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Erstveröffentlichung in / First published in:

Textile Research Journal. 2016, 86(11), S. 1220 – 1227 *[Zugriff am: 07.08.2019]*. SAGE journals. ISSN 1746-7748.

DOI: https://doi.org/10.1177/0040517515617425

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Textile Research Journal
2016, Vol. 86(11) 1220–1227
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Development of seamless woven node element structures for application in integral constructions

**Monireh Fazeli, Matthias Hübner, Theo Lehmann,
Ulrike Gebhardt, Gerald Hoffmann and Chokri Cherif**

Abstract

In order to advance consistent lightweight construction principles in automotive and mechanical engineering, support frame construction made from high-performance materials is becoming more commonplace. These consist of complexly structured nodular connection elements. The required connection elements have not yet been produced satisfactorily. The developed node element structures in this paper are produced on a shuttle weaving loom by flattening and weaving them as multi-surface woven fabrics. The development of the woven concept for the realization of node element structures is based on the fragmentation of the individual sub-elements. The goal of this research is development of a flexible technology for weaving fabrics and intended for the integral realization of woven nodular semi-finished products with complex geometries and connections, which are to be used to connect Fiber-reinforced Plastic components in support frame structures.

Keywords

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

In all areas of mechanical, vehicle and machine plant engineering, efforts are being made to reduce moving masses and offer lightweight construction design solutions to ensure a sparing use of finite resources. A vehicle body, which is the most promising part in terms of mass reduction potential, conventionally consists of a frame structure constructed from steel profiles or extruded aluminum profile in series vehicles.[1] Fiber-reinforced Plastic (FRP) profile components are produced from textile semi-finished products (woven, knitted, braided, etc.) with various resins, using a number of available manufacturing methods. However, the nodal elements in integral construction for the connection of the profiles are still missing. The currently applied FRP components do not yet completely fulfill the set requirements and have considerable development potential.

The high flexibility of weaving is an outstanding advantage for the manufacture of node element structures.[2–4] Patterns and product parameters can be varied without obstructions. On conventional machines, a diversity of structures can be realized without special devices or alterations.[5–8]

Weaving offers numerous possibilities to realize nodal structures. Two weaving methods are most commonly used: the semi-finished products are produced either as planar or as tubular woven fabrics.

For the production of planar woven fabrics, an area corresponding to the graphic representation of the desired nodal element is defined on the woven fabric. This approach relies on the principle of multilayered woven fabrics. In the area of the structural geometry, two fabric layers are woven separately to form a tube for the final profile. In the remaining area, the interlacing of all layers creates only a single woven fabric. Using Jacquard weaving, pattern-adapted weaving

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becomes possible. After the cutting of the geometry, the semi-finished products are folded out, resulting in a three-dimensional (3D) nodal element.[9]

Due to different degrees of bending in the node area, the transition from two dimensions to three dimensions is problematic. If only the graphic representation of a 3D node element structure (e.g. T- or I-shape) was used for the two-dimensional (2D) fabric formation, undesirable creases would occur in the surface of the node area of the 3D semi-finished product, as the created fabric is insufficient for the 3D form. This occurs primarily in the woven structures, which are very stable.[10] Therefore, the created fabric cannot be adapted to the 3D form. Several methods have been developed to avoid this problem.[11]

In the patent-protected method,[12] heat-activated fibers are used. These fibers are integrated below the surface, where a spatial deformation is required. When heated, the fiber length changes, causing a deformation of the structure. This method is largely used for the manufacture of semi-finished products for energy, electronics and telecommunication applications.

The method developed by Taylor[9] segments the nodal area during the re-shaping from 2D to 3D woven structures after bulging. Each segment has a separate weave pattern. The resulting local variation of the woven fabric density creates a shell-shaped geometry. This ensures a fluent transition between the hollow profiles aligned in different directions.

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 element. According to the company, this was realized on a weaving machine with an additional Jacquard unit. The node is made from a plain weave fabric and is molded in a second process step.[13] No variation of the weave pattern is performed.

