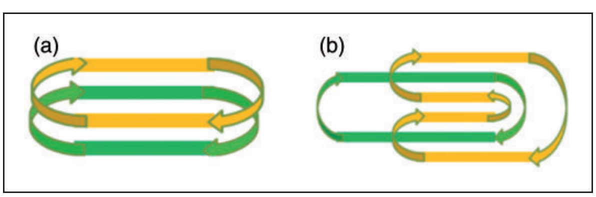


Figure 6. (a) The sub and main tube intersect. (b) The folded sub and main tube intersect. (Color online only.)

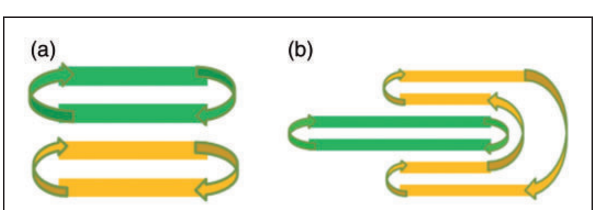


Figure 7. (a) The sub tube placed on the main tube. (b) The folded sub tube wraps around the main tube. (Color online only.)

The sequence of the individual tubes in relation to each other

The position of tubes in relation to each other is crucial for developing the node structures and it varies in different structures according to the number of the tubes and node element configuration. Figures 5–7 show different positioning of the green main tube(s) and orange sub tube(s) in different weave sections of the node structures. The folded variant of the sub tube is usually necessary for developing woven spatial node structures. When using more than two tubes, these arrangements are also valid.

Figure 5 shows the position of the main tube (green tube) and sub tube (orange tube) in relation to each other while the sub tube runs within the main tube. In variant Figure 5(b), the sub tube is based on four warp layers and is produced as a folded tube. This positioning variant is used for developing the W structure.

Figure 6 shows the positions of the main tube and sub tube in relation to each other while the sub tube and the main tube intersect. The intersection of the tubes occurs within the floating section and plays a significant role for three dimensionality in the connection area between tubes. Figure 6(b) illustrates the intersection between two tubes while the sub tube is folded.

Finally, Figure 7 shows the positions of the main tube and sub tube in relation to each other while the sub tube is placed on the top of main tube in Figure 7(a) and is wrapped around the main tube in Figure 7(b).

The LI structure

Flattening process

As shown in Figure 8, the LI structure represents the axes of a 3D Cartesian coordinate system and is derived

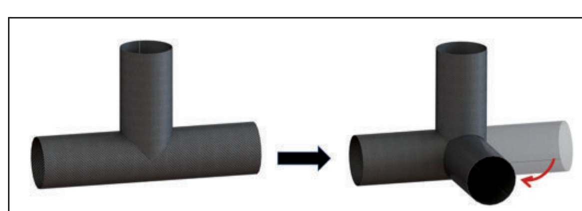


Figure 8. Transformation from T-structure into LI structure.

Figure 9. Schematics for flattening of the LI structure. (Color online only.)

from the T-structure by altering the intersection angle of the two tubes. With this transformation, the straight, continuous main tube in the T-structure changes into two perpendicular tubes.

In order to weave the LI structure on a conventional weaving loom, the structure must be first flattened into a 2D node schematic in a manner in which all tubes can be woven seamlessly in the longitudinal direction. For this purpose, tube 2 is cut along the light green cut edge 1–2, and tube three is cut along the dark green cut edge 1–3, before being folded into the plane of tube 1 (see Figure 9). The free areas created between tubes 1 and 2 on the top side of the weave and tubes 1 and 3 on the bottom side are filled with warp yarn floats. These are marked in Figure 9 by the section marked in red dashes. In post-processing, the floats are pulled, which puts the cut edges back together and erects the structure.

Mathematical approach for calculating the flattening geometry

In the weave pattern diagram, the cut edges are represented by the flattening curves. Size, geometry and position of the floating section are determined here by means of the flattening curves. These flattening curves can be determined mathematically. Therefore, the intersection line (light green cut edge 1–2) of the tubes is calculated based on the intersection of cylinders according to

