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Proposing a virtual simulation method to predict the shape-fidelity of 3D-knitted-textiles using knit-meshes and geometric invariants

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Abstract. Though the level of machine digitization in flatbed-knitting (FBK) today is high, the design and development of knittable data sets are still currently very time-consuming, digital simulations methods are calculation expensive and insufficient in terms of accuracy of fit and technical properties. Knitting process retrofitting activities are executed mostly manually by an operator on the basis of the operator´s experience. This circumstance makes it more difficult to use the diverse potential for flexibility and on-demand purposes in future-networked-production for lightweight constructions for Automotive, Aerospace and aviation or Medical-Products. New easy-to-learn, intuitive, calculation inexpensive digital augmented workflows for the planning of knitted objects with complex 3D-shapes are needed. With regard to the requirements of composite forming, the aspects of wrinkling, slip and permeability are of particular importance. However, flatbed-knitted fabrics are subject to different requirements in some cases, which implies different questions from those posed by research in the area woven textile composites. In order to address a few of the questions raised by previous research on textile composites, this paper covers some of the current research topics in the field of 3D-knitted flatbed-knitting fabrics and shows references as well as potentials to already researched problem fields of textile reinforced composites. In doing so, the author strongly refers to the topics of the summarizing publication "Advances in composite forming through 25 years of ESAFORM" by P. Boisse et al. [1].

Introduction

To give a first impression of the current possibilities and concepts in the development of three-dimensional shaped flatbed-knitted textiles, a brief summary of current geometry-based approaches follows. The approaches presented currently show their greatest potential at the level of purely plastic-shape reproduction. Special consideration of material parameters to extend the product properties of the planned object are given little attention here. However, the presented methods could be suitable to derive FEM-calculable models on macro-scale level. A standardization towards certain restricted geometric variables is emerging. Most noticeable is the representation of a knittable geometry in quad and partial triangle meshes (Fig. 1).

The formation of these types is described in the following. Furthermore, technical knitted fabrics with different property zones in particular are currently a major focus of the author's work. The mutually influencing material and stitch properties generally lead to results that are difficult to predict in the initial development stages. In the field of today's "craft / non-simulation-based" planning and individualization of 3D-knitted-technical-textiles, these property zones play a major role. On the one hand, mesh ratios are used to influence the plastic-shape and, on the other hand, to design zones with references to external forces. Different mesh-loop ratios often result from technical knitting/binding variations for loop formation. These are also not considered in depth here. In Yordan Kyosev's publication from 2019 entitled "Topology-Based Modelling of Textile Structures and Their Joint Assemblies", these are considered in more detail. Specifically, starting on page 100 of the aforementioned publication, the framework for FEM calibrations at the meso-scale level is described.

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Depending on the yarn properties at the micro-scale level, for example, the stitch height in combination with the pre-tensioning by yarn feeders has an influence on the strength of the knitted fabric under pressure and tension on macro-scale or product-scale level. The product scale level can be seen as the sum of all parameters acting on the entire textile-product. In order to be able to represent property changes at this level, additional geometry-based calculation models are required in addition to all the other levels mentioned above. Therefore, at the end of this paper, the author presents a new approach with reference to the mentioned influences of the stitch ratio on product-scale level.

In addition to the basic principles introduced below for the development of geometric standards, the author considers the field of research (varying ratios) to be one of high priority for technical design using digital simulations.

As illustrated, different stitch ratios have a major influence on the technical properties, shape contours and surface finish of 3D knitted technical textiles. The basic technical possibilities for influencing shape and thus important design criteria for three-dimensional technical textiles are, in addition to the stitch ratios: Darts and Notches, short- and Long-Rows with decreases and increases. In all these areas, elastic yarns and yarns with different properties can have a strong influence on the prospective shape. Knitted fabrics also have a highly indiscreet structure. This reality assumption makes it difficult to calculate distortions or other plastic and material property changes using FEM methods. Taken together, this forms a complex set of requirements for future tools for digital simulation, especially with regard to industrial use.

FEM-Simulations

Y. Kyosev sums up this challenge in textile technology in general as follows: during the modelling with FEM, the real system (…) has to be idealized first in order to achieve a somewhat simplified physical system. This first step is the building of the physical model, where certain assumptions have to be made [2].