The bifurcate tubular structures are used in medical textiles. For instance, they serve as blood vessel prosthesis. Weaving with a shuttle weft insertion technology and the resulting constant bilateral change of the weft yarn allows the production of tubular woven fabrics on the shuttle weaving loom. This technology is used for the manufacture of simple nodal elements. The bifurcate structures can be produced on a conventional weaving loom by separating the warp yarns in two groups across the fabric width, after the weaving of the main tube is completed. This approach requires two shuttles arranged at both sides of the fabric. The shuttles run consecutively in opposite directions from one edge to the middle of the fabric, and vice versa. Thus, two tubes are woven simultaneously and next to each other.[14]

For the production of tubular woven fabrics, Jacquard control is used. Fundamentally, the desired node element structure is geometrically developed in a manner that places the involved tubes on top of each other. This creates a structure with different numbers of fabric layers in neighboring areas, which is easily realized using Jacquard techniques. The area for the realization of the tube is freely selectable. The tube diameter can be varied gradually during weaving. This method allows the manufacture of various structures, such as structures with circumferences changing along the profile length. Changing the layer does not create gaps in the node area, which is an advantage not offered by the abovementioned method.[15]

Even though there are currently several methods available for the production of nodal elements, restrictions do exist.

Unfortunately, the production of nodal elements from planar woven fabrics requires post-processing efforts to remove the excess fabric. This results in the loss of a large part 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. Nodal element 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 element structures.

It can be concluded that no available method is currently fit to fulfill the growing requirements of configuration or mechanical properties of the node element structures. This limits application possibilities of such components as frame structure in lightweight construction. To further expedite consistent lightweight construction in automobile and mechanical engineering, this work will systematically develop a fabric formation concept for the production of load adjusted nodal element structures from high-performance filament yarns in integral construction, exemplified by the T-node and X-node. Structurally, these are tubular forms consisting of several layers. To develop weave patterns for the T-node and X-node, software tools (DesignScope Victor, EAT GmbH) are used and the fabrics were developed on a modern narrow shuttle loom by Mageba Textilmaschinen GmbH & Co. KG (Figure 1).

Systematic weave pattern development of node element structures

Three-dimensional woven structures can be produced on conventional (2D) weaving machines by flattening and weaving them as multi-surface (e.g. tubular) woven fabrics. After the removal of the woven semi-finished product from the machine, it is erected or shaped as desired. In general, the transformation of 3D

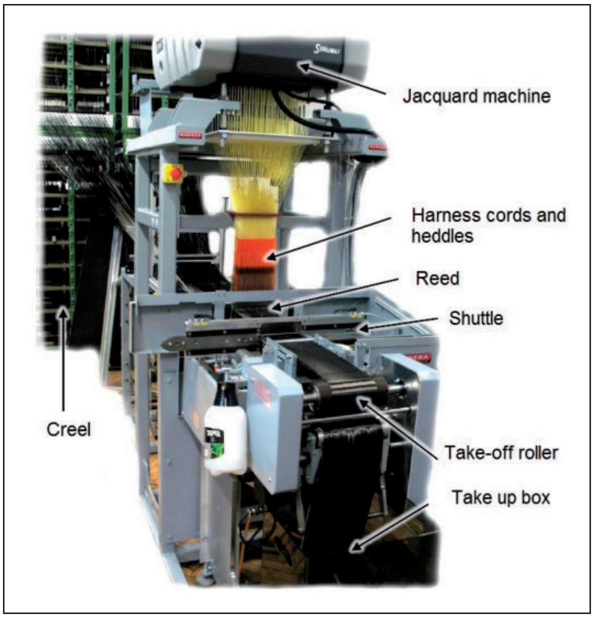


Figure 1. ITM narrow shuttle loom set up.

semi-finished products into weave-technically producible structures can be divided into three main process steps. These are explained as follows.

1. Developing the desired structure: this includes the shaping of the original 3D form into a weave-technically (woven) producible planar structure. Several development variants are possible for the same 3D structure.
2. For each development variant, a number of yarn arrangement possibilities are designed, which have to be realizable by the loom. This allows the pinpointing of the most readily realizable variant. The selected development variant should be characterized by an optimized yarn orientation and subsequently excellent properties and producibility.
3. Corresponding to the selected variant, the weave patterns of the specific structure are developed, and then used to realize the desired final product on the weaving machine.

With this method, numerous complex 3D structures can be realized using conventional loom technology without any special modules or technologies. Based on above-mentioned steps, the textile-technological production concept of nodal element structures on a shuttle narrow weaving loom are developed with the example of T- and X-node elements.

