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Erstveröffentlichung in / First published in:

Textile Research Journal. 2018, 88(2), S. 213 – 224 [Zugriff am: 07.08.2019]. SAGE journals.
ISSN 1746-7748.

DOI: <https://doi.org/10.1177/0040517516677231>

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Geometrical design and forming analysis of three-dimensional woven node structures

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Textile Research Journal
2018, Vol. 88(2) 213–224
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DOI: 10.1177/0040517516677231
journals.sagepub.com/home/trj

Abstract

Structural frames have been established in many technical applications and typically consist of interconnected profiles. The profiles are commonly joined with node elements. For lightweight structures, the use of composite node elements is expedient. Due to the anisotropic mechanical properties of the fibers, high demands are placed on the orientation of the fibers in the textile reinforcement structure. A continuous fiber course around the circumference and at the junctions is necessary for an excellent force transmission. A special binding and forming process was developed based on the weaving technology. It allows the production of near-net-shaped node elements with branches in any spatial direction, which meet the requirements of load-adjusted fiber orientation. The principles by which these three-dimensional (3D) node elements are converted into a suitable geometry for weaving as a net shape multilayer fabric are reported. The intersections of the branches are described mathematically and flattened to a plane. This is the basis for the weave pattern development. Forming simulations on the macro- and meso-scales complement the analyses. A macro-scale model based on the finite element method (FEM) is used to verify the general formability and the accuracy of the flattenings. Since yarns are pulled through the textile structure in the novel forming process, the required tensile forces and the pulling lengths of the individual yarns are analyzed with a meso-scale FEM model. The flattening for two different node structures is realized successfully, and the simulation proves formability. Furthermore, the necessary forming forces are determined. Finally, the developed method for flattening the 3D geometry is suitable for the design of a variety of spatial node structures and the simulation supports the design of automated forming processes.

Keywords

spatial node structures, weaving, intersections, flattening, finite element simulation

Textile reinforcement structures in lightweight applications are of practical relevance in a number of sectors. They are established in technical applications and industries, such as aerospace, automotive, construction and sports. Structural frames are used in many applications,¹ for example, in car body constructions. These frameworks consist of profiles that are joined with node elements. The consistent implementation of lightweight design creates a demand for composite profiles and, thus, node elements made of fiber-reinforced composites. For profiles made of composites, a variety of production techniques are available, among them pultrusion and braiding. However, the manufacturing of load-adjusted node elements is still insufficiently studied. Due to the anisotropy of the fibers, such node elements place

a high demand on the textile reinforcement structure. Moreover, a continuous fiber course around the circumference and at the junctions is necessary for force transmission.

Braiding technology is a promising way to produce such three-dimensional (3D) node elements.

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Braided structures are characterized by their great variety of possible shapes. Nevertheless, a flexible production of complex 3D geometries has not been established so far due to the high investment and preparation costs (e.g. core production).² An alternative approach for the manufacturing of 3D structures is presented by weaving technology.^{3–5} Various methods have been developed for producing 3D woven node structures.^{6–8} However, the requirements of a load-adjusted design were not fully achieved. Zheng et al.⁶ presented a method for the design and manufacturing of integrated 3D woven T-nodes. The presented node elements do not fully reproduce the required geometry, and the reinforcement fibers are not oriented continuously around the circumference of the circular tubes. The company Sigmatex Ltd presented a 3D woven node element based on stitched multilayer woven structures with integrated pockets.⁸

A new approach to produce seamless woven node structures for integral constructions was introduced by Fazeli et al.⁹ The presented T-node elements meet the requirements of continuous fibers around the circumference and at the junctions. In this method, the node structures are woven flat in several layers and, afterwards, selected yarns are pulled through the structure to form the 3D shape. Furthermore, it becomes possible to manufacture nodes with branches in any spatial direction. The basis is a flattening of the 3D node geometry in order for it to be woven as a net-shaped multilayer fabric.⁹ Thus, the aim of the current paper is to develop principles by which 3D node elements are converted into a flat geometry that is suitable for weaving. The intersections of the single branches of the 3D connector element are of special interest.

ElMaraghy et al.¹⁰ and Stockie¹¹ fundamentally described how the intersection of cylinders, in this case the intersection of the branches, is calculated. For the description of spatial node elements, the intersection of cylinders that are randomly oriented to each other must be calculated and subsequently flattened on a plane. This is the basis for the subsequent development of the weave pattern.