To address the problem of abstracting real complexity in the field of flatbed-knitting, the author proposes the reduction of complexity in the form using of discrete Knit-Meshes. These digital Knit-Meshes in the form of stitch-ratio-proportion quad-meshes and partly triangulated quads can be used for dynamic-FEM calculation. Similar to the digital simulation of woven surfaces, the properties on the three levels: micro-, meso-, and macro-scale level give important parameters for the calculation. For the calculation method proposed in the paper, the author follows Y. Kyosev's statement: "The macro scale is the most important for the applications. It deals with the mechanical behaviour of the structure as a continuum membrane or plate with known properties" [ibid.]. Furthermore, Kyosev describes that there are several methods to obtain the properties at the macro-scale level, which are mostly derived on the specifications of the meso-scale. Most often, various mechanical tests with material samples are used [ibid.].

Despite the necessary connection of the different property levels described by Kyosev, the author devotes himself for the time being only to the macro level. This serves to set up a digital simulation model for deriving the internal forces at different stitch ratios within a knitted fabric.

In addition to the references to the field of textile composites outlined in the further text, the large medical technology companies and their customers in particular would have great advantages from further process innovations in the digital design of flat-knitted products. Since the author's previous focus has been on consumer products and medical devices, the demonstrator of the paper for the purpose of illustrating the process, in dealing with varying ratios, will be a bandage.

By using 3D CAD data from 3D scans and FEM calculation methods, the processes in the individualization of bandages could be further simplified in the future. In particular, specific body parts with high concave and convex plasticity (e.g., popliteal fossa, crook of the arm, kneecap) can

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benefit from the use of scan data and semi-automatic data set optimization. Prosthetic applications would also be conceivable with reference to textile composites.

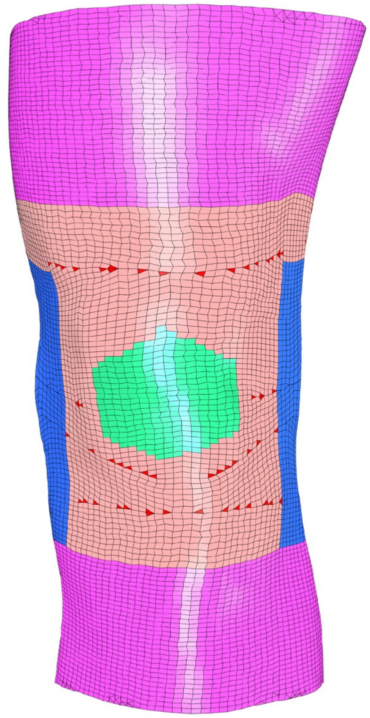

Fig. 1. Function zoned and topography optimized knit mesh.

Knit-Meshes

Several methods are currently known for creating knittable mesh topologies. K. Wu et al. describe in their publication "Wearable 3D Machine Knitting: Automatic Generation of Shaped Knit Sheets to Cover Real-World Objects," 2021, the following approach. The first step is to convert the cut mesh into a quad-dominant mesh where there are only triangles, quadrilaterals, and pentagons exist and all faces have the same size and the and have the same ratio between the edge lengths of course and wale [3].

Furthermore, they describe that the directions of course and wale are already determined during a surface cutting procedure. In two referenced earlier works, previous developments are introduced. Herein they also describe, on one hand, a vektorfield-oriented anisotropic remeshing pipeline and, on the other hand, the use of a local anisotropic parameterization method in conjunction with an extraction approach to generate an anisotropic quad-dominant mesh with relatively few triangles and pentagons [ibid.]. Through this form/step of categorization and modularization, they achieve an anisotropic quad-dominant mesh. In particular, this geometric property supports a later good calculability in the form of FEM calculations.

G. Nader et al. described another, partly similar, process in their 2021 published Work “KnitKit: A flexible system for machine knitting of customizable textiles”. The construction of the knit mesh starts here with a parameterization which generates orthogonal stripes with equal distances. It is followed by a remeshing step, which generates an adequate quad-dominant Knit-Mesh. The edges of this mesh are consistently aligned with the knitting direction and are divided into two groups: course-edges and wale-edges [4].