Typical node elements are structures consisting of various circular cylindrical tubes. In each structure, a main tube can be assigned, which is constructed continuously throughout the entire component. Several tubes leading in various directions are integrated into this main tube. The node connections only occur at the surface of the main tube. On the whole, a structure is created in which several tubes branch off the main tube. Generally, the tubes can have various diameters. However, the diameters of the individual branched tubes are usually not larger than that of the main tube.

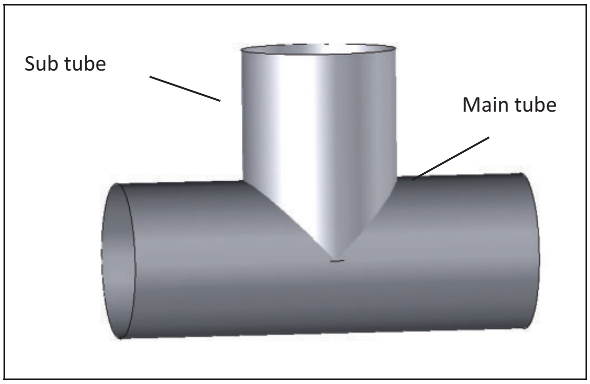


Figure 2. Three-dimensional model of a T-node element.

A T-node serves as the base for node element structures. This frame consists of two tubes of similar diameter, arranged perpendicular to one another. Figure 2 shows the 3D model of a T-node element. Based on this shape, the node element structure is systematically developed with regard to weave patterns and technology.

Various variants were developed for the realization of this structure. These are detailed in Figure 3.

In the first variant, the T-structure is folded flat. The figure shows that the T-shape remains after development. In the second variant, the sub tube (blue tube) is placed on the main tube (gray tube) in such a manner that places both flattened tubes on top of each other. This results in a multi-surface in which the sleeve of the main tube is arranged straight. Alternatively, the two arms of the main tube can be folded in Variant 3. The developed structure bears close resemblance to Variant 2. The difference is in the folded layout of the flattened main tube.

As the structure is to be realized on a narrow shuttle weaving loom, Variant 1 is an unsuitable choice. Depending on the dimensions of the required component, the necessary fabric width can exceed the maximum working width of the narrow shuttle loom. This development variant does not allow the manufacture of seamless, tubular woven fabrics. Furthermore, structural homogeneity in the node area cannot be guaranteed. In contrast, the two other variants offer the advantage of hassle-free manufacture of narrow and tubular woven fabrics on a narrow shuttle loom. As mentioned above, it is important to ensure a continuous construction of the main tube. Variant 3 connects two individual woven fabric layers to create a fold in the center of the main tube, which does not

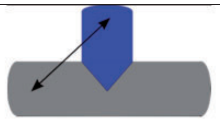
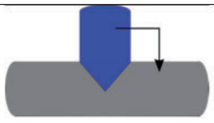
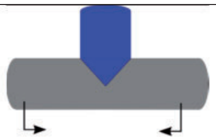
Variant	1	2	3
3D model			
Flattened schematic			

Figure 3. Development variants of a T-node element. (Color online only).

meet this requirement. In development variant 2, none of these restrictions occur. Therefore, it presents the best possible option for weave pattern development of the T-node element structure.

Developing and manufacturing the woven T-node element

The T-structure (Figure 2) consists of two identical-diameter tubes placed perpendicularly on top of each other. As marked in Figure 4(a), the straight bottom tube will be referred to as the main tube, and the shorter, superimposed tube as the sub tube. As presented in Figure 4(b), the sub tube is folded in a manner that places it on the rear part on the main tube. In addition, the model of the T-structure has to be cut open along the edge colored in light green in Figure 4(b). The resulting gap, which is marked red in Figure 4(b), is filled with floating yarns (Figure 4(c)). 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 Figures 4(d) and (e).

Size, geometry and position of the floating section are determined by means of the development curves. These can be calculated mathematically (Figure 5).

The course of the warp yarns within the T-structure, and the consistent correlation of the warp yarns to a tube, are shown in Figure 6. The green warp yarns in Figure 6 form the main tube. This tube is woven with a weft bobbin, which is also colored in green in Figure 8. The warp yarns of the sub tube are marked in orange, and are woven with a separate weft bobbin also colored in orange in Figure 8.