$$\begin{pmatrix} x_i \\ y_i \\ z_i \end{pmatrix} = \begin{pmatrix} \begin{cases} \frac{R}{\sqrt{2}} \cdot \sqrt{2 - \left(\sin\theta - \sqrt{1-\sin^2\theta}\right)^2}, & 0.75\pi \le \theta < 1.25\pi \\ -\frac{R}{\sqrt{2}} \cdot \sqrt{2 - \left(\sin\theta - \sqrt{1-\sin^2\theta}\right)^2}, & 1.25\pi \le \theta < 1.5\pi \\ -\frac{R}{\sqrt{2}} \cdot \sqrt{2 - \left(\sin\theta + \sqrt{1-\sin^2\theta}\right)^2}, & 1.5\pi \le \theta < 1.75\pi \end{cases} \\ \frac{R}{\sqrt{2}} \cdot \left(\sin\theta - \sqrt{1-\sin^2\theta}\right) \\ -R \cdot cos\theta \end{pmatrix} \tag{1}$$

where R is the radius of the cylinders (tubes) and θ is an angle parameter. In the next step the intersection line is flattened on the xz-plane, whereby the x-coordinate is flattened on the plane and the z-coordinate is shifted along the z-axis. The equation for the flattening curve is

$$\begin{pmatrix} x_f \\ z_f \end{pmatrix} = \begin{pmatrix} -R \cdot \arccos\left(\frac{x_i}{R}\right) + \frac{R\pi}{2} \\ z_i + R\sin\left(\frac{\pi}{4}\right) \end{pmatrix} \tag{2}$$

The algorithms for the calculation of the flattening of different node structure geometries are implemented in an Excel file (cf. Figure 10).

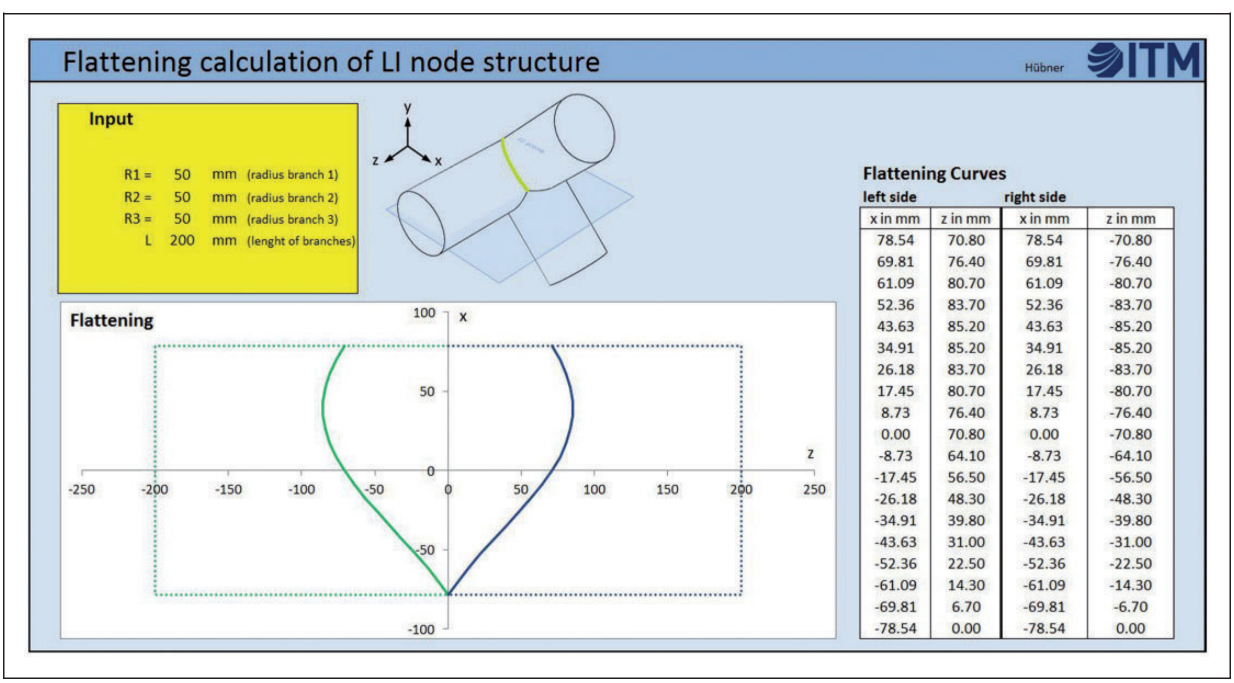
Weave pattern development

Maintaining the dimension of the tubes at the node point of the LI structure where three tubes intersect without distorting the surrounding area must be taken into consideration for the weave pattern development. To achieve this goal, the weave pattern of the LI structure is divided into four main sections (Figure 11) as follows.