To create the wale and course contours/curves, they use a unit vectorfield-based analysis of the surface of an input mesh at each node/vertex. At each vertex of the input triangular mesh, they start by computing $\vec{v}$c as the rotation of $\vec{v}$w by π /2 in the respective local tangent plane. From

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this cross-field ($\vec{v}c$; $\vec{v}w$) there is an orthogonal, equally spaced stripe pattern computed using Knoppel et al.'s [2015] method [ibid.]. In another concept, first published in 2019 by Mariana Popescu, a graph-theoretic foundation is set. Basically, a 3D geometry, Mesh or NURBS-Surfaces, is needed. A gauge edge and a knit-end-edge are marked with curves or surface edges. Between two more "left-side" & "right-side" bounding edges, an intermediate frequency curve (tween curve) or contouring curve series is created. These are subsequently subdivided in weft-direction in the height dimension of the planned stitch-ratio [5]. To create the warp lines of the knitting pattern, the vertices must be connected by edges. Resulting Edges describe the directions of the knitting pattern and represent the weft and warp directions of the knitting pattern. In the stitch creation step, only "weft" edges are added. Before the edges are added, for each vertex a set of potential connection points is defined. Two sets of at least four closest vertices on the adjacent contours are added to a list for the later Wire Frame-Mesh. If the four nearest points fall on the same coordinate, the knit-mesh will show a decrease or an increase. Through these superposed points the ends of a warp-line-segment will build a common end-point. This constructs a triangle as shown in red in Figure 1. This symbolizes a decrease or increase within the resulting mesh.

In a thesis published in 2020, Max Eschenbach summarizes various approaches, but especially M. Popescu's graph-based computational basis of knit meshes and knittable paths in a compendium. Part of his work is the publication of Cockatoo, which is a prototypical open-source software toolkit for generating (3d) knitting patterns from NURBS surface and mesh geometry [6].

Due to the comprehensibility of the latter approaches, the same categorization/modularization is applied in the further process. It is assumed that both the computability by kinematic-FEM-Computation and the basic structure of the mesh by quad-dominance and decrease/increase-triangles are well suited for the evaluation and simulation processes presented in the following.

The basic design features of an FEM-compliant geometric calculation basis are derived from the general remarks on textile FEM calculation by L. Girdauskaite et al. and interpreted for the present focal field of technical flat knitting. Girdauskaite et al. describe the basic method in an article summarizing on textile physical tests [7].

The crossing points of weft and warp lines represent the joints for a kinematic FEM calculation explained later. Between the crossing points, constructed lines behave like rods with constant or limited flexible length. This flexibility allows a later consideration of constituent material properties. However, these are not yet considered in the present paper. An outlined concept for linking the macro-scale-knit-meshes with the meso-scale-binding-variants is touched upon under headline Experimental measurement.

The purpose of the presented process is the evaluation of form-giving cut features and the subsequent fit optimization by means of additionally entered different stitch ratios. However, as described, an accurate distribution of forces at the macro level requires further linkage with property models at the meso-scale level. These will be considered in further studies.

Simulation Differences for Woven Textiles

At this point, the research results presented so far will serve as a comparison between digital simulation of woven and knitted textiles. Due to the technical characteristics of the structure and the machine binding logic of both textile-production-methods (Knit & Woven Fabric), fundamental differences arise. These differences create very different geometric assumptions at the macro- and meso-scale levels for calculating shear and other material properties such as the effects of stress and strain on the textile.

Measuring Textile Composites, Knitted & Woven Materials

Analysis and modelling of the deformation behaviour of fabrics, textile composites and prepregs can be performed more or less at one or more of three scales: (1) microscopic, (2) mesoscopic, and (3) macroscopic. In terms of scale, simulations of flat-knitted three-dimensional textiles are

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currently mostly subjected to macroscopic analyses of the behaviour of the entire mesh shell/geometry (continuum membrane; Kyosev:2019), similar to the summary publication mentioned above regarding woven textiles by P. Boisse et al [8]. Since simulation methods at the macro level for three-dimensional flat knitting have so far been little standardized and are often very application-specific, (1), (2) and (3) are currently usually considered separately or a link is neglected.

Another complicating factor is that there are no generally valid calculation concepts for the shear behaviour of the individual stitch loops, taking into account different ratios, or the many different combinations for stitch loop/mesh formation and various knitting techniques (e.g., plating, weft insertion). Compared to woven fabric, the complexity of derivation increases here. This is because a stitch loop has multidirectional intersections and connections, as shown below.