Basically, the weave pattern of the T-structure is divided into three main sections (Figure 7):

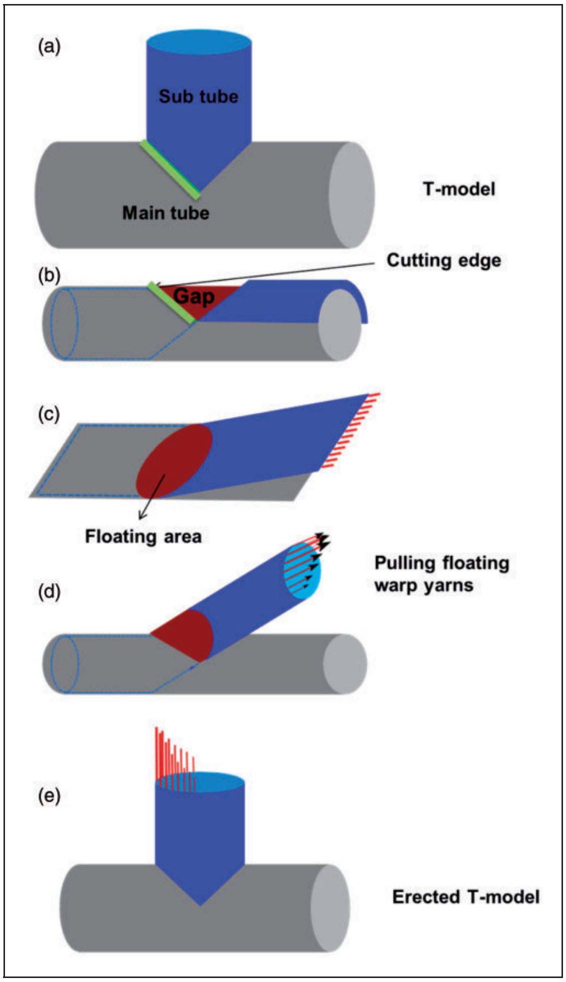
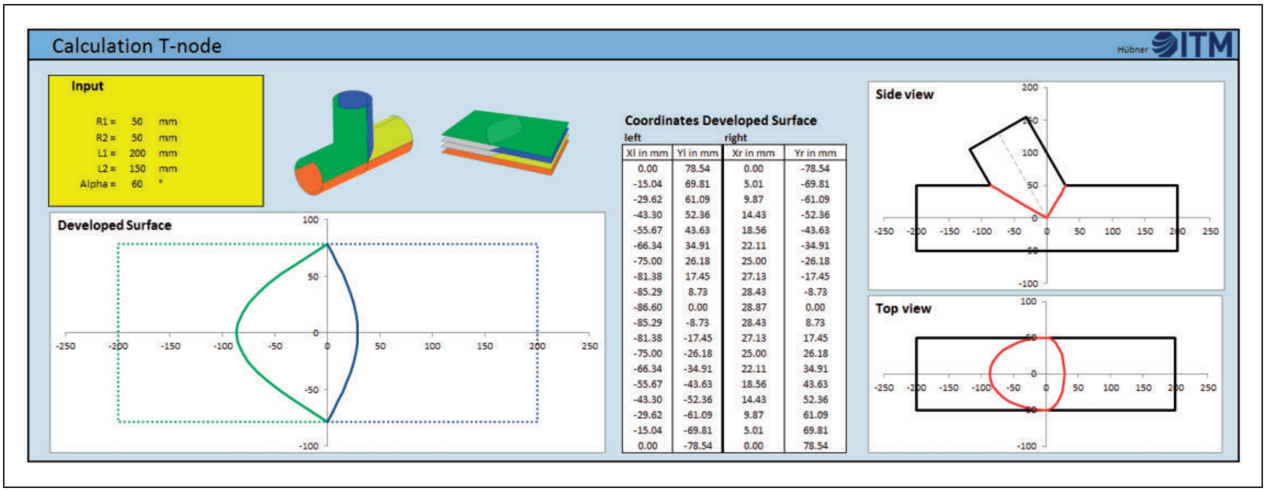


Figure 4. Schematic erection of the T-structure: (a) T-model; (b) folded T-model with gap; (c) flattening schematic with floating yarns; (d) and (e) erection process of the T-model. (Color online only.)