- Section A: tube 2 runs within tube 1.
- Sections B1 and B2: transition area in which the interior layers of tube 1 exchange their position with the exterior layers of tube 2 and are floated. At the transition from section B1 to section B2, the weft bobbin allocation to the individual fabric layers changes.
- Section C: tube 1 is above tube 2, and each tube is woven with a separate weft bobbin.

As the weft insertion on the shuttle loom is performed by means of bobbins, there is always a closed selvedge, which requires further considerations regarding the weft sequence process for the production of the node structure. The weft sequence of the LI structure is shown in Figure 12. Figure 13 illustrates the position of the layers along the LI structure.

In Figure 12, the allocation of the weft bobbins to the individual warp yarn layers in the respective weave sections is illustrated. In section A, the orange weft bobbin weaves the exterior tube while the green weft bobbin creates the interior tube. The transition from weave section A to weave section B1 is performed along the flattening curve 1 (Figure 11). Here, the interior layers of tube 1 exchange their position with the exterior layers of tube 2 and are floated. The orange weft bobbin keeps weaving tube 1, which is now inside the structure. The green weft bobbin is inserted into weave section B1 as a weft float underneath the light green and dark green warp yarn layers, with 'underneath' referring to their position in relation to the structure. From section B2 onwards, the orange weft bobbin weaves the top tube (tube 2), and



x in mm	z in mm	x in mm	z in mm
78.54	70.80	78.54	-70.80
69.81	76.40	69.81	-76.40
61.09	80.70	61.09	-80.70
52.36	83.70	52.36	-83.70
43.63	85.20	43.63	-85.20
34.91	85.20	34.91	-85.20
26.18	83.70	26.18	-83.70
17.45	80.70	17.45	-80.70
8.73	76.40	8.73	-76.40
0.00	70.80	0.00	-70.80
-8.73	64.10	-8.73	-64.10
-17.45	56.50	-17.45	-56.50
-26.18	48.30	-26.18	-48.30
-34.91	39.80	-34.91	-39.80
-43.63	31.00	-43.63	-31.00
-52.36	22.50	-52.36	-22.50
-61.09	14.30	-61.09	-14.30
-69.81	6.70	-69.81	-6.70
-78.54	0.00	-78.54	0.00

Figure 10. Determination of the flattening geometry of the LI structure by means of the Excel file.

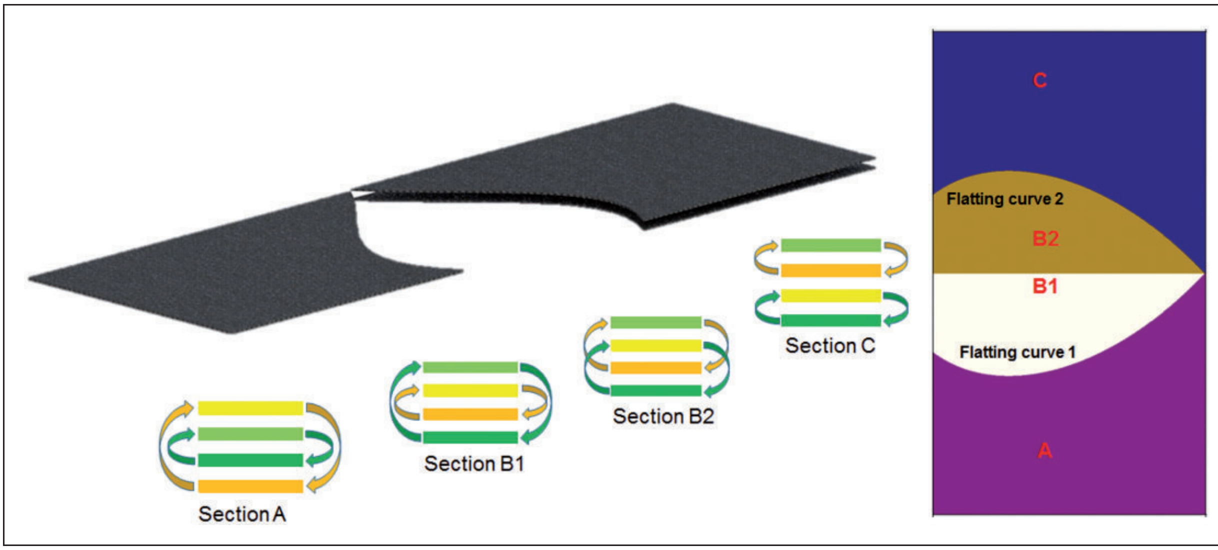


Figure 11. Segmentation of the LI structure in the flattened model and the position of the tubes in each section. (Color online only.)