Experimental Measurement

Experimental measurement for woven materials relates in part to the derivation of different shear angles. P. Boisse et al. describe essentially two different methods. One is the picture frame test and the other is the bias extension test [ibid]. Whether these two test methods are usable for the three-dimensional flatbed- knitting has to be evaluated in experiments. Furthermore, the researchers state earlier in 2017 that two relationships are required to analyse the results of an in-plane shear test [9]. A kinematic relationship that relates the in-plane shear angle to the extension of the Sample. For flatbed-knitting, the second dependence might be different and a third is required. For example, instead of shear angles, the focus of a question could be directions vectors related to truss centres resulting from the construction properties for stitch/mesh-loops at the meso-scale level. A mesh loop on the meso-scale level is described by a quad cell (polygon) in the digital model on the macro-scale plane. The centre of a truss can be related to one another cell-truss-centre. Changes in the positions of any node i in certain directions $\overrightarrow{vn}$ can be analysed. The resulting direction vectors can be used to optimize an FEM-based deformation analysis. The forces applied in warping experiments would then be expressed in "flow directions” within the knitted fabric. The third dependency can be achieved through investigations at the micro-scale level. Here we are concerned with the forces acting within the mesh loop elements at the yarn level. These can be represented in global coordinates by the relationships between the internal nodal forces and nodal displacements [10] within the truss:

$$F = Ku \tag{1}$$

Analyses could take the form of deviation measurements in applied 2D samples. This form of quality determination and analysis of visual warpage behaviour is today part of the craft practice in the development of three-dimensional knitted fabrics (for e.g.: car seats.). Color-coded zones or knitted-in measuring points could be detected and assigned with the aid of invariant moments (e.g.: Hu moments). This enables a point or area-accurate comparison between textile at rest and distortion.

Digital Augmented Experimental Measurement

Another possibility arises from taking 4D scans. With the help of the evaluation of different recording frames, the exact distortion behaviour in motion could be investigated. In the author's experience, point cloud data is also very well suited for machine learning-based analyses of the behaviour of specific clusters.

Colours, patterns or point-groups can be used as invariant moments or invariant geometries. Knitted-in position-sensors would also be conceivable.

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DIC, Invariant Moment & Geometries (3D-Scan)

The described procedures have similarities to the digital image correlation (DIC) which was described by Boisse et al. The DIC method is divided into a two-dimensional & a photogrammetric three-dimensional analysis method for pattern recognition.

The mentioned Hu-moments are rather used for shape recognition of geometries as a whole with closed contours. It hereby forms an important foundation in AI-assisted shape recognition. Based on the briefly described different approaches of image and geometry analysis, further methods can be designed which can be adapted for flat-knitting-/ and woven-textile-/ -based-composites. The experimental and digital augmented measurements and evaluations of deviations or errors will be important here in the future in order to achieve further simulation concepts for adequate computation.

Reengineering 3D-Scans and Remeshing

To obtain a computable mesh shell of a 3D scan or a 3D model, e.g., of a knee, the approaches presented above (Knit-Meshes) are partially applicable. Behind each of the approaches is the assumption that certain geometric properties are given. Therefore, the approaches can be described as application-specific. A generalistic approach for the construction of knit meshes is currently not known to the author. Therefore, each approach has advantages and disadvantages when applied to an arbitrary geometry. The author uses a workaround of proprietary software processes and commercial applications. These are described briefly below to provide a summary at the end of the paper with respect to the process foci described above (slip, wrinkling and permeability) in the development of textile-composite materials.

Knitting Technicians Best Praxis

The concepts presented for knit mesh creation have, as mentioned, in part very application-specific advantages & disadvantages. The author considers the lack of possibility to influence the position of darts or gores & notches to be the biggest disadvantage. In practice, these are used by knitting technicians in addition to changing the stitch ratio in order to influence the shape and material properties. The author therefore focuses on the removal and insertion of material quantities in certain cut sections with excess material or excessive stretch. Cut material-areas are adjusted at the edges and provided with the triangular shapes described above (increase/decrease) Afterwards the mesh is joined at row transitions. This is followed by the calculation of the internal warpage behaviour by means of kinematic calculation (Fig. 2).