Other objectives of this paper include the development of models for the forming of the 3D elements based on the finite element method (FEM), and the analysis of the forming process itself. Models on the macro-^{12,13} and meso-scales^{14,15} for the description of woven structures are readily available. Forming and draping simulations are generally used for the determination of the fiber orientation, structural deformations and shear analysis of technical textiles.^{16–21} With the macro-scale simulation, the general formability and the accuracy of the flattening are checked. Since for the forming of the node elements' individual yarns are pulled through the structure, the application of

a meso-scale approach will become necessary for the analysis of the yarn forces. Experimental studies on the yarn pull-out were described by Dong and Sun²² and Bilisik.²³ However, during forming of the node elements the yarns are not pulled out, but pulled through the textile structure. The description of this process becomes possible with the novel simulation models. The tensile forces applied on the individual yarns and the pulling length necessary to form the 3D node geometries can then be determined with the simulation model.

Material and methods

Material

It is possible to manufacture the 3D woven structures on a conventional weaving machine for two-dimensional (2D) fabrics.²⁴ The node elements discussed in this paper are produced on a modern narrow shuttle loom supplied by Mageba Textilmaschinen GmbH & Co. KG (Bernkastel-Kues, Germany). Node elements were realized with carbon filament yarn HTS40 (12K, 800 tex) from Toho Tenax Europe (Wuppertal, Germany). The fiber properties as specified by the manufacturer are summarized in Table 1. The warp density was 16 yarns/cm and the weft density was 20 yarns/cm for a four-layered fabric, as used in the T-node element.

Method of weaving and flattening 3D node structures

For weaving seamless spatial node structures on a conventional shuttle 2D weaving machine, it is necessary to flatten the 3D geometry, which is then woven as a multilayer fabric (e.g. tubular). Figure 1 shows the procedure of the flattening using the example of a T-node. For the T-node geometry, one branch is folded onto the other and one part of the intersection (orange line) is cut. The individual branches are then woven as tubes into and above one another, respectively. Since the weft yarns run circumferentially from the top to the bottom layer, high hoop strength of the branches is achieved. Algorithms for calculating the cutting line and flattened geometries are presented in the *Algorithms of the calculation of the intersection and the flattening section*.

Table 1. Fiber properties

Linear density (tex)	Grade	Tensile modulus (GPa)	Tensile strength ^a (MPa)	Elongation at break ^a (%)
800	12K	239	4620	1.8

^aBased on DIN 29965.

Figure 1. Procedure of flattening a T-node geometry. (Color online only.).

Figure 2. Flattening and weave pattern for a T-node: (a) schematic flattening and weave architecture; (b) woven structure with filling yarns (white).

In order to achieve the highest possible mechanical properties, a continuous fiber course between the branches is required. Thus, it is necessary to close the gap between the cut lines (orange lines in Figure 1) while forming the 3D structure. Therefore, the weave pattern in this area is adjusted to ensure that only warp yarns are inserted as floating yarns (and, if necessary, temporary filling yarns) and no weft yarns are inserted. By pulling the warp yarns in one branch through the structure, the gap is closed and the 3D geometry is formed. In this way, a 3D element with continuous fibers is produced.

A major challenge is the development of the weave patterns for the different zones, which is described in detail elsewhere.⁹ The flattening and a scheme of the corresponding weave patterns of a T-node are shown in Figure 2(a). The complex weave patterns are generated using the software DesignScope Victor by EAT GmbH (Krefeld, Germany). Figure 2(b) shows the planar woven structure with an integrated filler yarn. The filler yarn stabilizes the fabric during the weaving

process and is removed before formation of the 3D geometry. If an odd number of branches exist in the node element there is at least one branch with two layers of the tubular fabric, since the number of layers is constant while weaving the multilayer tube. To achieve the most accurate geometry and minimize structural deformations while forming, the accurate design and calculation of the flattening, especially the flattened intersection line, is particularly important.

Algorithms for the calculation of the intersection and the flattening

To achieve high geometry diversity, a parameterized calculation of the flattening is required. The calculation is based on the intersection of two cylinders. The problem is illustrated in Figure 3. In a Cartesian coordinate system (x,y,z) the first cylinder C_1 is orientated along the z -axis and the second cylinder C_2 is rotated around the y -axis by angle α , and the x -axis by angle β (cf. Figure 3).

In order to calculate the intersections $I_{1/2}$, the cylinder equations are equalized and the resulting system of equations is solved. If the cylinders penetrate completely, two equations exist for the intersection (cf. the Appendix). Figure 4 exemplarily shows the intersections of the cylinders with $R_1 = R_2 = 50$ mm and $0.9 \cdot R_1 = R_2 = 45$ mm.