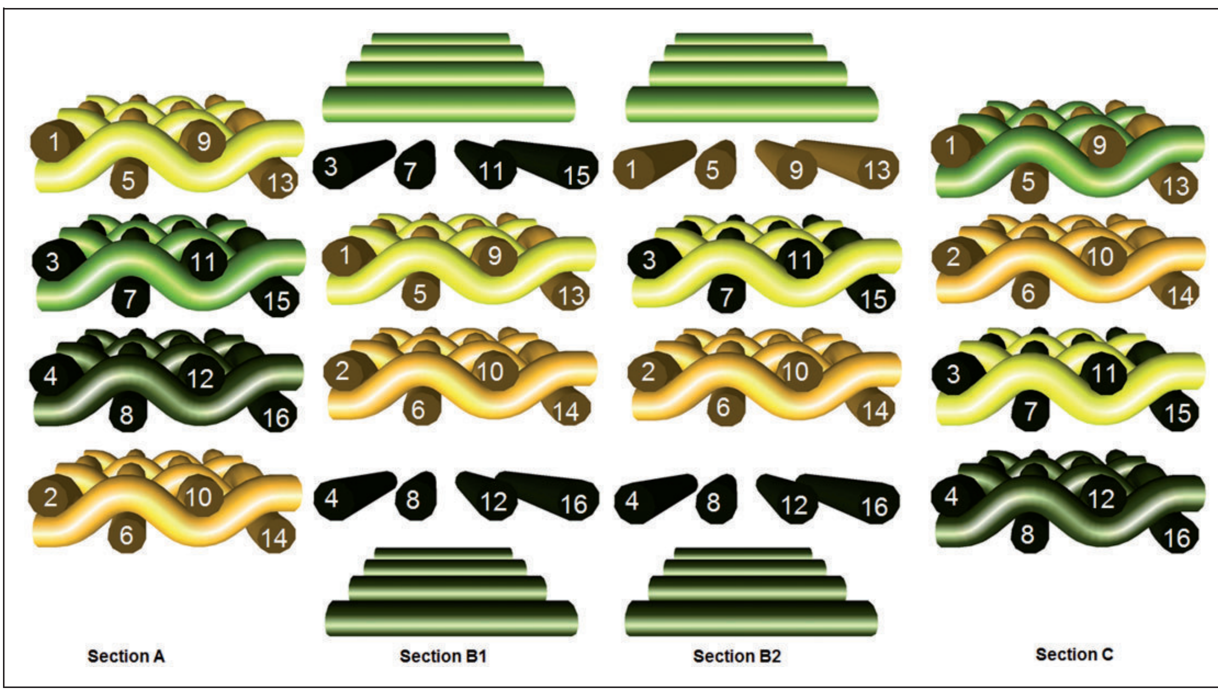


Figure 12. Weft cross-sections of the LI structure. (Color online only.)

the green weft bobbin weaves the bottom tube (tube 3). The weave section B2 transitions into weave section C along flattening curve 2 (Figure 11). Tubes 2 and 3 are separated by a final warp yarn layer change and are now on top of each other. The upper and bottommost layers are no longer floating, but woven in a plain weave.

Scaling the geometrical sizes for the weave pattern graphic

The unit for length measurements in the weave pattern diagram is pixels, each of which represents one interlacing of the warp and weft. The maximum length of a flattening curve is scaled by means of the weft repeat,