- Section A (including Section D): the sub tube runs within the main tube;
- Section B: transition section, in which the sub tube emerges from the main tube and floating yarns are woven;
- Section C (including Section E): the sub tube is placed on the main tube.

To avoid slippage of the weave structure at the edge of the floating area during weaving, filling yarns are inserted into the floating area. The weft material on



Calculation T-node

Input

R1 = 50 mm
R2 = 50 mm
L1 = 200 mm
L2 = 150 mm
Alpha = 60 °

Coordinates Developed Surface

left		right	
Xl in mm	Yl in mm	Xr in mm	Yr in mm
0.00	78.54	0.00	-78.54
-15.04	69.81	5.01	-69.81
-29.62	61.09	9.87	-61.09
-43.30	52.36	14.43	-52.36
-55.67	43.63	18.56	-43.63
-66.34	34.91	22.11	-34.91
-75.00	26.18	25.00	-26.18
-81.38	17.45	27.13	-17.45
-85.29	8.73	28.43	-8.73
-86.60	0.00	28.87	0.00
-85.29	-8.73	28.43	8.73
-81.38	-17.45	27.13	17.45
-75.00	-26.18	25.00	26.18
-66.34	-34.91	22.11	34.91
-55.67	-43.63	18.56	43.63
-43.30	-52.36	14.43	52.36
-29.62	-61.09	9.87	61.09
-15.04	-69.81	5.01	69.81
0.00	-78.54	0.00	78.54

Figure 5. Calculation of the development geometry of the T-structure by means of an Excel file. (Color online only.)

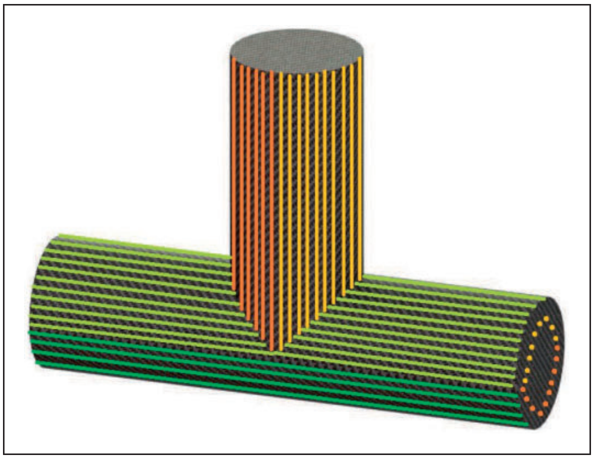


Figure 6. Warp thread course within the T-structure. (Color online only.)

the filling yarn bobbin is very smooth (PET 200 tex), which allows easy removal from the finished woven structure during the erection process (Figure 9). Each weft insertion from the filling yarn bobbin is performed as a loop in the appropriate shed. Thereby, the entire filling yarn can be removed by a single pull when the T-structure is erected. The filling yarn is exclusively inserted in Section B. These filling yarns interlace the floating warp yarns of the sub tube in a plain weave pattern. The corresponding weft yarn in the sub tube is located underneath the warp and filling yarns of the respective layer as a weft float.

This additional weft insertion (filling yarn) in Section B requires an extension of the weft repeat of the weave sections placed horizontally next to it. Section D is created, matching exactly the weave pattern in Section A, and only factoring in the filling yarn as a float over the structure. Analogously, the weave pattern in Section E matches the weave pattern in Section C. By automating the pulling process of the floating yarns, the insertion of filling yarns is unnecessary.