The next step is the calculation of the flattening $F_{1/2}$ of the intersection on the xz -plane, for which the z -coordinate remains the same ($z_F = z_{I1/2}$) and the x -coordinate is flattened on the plane. The flattened x -coordinate, x_F , is calculated from the arc length of a circle on C_1 and the intersection line. The equation for the flattening $F_{1/2}$ is

$$F_{1/2} = \begin{pmatrix} x_F \\ z_F \end{pmatrix} = \begin{pmatrix} -R_1 \cos^{-1}\left(\frac{x_{I1/2}}{R_1}\right) + \frac{R_1 \pi}{2} \\ z_{I1/2} \end{pmatrix} \quad (1)$$

Figure 3. Differently orientated cylinders ($R_1 = R_2$, $\alpha = 115^\circ$, $\beta = 25^\circ$).

Figure 5 exemplarily shows the intersection I_1 and the flattening F_1 of two cylinders. The other required dimensions for the flattened cylinders result from the circumference and the length of the cylinders.

Macro-scale model for the simulation of the forming process

To proof the formability and the deformation of the fabric, FEM simulations of the forming process are performed. Starting from the 2D structure, the forming into the final 3D node structure was simulated using LS-DYNA®. For the simulation, a shell-element-based continuum model with a suitable hyperelastic material model with an uncoupled stress update for woven fabrics previously presented^{12–14} was used. The following material parameters of the woven fabric are required for the macro-scale model: tensile, in-plane shear and bending behavior. Those material characteristics were determined with well-established textile testing technologies based on a reference fabric, as reported in the *Material testing* section. Since forming simulations were performed with a macro-scale model, the yarn structure of the weave was not accounted for. Thus, pulling of the warp yarns through the structure is not considered. However, the boundary conditions are chosen so that the gap of the cut intersection is closed while forming. Therefore, the displacement u of the related nodes n_i and n_j is constrained as

$$\begin{aligned} u_{x,n_i} - u_{x,n_j} &= 0; & u_{y,n_i} - u_{y,n_j} &= 0; & u_{z,n_i} &= 0; \\ u_{z,n_j} &= -z_{n_i} - z_{n_j} \end{aligned} \quad (2)$$

Here, it is assumed that the yarns slide through the structure and cause no deformation of the fabric.

Figure 4. Intersections of cylinders with different radii: (a) $R_1 = R_2$, $\alpha = 115^\circ$, $\beta = 25^\circ$; (b) $0.9 \cdot R_1 = R_2$, $\alpha = 115^\circ$, $\beta = 25^\circ$.

Figure 5. Flattening F_1 of intersection I_1 of cylinders with different radii: (a) $R_1 = R_2$, $\alpha = 115^\circ$, $\beta = 25^\circ$; (b) $0.9 \cdot R_1 = R_2$, $\alpha = 115^\circ$, $\beta = 25^\circ$.

$u_{z,yj}$ corresponds to the length that the yarn must be pulled and depends on the x -position of the yarn. Due to the geometry, each yarn is pulled with another length.

Meso-scale model for the analysis of yarn pulling

The pulling of the yarns through the textile structure leads to effects that are essential for the forming process. The gap between the branches is closed and a continuous course of the fibers is achieved. The macro-scale simulation model described above cannot represent yarn pulling. However, the pulling length and the force for the individual yarns are of special interest. The pulling length must be extended by l_{add} , which is the stretching of the yarn crimp while forming. These effects were analyzed with a meso-scale simulation model, in which the individual yarns of the textile structure were modeled.^{14,15} The yarns were modeled with shell elements in the LS-DYNA software. For a realistic representation of the yarn geometry and to avoid penetrations of the yarns, the shell thickness was adapted over the yarn cross-section.¹⁴

A previously presented approach for modeling fabrics on the macro-scale¹² was adapted to model the yarns in the meso-scale approach. To this end, the transverse isotropic mechanical behavior of the yarns was described with an orthotropic elastic material model in combination with the shell-element approach in a sufficient way. Furthermore, the low bending stiffness of the yarns was taken into account by the use of layered shell elements with adjusted material properties of the single layers.

For the simulation of yarn pulling, the necessary boundary conditions of the macro model were transferred to the meso model. Thus, it was possible to determine the necessary tensile forces for the forming of the 3D node element structure. Furthermore, the structural deformation was analyzed. In this case no shearing of

the structure occurred, but the warp yarns were stretched due to the pulling. The length by which individual warp yarns are stretched is necessary for an accurate forming. This additional length must be added to the length determined according to equation (1).