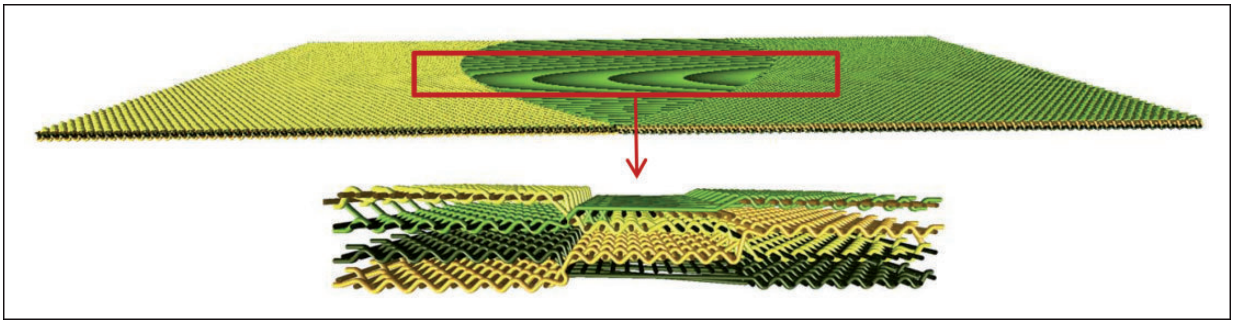


Figure 13. Weft cross-section of the LI-node structure along the structure.

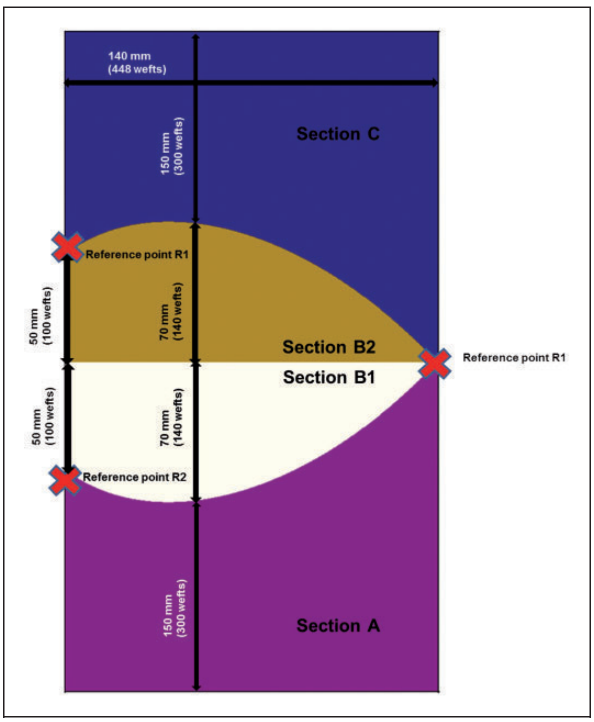


Figure 14. Weave pattern diagram of the LI structure.

the weft density and the number of layers. The height of the respective flattening curve is therefore calculated from

$$Weft\ repeat = \frac{\text{Geometrical length of a flattening curve} \times \text{number of layers}}{\text{length deduction per weft in mm}}$$

The specific data for the LI structure are as follows (Figure 14):

- geometrical length of a flattening curve (calculated from the geometrical ratio width: length of the curve) is 70 mm;
- number of weft yarn layers in the respective area is four (two layers per tube for two tubes);
- the weft yarn density is five wefts per centimeter, which results in a 2 mm deduction per weft row.

The required number of weft threads for section B1 as well as section B2 is therefore

$$\frac{70\text{mm} \times 4\text{layers}}{2\text{mm}} = 140\text{weft insertions}$$

Sections A and C have a geometrical length of 150 mm and four layers. This is equivalent to

$$\frac{150\text{mm} \times 4\text{layers}}{2\text{mm}} = 300\text{ weft insertions}$$

Reference points are necessary to position the flattening curves in the weave pattern diagram. The two points where all three tubes intersect serve as reference points. The reference point R2 for the right-hand edge of the weave is the intersection point visible in the back view in Figure 15. The reference point R1 for the left-hand edge of the weave is the intersection point visible in the front view in Figure 15. As shown in Figure 14, this reference point appears twice in the weave pattern diagram. At this point, the three tubes are connected only by pulling the floats. The length of the flattening curves at the height of the reference point R1 is calculated with the use of Excel file in Figure 10 for flattening curves 1 and 2.

Thus, the length of flattening curve 1 at reference point R1 results from

$$\frac{50\text{mm} \times 4\text{layers}}{2\text{mm}} = 100\text{ weft insertions}$$