In order to ensure a quantitative evaluation of the results, a geometric invariant is used. In addition to the visually observable effects, this gives another possibility to evaluate the shape accuracy after given adjustments.

Knit Mesh Preparation

A feature of the commercial NURBS modelling software Rhinoceros 3D is used to create the quad mesh. The integrated quad mesh tool allows a homogeneous quad recalculation of given NURBS or polygon geometries. The generated quad geometry is relatively uniform and quad-dominated. The ratio deviations from the actual mesh ratio are readjusted by dynamic relaxation. Here, as shown below, all segments dS are equated and relaxed in the knit-mesh ratio.

Dynamic Relaxation

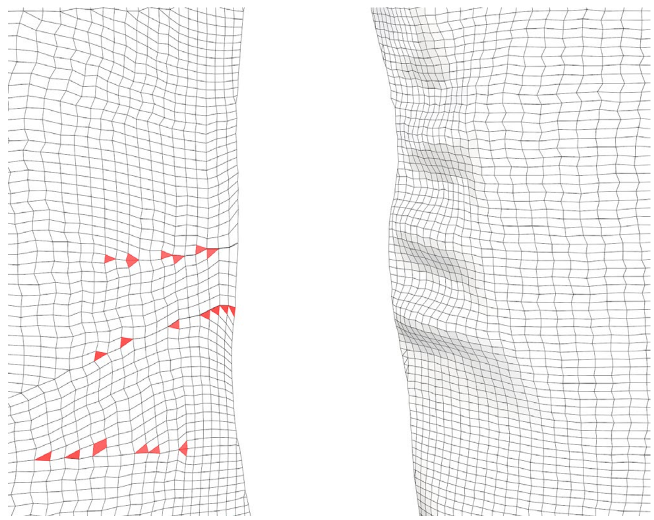
The dynamic relaxation method is based on discretizing the continuum under consideration by lumping the mass at nodes and defining the relationship between nodes in terms of stiffness. An iterative process is followed by simulating a pseudo-dynamic process in time, with each iteration based on an update of the geometry [11]. Considering Newton's second law of motion in the x direction at the i^{th} node at time t:

$$R_{ix}\,(t) = M_i\,A_{ix}\,(t) \quad (1)$$

The forces generated by the expansion of each edge segment led to a realignment of the whole mesh due to the internal references of the discrete structure.

According to the principle of equilibrium of forces, the relationship between the residuals and the geometry can be determined:

$$R_{ix}(t+\ \Delta t) =\ P_{ix}\,(t+\ \Delta t) + \sum \frac{T_m\,(t+\Delta t)}{l_m\,(t+\Delta)} \times \left(x_j(t+\quad \Delta t) -\ x_i(t+\ \Delta t)\right) \quad (2)$$



The sum must cover the forces in all the connections between the node and other nodes. By repeating the use of the relationship between the residuals and the geometry, and the relationship between the geometry and the residual, the pseudo-dynamic process is simulated. Residuals $T_m(t), R_i(t)$are computed until the structure is in static equilibrium [ibid.].

Reducing Wrinkles

Fig. 2 shows the comparison of a relaxed mesh-shell to an author-edited mesh-shell. The wrinkles that appeared after the material was relaxed into a uniform knittable mesh-ratio were achieved by removing material and changing the mesh proportions in certain areas. This process is described below.

FEM – Calculation

To simulate the shape accuracy of a knitted fabric, taking into account the knitted fabric weave and stitch ratios, three main laws can be required for the modelling of mechanical systems – kinematic, constitutive (material) and equilibrium [12].

Only kinematic equations were used to calculate the following patterns. Since textile kinematics assumes that relationships between the movement of individual nodes in a mechanical system consisting of nodes and connecting edges lead to internal deformations, a readability of a deformation due to external and internal force influences in the knit mesh can be assumed. The algorithms used are based on the basic algorithm of the kinematic model. All points $\vec{x}$ on a doubly curved geometry surface can be parametrically represented with surface coordinates u_i:

$$\vec{x} =\ \vec{x}\,(u_1, u_2) \quad (3)$$

The elementary length dS of a surface segment, between two closely spaced points/nodes (i, j) is given by the initial prepared Knit-Mesh and its constituent uniform mesh ratios. The stitch ratios correspond to the selected stitch ratios of a knitted fabric. In this case, an initial stitch ratio of 1.47 mm width and 1.1 mm height was chosen. For faster simulation calculation, the stitch ratio was multiplied by a factor of two (2.94 mm x 2.2 mm). The lower number of nodes (i, j) and edges speeds up the calculation.