Material testing

The required input data for the macro-scale simulation model was determined with reference fabrics consisting of one layer of the multilayer fabric. The mechanical properties were determined according to the applicable standards.

The non-linear stress-strain behavior under tension was determined in the standardized tensile test according to DIN EN ISO 13934-1.²⁵ The tests were performed with a specimen size of 50 mm × 200 mm and a speed of 20 mm/min.

For testing the shear behavior, the picture frame test was used.²⁶ The textile specimen (300 mm × 300 mm, sheared area: 200 mm × 200 mm) was fixed onto the frame with needles, which allows rotation of the fabric. Thus, the influences of tensile forces due to clamping were significantly reduced.

The bending behavior of the fabric was tested with the cantilever bending test according to DIN 53362.²⁷ The test was performed with an automated cantilever testing device ACPM 200 supplied by Cetex GmbH (Chemnitz, Germany). The specimen size was 25 mm × 250 mm and the testing speed was set to 120 mm/min.

Furthermore, the properties of the reinforcing yarns and their tensile behavior were determined according to ISO 3341:2000.²⁸ The coefficient of friction between the yarns was determined by the inclined plane method.²⁹ A testing device according to Bobeth et al.²⁹ was built. Two yarns were clamped horizontally in parallel and a third yarn was placed in a bracket on top. Then, the angle of the parallel yarns to the horizontal was

increased slowly. As soon as the upper yarn slipped, the friction coefficient was calculated from the associated angle.

To experimentally analyze the behavior of the yarn while it is pulled out of and through the fabric, respectively, yarn pull-out tests were performed. The tests were performed in the warp direction of the fabric with a specimen size of 50 mm × 140 mm. The total pull-out displacement was 150 mm and the pull-out velocity was 50 mm/min. Figure 6(a) shows the experimental set-up of the test and Figure 6(b) presents a typical force–displacement curve. Initially, the pull-out force increases as a result of the static friction and the crimp extension of the yarn. After the force reaches a maximum it decreases with slip and stick effects^{30,31} when the warp yarn crosses the weft yarns.

Results and discussion

Flattening of node elements for the weave pattern design

Flattenings for a variety of node elements can be realized with the formulated equations, wherein the radii and the orientation of the branches can vary from each other. It is advantageous if a plane of symmetry exists in the node element as reference for the flattening. Figure 7 shows various sample node elements and the corresponding flattenings. As can be seen in Figure 7(b) for an angular T-node, the flattening is non-symmetric. By combining and adapting the boundary conditions of the intersections I_1 and I_2 , spatial corner node elements can also be realized. For the LI-node (Figure 7(c)), segments of I_1 ($\theta \in [0.75\pi, 1.5\pi]$) and I_2 ($\theta \in [0.5\pi, 0.75\pi]$) are combined and shifted by R_2 in the

z -direction. To get the flattening curve for the other two cylinders, the one from the first must be reflected around the x -axis (cf. Figure 7).

Those calculated flattenings are the groundwork for the design of the weave patterns as shown by Fazeli et al.⁹ Therefore, the flattenings were converted into a graphic and imported into DesignScope software, which was used for weave pattern development. An adjustment of the profile cross-sections is also possible. For an elliptical cross-section, only the cylinder equations have to be adapted. The subsequent procedure corresponds to the one shown for circular cylinders.

Forming and simulation of the node elements

With the forming simulation, the forming process and all necessary boundary conditions, such as fixing zones and the pulling length of the single yarns, can be analyzed and proven. Figure 8 shows the results of the forming simulation on the macro level for the T- and LI-nodes. For both structures it can be seen that only low shearing and, thus, a low in-plane structural deformation occurs. The largest deformation was found in the transition areas between the branches. On the branches themselves, almost no shearing of the fabric was detected.

The pulling length for each floating yarn depends on its x -position and can approximately be calculated based on equation (1) for the T-node with $R_1 = R_2 = 50$ mm by

$$u_{z,nf} = 2 \cdot \left(-8.3 \cdot 10^{-3} \cdot x_{\text{yarn}}^2 + 5 \cdot 10^{-15} \cdot x_{\text{yarn}} + 48.9 \right) + l_{\text{add}} \quad (3)$$

Figure 6. Yarn pull-out test: (a) experimental set-up; (b) typical pull-out force displacement curve.