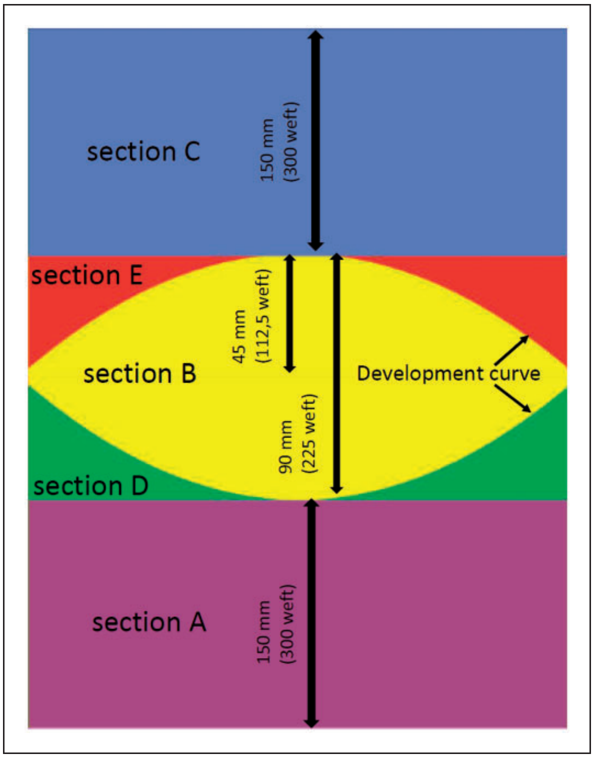


Figure 7. Flattened schematic, weaving pattern diagrams and weft sequences of the T-structure. (Color online only.)

These sections are easily visualized with a layer cross-section. They are shown in Figure 8 to the right of flattened schematic for the respective sections.

The resulting development curves correspond to the encounter lines between the main and sub tube in the T-structure's flattened state. The required number of weft threads (weft repeat) for the yellow area between

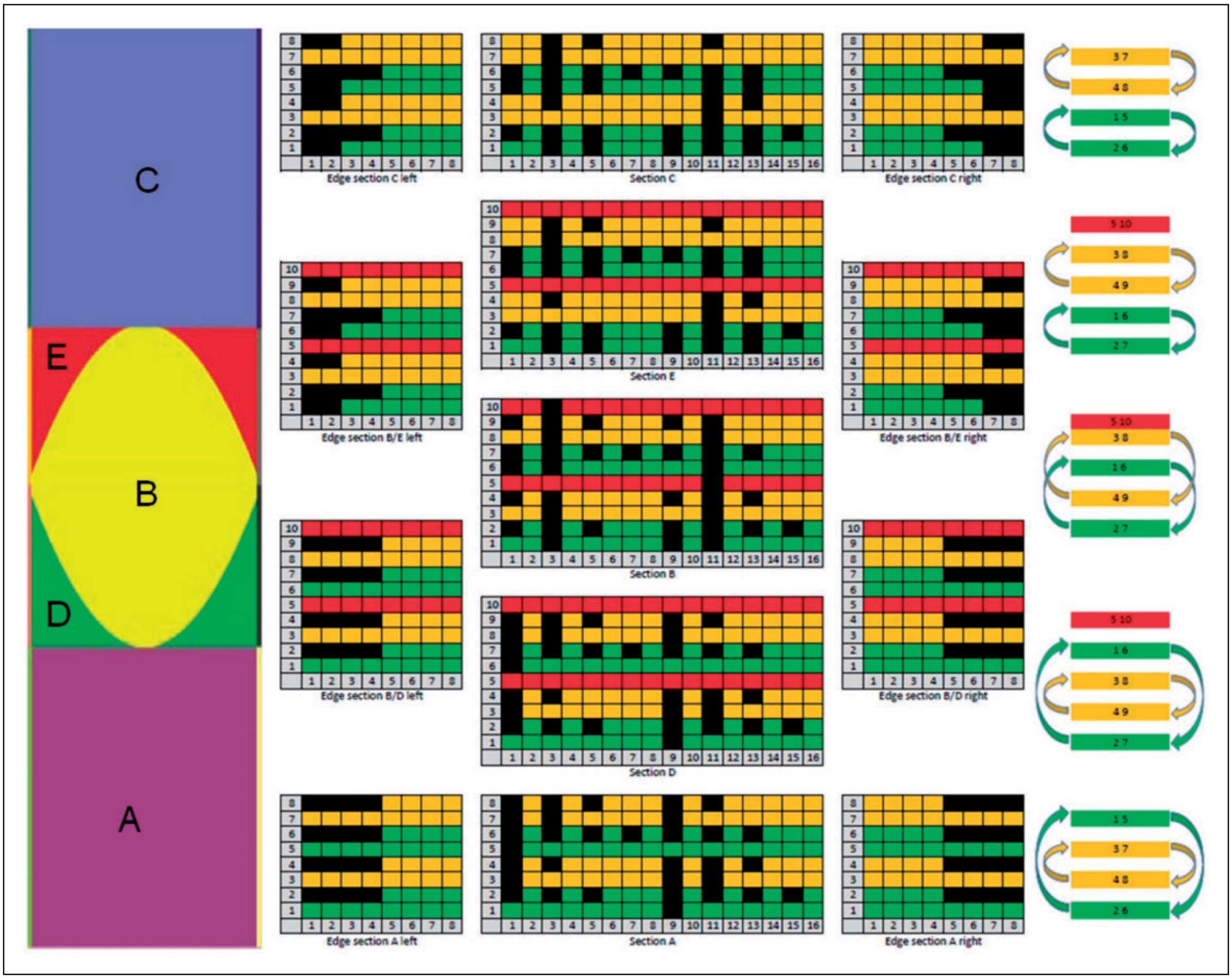


Figure 8. Flattened schematic of the T-structure.