$$dS^2 = G_{ij} du_j du_i \tag{4}$$

An angular threshold is used to define the possible shear inside each triangular face of the triangulated simulation quad-meshes. This threshold value is basically present. It is represented by the given initial angle of the triangular legs of each face. This determination thus represents a part of the Stiffness matrix, where K is the stiffness matrix of the system, u is the vector with the nodal displacements and F represents the external forces.

$$K \cdot u = F \tag{5}$$

In addition, internal forces act. The external forces pull the Knit-Mesh against a given avatar, which acts as a collision object. While the internal forces are generated by the one recurrence of the inner triangles edges(diagonals). These represent a simplified truss. This form does not give exact results, but serves as a necessary variable for the computational model. The virtual external work is due to the external forces described and can be represented by Eq. 1.

The equilibrium state is reached when the nodal displacement u_i = is less than 0.01mm/s for given forces δW_i.

The material constitutive parameters were disregarded for the time being, since a large number of experimental measurements are necessary for this. T. Pusch sums up that: due to the strong anisotropy of continuous fibre fabrics, the material properties depend on the type of loading. This requires a high level of testing for a complete experimental analysis. In general, the directional properties can be investigated in tension, compression, bending, and shear tests by experimental measurements on knitted material specimens fabricated for survey purposes [13]. Yarn elongation and/or stretching are considered to be neglected for the time being in the descriptions of deformation shown. Truss and Quad-Edges behave roughly stiffly.

Geometric Invariants

In a digital simulated polygonal representation of a knitted fabric (zoned Knit-Mesh, Fig. 1), geometric invariants are required in order to draw conclusions about the shape reproduction of knitted fabric (shape-fidelity) due to compressive, tensile and relaxation stress. In this case, invariance can be related to physical reality. However, this requires a high level of testing for a complete experimental analysis as mentioned above. Invariance describes a property that remains unchanged after operations or transformations of a certain kind have been applied to objects. The author hypothesizes that on the one hand distance deviations between the simulated knit geometry and a 3D-Scan-avatar-model may be suitable for a) predicting shape-fidelity from given deviations and b) enabling optimized parameter sets for repeated FEM simulation. On the other hand, area deviations in the quad faces and length deviations of the warp-/ and weft-, truss-lines or of the edges of the faces could be used to evaluate strongly overstretched areas. The method proposed extends the previous experimental measurements and proposes a purely digital computational model for virtual simulation. In further research, this digital data can be enriched with real measurement data to obtain a material property (micro-/ & meso-scale) database. This database may then be used to inform future simulations of knitted fabric. Furthermore, it may serve as training data for machine learning algorithms.

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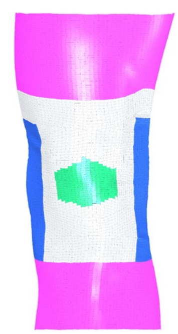
Used Geometric Invariants

To evaluate the kinematically calculated distortions resulting a) from the cutting treatment and b) from altered mesh ratios, a distance deviation between the 3D scan and the approximated knitted mesh structure is used as a geometric invariant for quantifiable quality determination.

Distance-Map

In order to display the deviations of the generated knitted fabric quantitatively, a point cloud of the 3D scan is compared with the calculated knitted topography. For this purpose, a tool for distance analysis of geometry and point clouds in the Rhinoceros 3D software is used. Four different additionally applied mesh ratios were calculated. The deviations and *Input-zones* are shown in Table 1.

Table 1. List of deviation und ratio variants.

Deviations	Example 1	Example 2	Example 3	Example 4
Mean	0.3021334 mm	0.2793425	0.2868251	0.2223705
Standard	0.8120128 mm	0.7525181	0.7775481	0.5867296
Average	0.02830526 mm	0.02766336	0.02774314	0.02790652
Max.	14.86173 mm	9.210369	8.264878	4.742685
Mesh Ratio Zone (mm)	Equal (grey) Course 1,47 Wale 1,1	Equal: 1,47/1,1 Red: 1,47/0,8	Equal: 1,47/1,1 blue: 0,8/0,8	Equal: 1,47/1,1 Red: 1,47/0,8 blue: 0,8/0,8 green: 0,6/0,8
Ratio Plot				

Summary

At the beginning, the special requirements and challenges for working with woven-based composites were outlined. These can be found in: wrinkling, permeability and slippage.