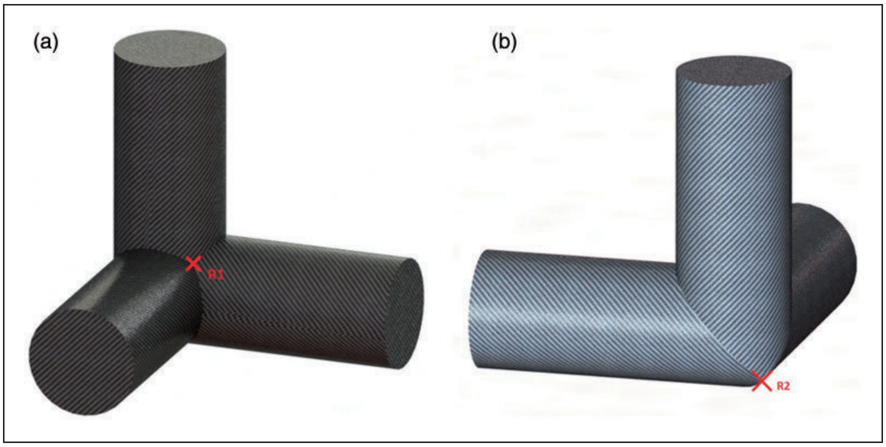


Figure 15. Position of the reference points in the LI structure. The geometrical length of flattening curve 1 at reference point R1 is 50 mm and the geometrical length of flattening curve 2 at reference point R2 is also 50 mm. (a) Front view - Reference point R1, (b) Back view - Reference point R2.

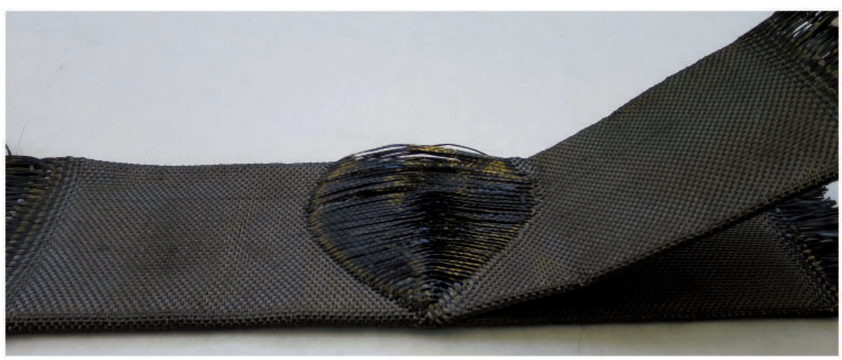


Figure 16. Woven LI structure before erecting.

The length of flattening curve 2 at reference point R2 results from

$$\frac{50\text{mm} \times 4\text{layers}}{2\text{mm}} = 100\,\text{weft insertions}$$

All measurements, reference points and individual weave areas are summarized in Figure 14.

Manufacture of the LI structure

To demonstrate the feasibility of the functional model, a carbon filament yarn of 800 tex fineness as the warp (warp density: 16 yarns/cm/4 layers) and weft (weft density: 20 yarns/cm /4 layers) yarn is used. After realization of the weave pattern diagram for each section, the complete weave pattern for the LI structure was designed by means of EAT 3D Weave software and was transferred to the Stäubli Jacquard software program on the Mageba narrow shuttle loom for the weaving process.

The woven LI structure before erecting is illustrated in Figure 16. Figure 17 shows the manufactured woven LI structure. Comparing the woven structure with its computer-aided design (CAD) model (Figure 8) shows the feasibility of this method. It is of high quality, especially in the node area, and it has excellent three dimensionality.

The W structure

Flattening process

Another spatially branched woven node structure whose weave development will be discussed in this paper is the W structure. The CAD model for the W structure is shown in Figure 18. This construction is a further development of the planar X structure. The angle between the two tubes of the X structure is decreased from 180 to 135 degrees. This creates a spatial structure in which the tubes are no longer on the same plane.

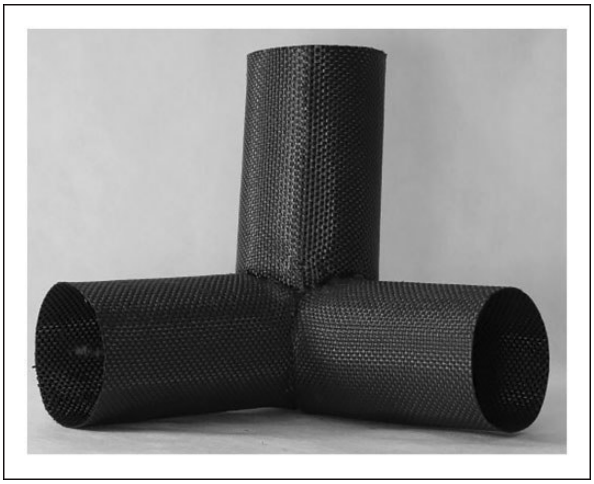


Figure 17. Finished woven LI structure.