development curves in the flattened schematic of Figure 5 results from the following:

$$\mathit{Weft\ repeat} = \frac{\text{diameter of tube in mm} \times \text{number of layers}}{\text{length deduction per weft in mm}}$$

- the diameter of the tube: 90 mm;
- number of weft yarn layers in the respective area: five (two layers per tube + one layer filling yarns);
- weft yarn density: five wefts per centimeter, which results in 2 mm deduction per weft row.

Adding these numbers results in the required number of weft threads for the yellow area:

$$\frac{90\ \text{mm} \times 5\ \text{layers}}{2\ \text{mm}} = 225\ \text{weft insertions} \qquad (1)$$

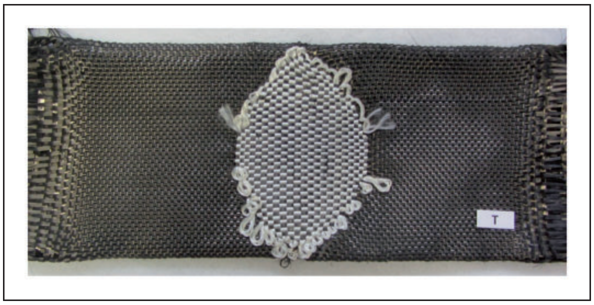


Figure 9. Woven T-structure before erecting (the white yarns are filling yarns).

Sections A and C have a length of 150 mm, and four fabric layers each, as the filling yarns are omitted. This corresponds to

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

All measurements based on above-mentioned calculations and an overview of the individual weave sections are given in Figure 7. To realize the functional model, a carbon filament yarn of 800 tex fineness as warp (warp density: 16 yarns/cm/4 layers) and weft (weft density: 20 yarns/cm/4 layers) yarn is used.

The geometry of the T-structure is realized by the development curves and the resulting flattened schematic (Figure 8, left-hand picture). The arrangement of the layers results from the warp cross-sections and the resulting weave pattern diagrams. Considering the affiliation of the warp yarns and weft bobbins to their respective tube, the layers can be re-arranged completely, if necessary. Thus, the transition from Section D to Section B is created by re-arranging the top layers of the main tube and sub tube. This lifts the top layer of the sub tube from the main tube. As the transition is not horizontal but along the development curve taken from the spreadsheet in Figure 5, the green cutting edge from Figure 4(b) is executed precisely. The floating of the top layer of the sub tube allows a shortening of this layer in Section B. The T-structure realized geometric fidelity, and the pulled warp yarns form a clean warp yarn course in the shortened top layer of the sub tube.

The rear edge between the main tube and sub tube is also created by a geometric fidelity layer change of the top layer of the main tube with the bottom layer of the sub tube at the transition area from Section B to Section E. This layer change lifts the sub tube out of the main tube, and both tubes are cleanly located on top of each other in Section C.

The individual weave pattern diagrams are assembled in the center of Figure 8. Their colored background denotes their affiliation with a weft bobbin. For example, wefts 1, 2, 5 and 6 in Section A of the weave pattern are highlighted in green, as these wefts are inserted into the main tube with the weft bobbin marked green. In the right-hand side, the order and position of the weft insertions into the respective tube are compiled schematically. The red bar set at a distance to the top layer represents a floated filling yarn insertion, while the bar without distance represents the insertion of a filling yarn into the top layer.

After realization of the weave pattern diagram for each section, the complete weave pattern for the T-structure was prepared 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. Figure 9 shows the woven T-structure before erecting.