From the author's point of view, the basic assumptions for calculation and analysis models behave somewhat differently. This is mainly related to the more complex material-internal force relationships. Nevertheless, the surveying apparatuses can be used to analyse the material behaviour under other implications. These were listed under the heading "Experimental Measurement" and "digital augmented experimental measurement".

References

[1] P. Boisse, G. Akkerman, P. Carlone, L. Kärger, S.V. Lomov, J.A. Sherwood, Advances in composite forming through 25 years of ESAFORM, in: Int. J. Material Forming, Springer-Verlag Fr. SAS, part of Springer Nature (2022) 30. https://doi.org/10.1007/s12289-022-01682-8

[2] Y. Kyosev, The finite element method (FEM) and its application to textile technology, in: V. Dieter, Simulation in textile technology, Woodhead Publishing Ltd., Oxford, 2012, pp. 172-222. https://www.doi.org/10.1533/9780857097088
[3] K. Wu, M. Tarini, C. Yuksel, J. McCann. X. Gao, Wearable 3D Machine Knitting: Automatic Generation of Shaped Knit Sheets to Cover Real-World Objects, IEEE Trans Vis Comput Graph IEEE T VIS COMPUT GR 28 9 (2022) 3180-3192. https://www.doi.org/10.1109/TVCG.2021.3056101
[4] G. Nader, Y.H. Quek, P.Z. Chia, O. Weeger, S. Yeung, KnitKit: A flexible system for machine knitting of customizable textiles - Supplemental Document, ACM Trans. Graph. 40, 4, Article 64 (2021). https://doi.org/10.1145/3450626.3459790
[5] M.A. Popescu, KnitCrete: Stay-in-place knitted formworks for complex concrete structures, ETH-Dissertation, Serie: ETH-Dissertation, Nr.26063 (2019). https://www.research-collection.ethz.ch
[6] M. Eschenbach, Cockatoo (2020). https://github.com/fstwn/cockatoo [acs: 02.01.2023]
[7] L. Girdauskaite, G. Haasemann, S. Krzywinski, Modellierung und Simulation, in: C. Cherif, Textile Werkstoffe für den Leichtbau, Springer-Verlag Berlin, Heidelberg, 2011, pp. 573-663. https://doi.org/10.1007/978-3-642-17992-1
[8] P. Boisse, G. Akkerman, P. Carlone, L. Kärger, S.V. Lomov, J.A. Sherwood, Advances in composite forming through 25 years of ESAFORM, in: Int. J. Mater. Form. Springer-Verlag Fr. SAS, part of Springer Nature (2022) 30. https://doi.org/10.1007/s12289-022-01682-8
[9] P. Boisse, N. Hamila, E. Guzman-Maldonado, Angela Madeo, G. Hivet, F. Dell'Isola, The bias-extension test for the analysis of in-plane shear properties of textile composite reinforcements and prepregs: a review, Int. J. Mater. Form. 10 (2017) 473-492. https://hal.archives-ouvertes.fr/hal-01313827
[10] Y. Kyosev, Topology-Based Modeling of Textile Structures and Their Joint Assemblies: Principles, Algorithms and Limitations, Springer Nature Switzerland, Cham, Switzerland, 2019. https://doi.org/10.1007/978-3-030-02541-0
[11] W.J. Lewis, Tension Structures: Form and Behavoir, Thomas Telford Publishing, London, 2003. 978-0-7277-3236-1 (ISBN)
[2] Y. Kyosev, The finite element method (FEM) and its application to textile technology, in: V. Dieter, Simulation in textile technology, Woodhead Publishing Ltd., Oxford, 2012, pp. 178. https://www.doi.org/10.1533/9780857097088
[13] T. Pusch, Textilphysikalische Prüfungen, in: C. Cherif, Textile Werkstoffe für den Leichtbau, Springer-Verlag Berlin, Heidelberg, 2011, pp. 509-572. https://doi.org/10.1007/978-3-642-17992-1