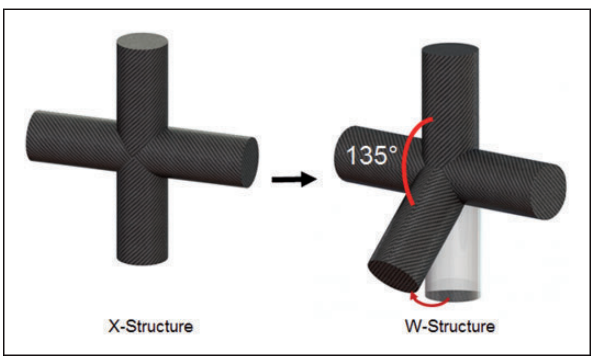


Figure 18. Transformation from the X structure to the W structure.

Weave pattern development

Figure 19 shows the schematics for flattening of the W structure, where the two sub tubes must be wrapped around each other in their intersection area and also around the main tube. The position of tubes in relation to one another is illustrated in Figure 20. This positioning results in a weave diagram whose weave sections not only change in the warp direction but also in the weft direction. Therefore, the weave pattern of the W structure is divided into sections 1, 2, 3 and 4 in the weft direction and sections A, B and C in the warp direction.

- Section A
- Sections 1, 2 and 4 The orange and green sub tubes run within the blue main tube.
- Section 3 The orange and green sub tube intersect.
- Section B
- Sections 1, 2 and 4 Transition section, the orange and green sub tubes emerge from the blue main tube. The upper layer and the bottom layer of both sub tubes are floated.
- Section 3: The green and the orange sub tube intersect. The first and second upper layers of green sub tube are floated.
- Section C
- Sections 1, 2 and 4 The orange and the green sub tube are placed around the blue main tube.
- Section 3 The green sub tube is folded around the orange sub tube.

The exact layer divisions and the wrap cross-sections in sections A, B and C are shown in Figures 21–23.

The mathematical approach for calculating the flattening geometry and scaling the geometrical sizes for the weave pattern graphic of the W structure follows the same procedures as for the LI structure.

Figure 19. Schematics for flattening of the W structure.

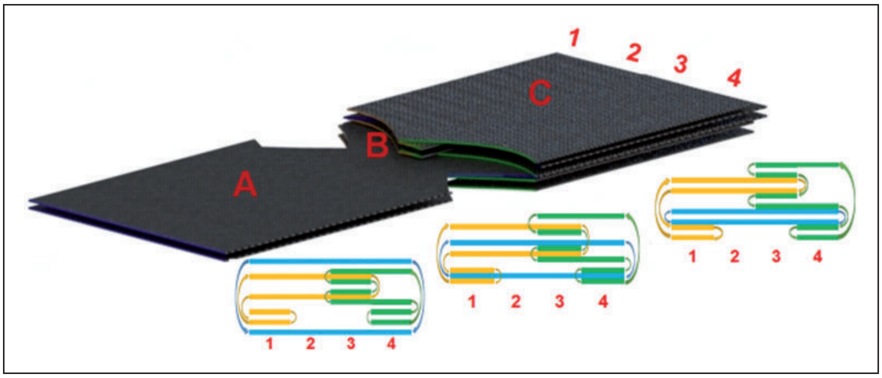


Figure 20. Segmentation of the W structure in the flattened model and the position of tubes in each section. (Color online only.)

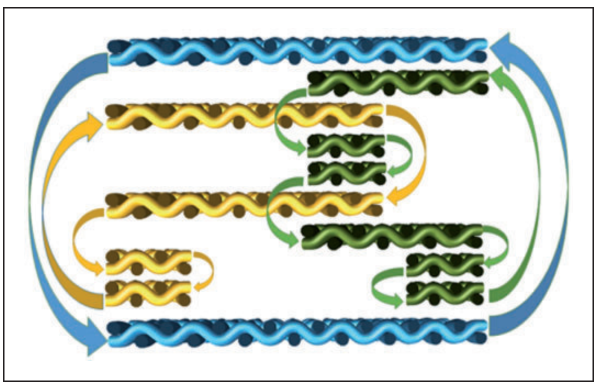


Figure 21. Wrap cross-section in section A.