Figure 7. Flattening for different node elements: (a) T-node, $\alpha = 0^\circ$; $\beta = 90^\circ$, I_1 ; $0 \leq \theta \leq 2\pi$; (b) T-node angular, $\alpha = 0^\circ$; $\beta = 65^\circ$, I_1 ; $0 \leq \theta \leq 2\pi$; (c) LI-node, $\alpha = 90^\circ$; $\beta = 45^\circ$, I_1 ; $0.75 \pi \leq \theta \leq 1.5 \pi$, I_2 ; $0.5 \pi \leq \theta \leq 0.75 \pi$.

Figure 8. Results of forming simulation, forming from initial flat to three-dimensional geometry, shearing of the fabrics: (a) T-node element; (b) LI-node element.

and for the LI-node with $R_1 = R_2 = R_3 = 50$ mm by

$$u_{z,nj} = 2 \cdot (2 \cdot 10^{-7} \cdot x^4 - 4 \cdot 10^{-5} \cdot x^3 - 7 \cdot 10^{-3} \cdot x^2 + 0.7 \cdot x + 70.7) + l_{\text{add}} \quad (4)$$

Here l_{add} is the additional pulling length of the yarns that is caused by the yarn crimp within the fabric. It depends on the structure of the fabric and the length the yarn must be pulled through the fabric. In the macro-scale simulation l_{add} is not taken into

account ($l_{\text{add}} = 0$). For the real forming process, however, l_{add} is crucial to close the gap between the branches completely. This additional length was determined with the meso-scale simulation model, since it represents the single yarns in the fabric.

Pulling of the yarns through the textile structure

To evaluate the quality of the meso-scale modeling approach, the yarn pull-out test was simulated in the first step. This achieved a good correlation of the maximum tensile force and the following force characteristic between the experiment and simulation. The slip-stick effect is more pronounced in the simulation results, but an estimation of the force is still possible. Since the yarns are pulled through the structure while forming the node element, the force characteristic for this case was determined. The results for a specimen length of 140 mm are summarized in Figure 9.

While pulling out the yarns, the pull-out force decreases with increasing pull-out length. This is due to a reduced length of the residual yarn in the structure and, thus, a decreased effective friction surface. However, while pulling the yarn through the structure, the force remains nearly constant at a higher level because the effective friction surface is constant. The transition from static friction and yarn crimp stretching to the slick and slide behavior is clearly recognizable in Figure 9. The force required for pulling the yarns through the structure depends on the traversed length and is, thus, different for each yarn. For the T-node element the yarns in the center must be pulled further and faster than yarns at the edges, but the traversed

Figure 9. Pull-out/pull-through forces by experiment and simulation (specimen length 140 mm).

Figure 10. Pulling length of the individual yarns (every fourth yarn; T-node, branch length 150 mm).

Figure 11. Pulling forces of the individual yarns (every fourth yarn shown; T-node with branch length of 150 mm).

Figure 12. Final woven node structures: (a) T-node element; (b) LI-node element.

length is smaller in comparison to the yarns at the edges. Figure 10 shows the pulling length for every fourth yarn necessary to form the T-node element with a branch length of 150 mm. The total length results from equation (1) and the stretching of the yarn crimp.

Different yarn pulling lengths across the fabric width required to form the node elements mean that different tensile forces are required for each yarn. The forces for forming the T-node were identified by finite element simulation and are shown for selected yarns in Figure 11. As can be seen, the force for the yarns

at the edges is higher than for the yarns in the center of the structure. The yarns in the center must be pulled further, but the structural integrity is inferior in terms of length they are integrated into in the weave structure. This results in lower forces. Yarns with identical pulling force are crossing the same number of weft yarns, due to the weft density of the fabric.

The pull-through process, especially the pull-through distance, determines the length of the tubes. During the forming, it has to be ensured that only minor or no structural deformations occur and that

the weft yarns remain in their position. Furthermore, fiber damage due to friction may occur with long pull-through distances. Fazeli et al.⁹ presented the weaving technology for producing 3D woven node structures. The final woven and formed T- and LI-node elements are shown in Figure 12. An excellent correlation with the target geometry was obtained. These structures also demonstrate the very good suitability of the shown method for the production of spatial node elements. The produced structures satisfactorily fulfill the high requirements placed on fiber-reinforced node structures.