Figure 10 shows the finished woven T-Structure. Comparing the woven structure with its computer-aided design (CAD) model (Figure 2) shows the feasibility of this method; it is of high quality, especially in the node area between the main tube and sub tube, and it has excellent three dimensionality. With the above-mentioned method, different nodal structures can be produced. Figure 11(a) shows the warp threads course within the X-structure and Figure 11(b) shows the finished woven X-structure. The entire X-structure is created analogously to the T-structure. The main tube and sub tube 1 form the T-structure described above, whereas the main tube and sub tube 2 are combined into a variation of the T-structure that faces downward and is worked back to front.

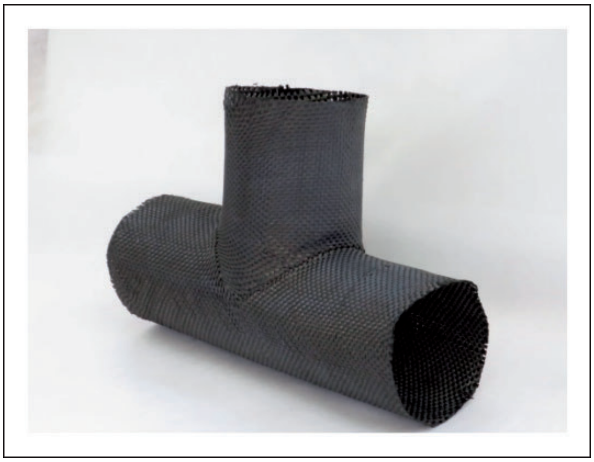


Figure 10. Finished woven T-structure.

Conclusion and outlook

This work was concerned with the development of weave design and exploration of technological solutions for the production of woven node element structures from carbon filament yarns, exemplified by T- and X-node elements. At the core of development was the textile-technical realization of versatile component configurations and requirement-adapted, fluent connection points of the seamless tubes. This is based on the narrow shuttle weaving technology and its inherent high potential for productive, economic and reproducible production of narrow, tubular fabrics. Strategically, the development embodies an enormous contribution to lightweight construction and to the conservation of resources, especially of energy.

The development of the woven concept for the realization of node element structures was based on the fragmentation and development of the individual sub-elements, as the structure can only be produced on the narrow shuttle weaving loom when laid flat. By fragmenting the tubes, a main tube was identified. This tube had a straight and continuous construction in the node element structure, and further tubes branched off from it.

The developed concept in this paper can be used to produce a nodal structure with branched tubes oriented in different planes (spatial nodal structures). Furthermore, the V- or Y-shaped weaving reeds and the laterally mobile hooks of the Jacquard machine

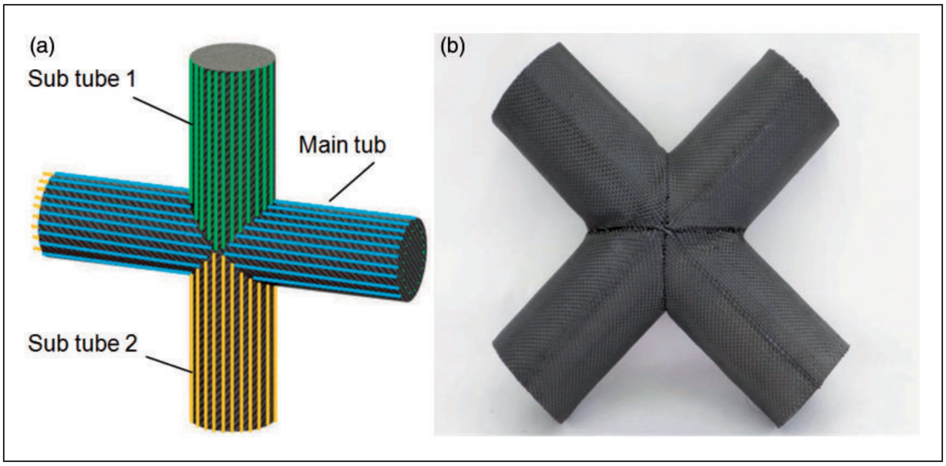


Figure 11. (a) Warp threads course within the X-structure; b) completed X-structure.

offer the possibility to extend the configuration versatility of the woven node element structures. These reeds offer possibilities to vary the diameter of the tubes by varying warp density. These machine modifications are necessary to attain the diverse geometry of the nodal element structures for lightweight construction applications. The developed concept presented in this paper can be used for producing complex woven structures on the broad weaving loom. 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 17591 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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