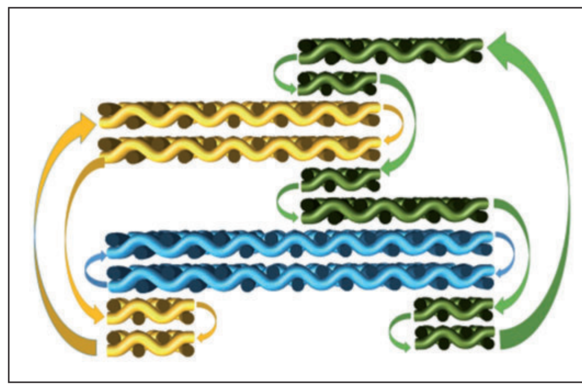


Figure 23. Wrap cross-section in section C.

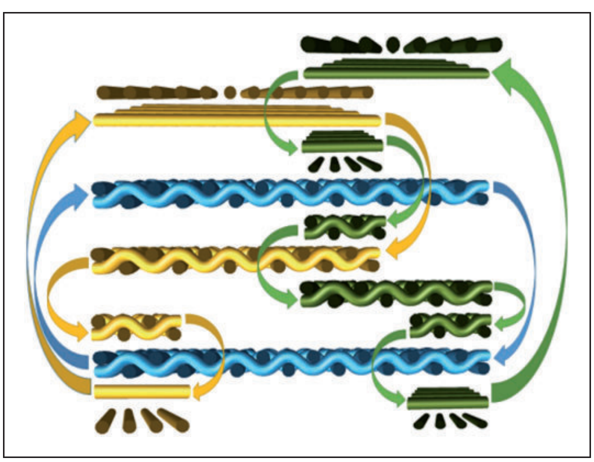


Figure 22. Wrap cross-section of the flattening curves (section B).

The woven W structure is illustrated in Figure 24. The manufactured W structure reflects a high degree of accuracy according to its developed CAD model. The transitions between the individual tubes are smooth, and the yarn course inside the structure is properly completed.

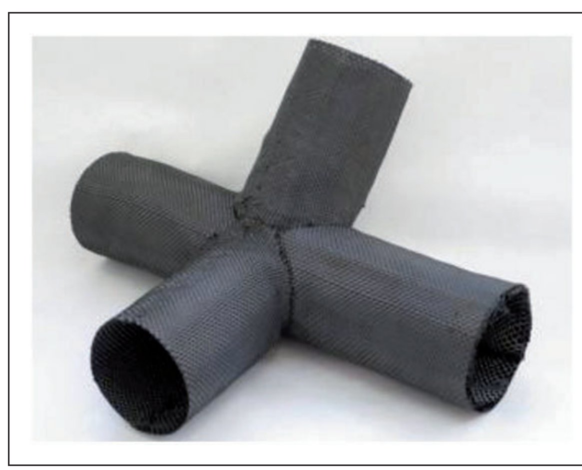


Figure 24. Completed W structure.

Conclusion

The introduced weaving concept in this work allows for the production of spatially branched nodal structures on a conventional weaving loom without any special equipment necessary. Within the work carried out, the developed node structures always consist of several intersecting tubes. The position of tubes in relation to each other, especially in the node area where the floating occurs, is crucial for developing the node structures and will vary in different structures regarding the node structure configuration. By using mathematic calculation, the position of the individual tubes in relation to each other can be precisely determined. Therefore, a vast range of nodal configurations can be manufactured by using this method. Afterwards, the 3D node structure can be realized by erecting into the 3D configuration by drawing the floating yarns. As a result, post-processing efforts, such as cutting, are no longer necessary. Thus, it could be concluded that this manufacturing method has a high level of material efficiency that was not supported by available manufacturing methods explained in the introduction. Strategically, the development embodies an enormous contribution to lightweight construction and to the conservation of resources.

However, despite the great advantages of the developed weaving concept in the present study, there is a huge demand for further research. As mentioned above, the drawing of floating yarns for the erection of nodal structures is necessary. This step in the work was operated manually. For the implementation of this method in a fully integrated production chain, an automated procedure for drawing the floating yarns is required. The analysis of the required forces for drawing the floating yarns is the starting point for the realization of respected automated procedure. Based on these analyses, a finite element model for the simulation-assisted development has to be conducted.

The developed concept presented in this paper has huge potential for establishing a reproducible and fully integrated production chain of a vast range of node structures, as well as highly complex 3D woven structures for application in the composite industry.

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 17591 BR and 18782 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.

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