Conclusions

The presented method enables the production of 3D woven node elements with branches in all spatial directions with different angles and radii on the basis of the narrow shuttle loom weaving technology. Using the shuttle loom and the integration and pulling of floating yarns ensures continuous fibers around the circumference and at the transition of the branches. Thus, weak spots of the node structure are minimized. For even better mechanical properties more layers can be woven in the branches with an adjustment of the weave pattern. Furthermore, great geometry diversity is possible, for example, by adjusting the cross-sections of the branches. The near-net-shaped weaving reduces both the consumption of material and the number of manufacturing steps in composite manufacturing processes.

The developed algorithms for calculation of the intersections and the flattenings are the basis for the weave pattern development and the forming process design. It is possible to calculate weave geometries for any direction and number of spatial branches. With a little adjustment, other cross-sections, for example, elliptical, are also possible. Furthermore, the length the individual floating yarns are pulled through the textile structure to realize a 3D woven node element can be determined.

The forming simulation on the macro-scale uncovers problems of the flattenings at an early stage of the development process and various forming concepts can be tested virtually in order to enable an automated forming of the node elements. Forming simulation results show that almost no in-plane structural deformations, such as shearing, occur. Thus, the final fiber orientation is controllable.

The meso-scale analysis of the required fiber pulling provides further information on the effective pulling length and the necessary forces for the forming of the node element based on the geometric data and the

weave pattern. Finally, the practical realization of woven node element structures was proven.

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 supported 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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Appendix

Equation cylinder C_1 :

$$C_1 = \begin{pmatrix} x_{C1} \\ y_{C1} \\ z_{C1} \end{pmatrix} = \begin{pmatrix} R_1 \cos(\theta_1) \\ R_1 \sin(\theta_1) \\ v_1 \end{pmatrix} \quad (\theta_1 \in [0, 2\pi], v_1 \neq 0)$$

where R_1 is the radius of cylinder C_1 , θ_1 is the angle parameter and v_1 is the length of the cylinder.

Equation cylinder C_2 :

$$C_2 = \begin{pmatrix} x_{C2} \\ y_{C2} \\ z_{C2} \end{pmatrix} = (R_y R_x) \begin{pmatrix} R_2 \cos(\theta_2) \\ R_2 \sin(\theta_2) \\ v_2 \end{pmatrix} \quad (\theta_2 \in [0, 2\pi], v_2 \neq 0)$$

$$C_2 = \begin{pmatrix} R_2(\cos(\theta_2)\cos(\alpha) + \sin(\alpha)\sin(\beta)\sin(\theta_2)) + \sin(\alpha)\cos(\beta)v_2 \\ R_2\sin(\theta_2)\cos(\beta) - \sin(\beta)v_2 \\ R_2(-\cos(\theta_2)\sin(\alpha) + \cos(\alpha)\sin(\beta)\sin(\theta_2)) + \cos(\alpha)\cos(\beta)v_2 \end{pmatrix}$$

where R_2 is the radius of cylinder C_2 , θ_2 is the angle parameter, v_1 is the length of the cylinder, α is the rotation angle around the y -axis and β is the rotation angle around the x -axis.

Full equation for the intersection:

$$I(\theta) = \begin{pmatrix} x_i \\ y_i \\ z_i \end{pmatrix}$$

$$x_i = R_1 \sqrt{\frac{\{R_1 - R_2 \sin(\theta) \cos(\beta) + \sin(\beta) v\} (R_1 + R_2 \sin(\theta) \cos(\beta) - \sin(\beta) v)}{R_1^2}}$$

$$y_i = R_2 \sin(\theta) \cos(\beta) - \sin(\beta) v$$

$$z_i = R_2 (-\cos(\theta) \sin(\alpha) + \cos(\alpha) \sin(\beta) \sin(\theta)) + \cos(\alpha) \cos(\beta) v$$

where

$$v = \left(\sqrt{\frac{\left\{ -(\sin(\alpha) \sin(\theta) (\sin(\alpha) (\sin(\beta)^2 (\sin(\beta)^2 + 2 \cos(\beta)^2) + \cos(\beta)^4) \sin(\theta) + 2 \cos(\alpha) \sin(\beta) \cos(\theta)) \right. \right.}{\left. \left. + \cos(\alpha)^2 \sin(\beta)^2 \cos(\theta)^2 \right) R_2^2 + (\sin(\beta)^2 + \sin(\alpha)^2 \cos(\beta)^2) R_1^2 \right.}} \right. \\ \left. + \cos(\beta) ((1 - \sin(\alpha)^2) \sin(\beta) \sin(\theta) - \cos(\alpha) \sin(\alpha) \cos(\theta)) R_2 / (\sin(\beta)^2 + \sin(\alpha)^2 \cos(\beta)^2) \right)$$