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Geometric and Structural Model of a Spatial Knitted Product

Abstract

The paper presents a structural and geometric model of spatial warp-knitted fabrics using an angular solid of square cross-section as an example. An algorithm for designing the geometry of knitted fabric's spatial architecture with references to two components: the external and internal layer was determined. The structure of stitches of the structural elements of knitted fabric was presented. An algorithm for modelling the structure of spatial knitted fabric and composite was also determined. Computational procedures of the structural and physical parameters of knitted fabrics and composites were described, on the basis of which the program for simulating their properties was constructed.

Key words: *spatial warp-knitted fabrics, knitted composites, geometrical model, structural model, composite structure, geometric designing algorithm, structural designing algorithm.*

Introduction

Spatial warp-knitted fabrics are an innovative group of technical textiles of a wide area of applications, mainly as a spatial reinforcement for fibrous composites, applied in lightweight yet high-strength engineering structures of various types. In the process of designing a knitted fabric, a description of their spatial geometry and determination of their physical parameters, including mechanical properties, both in terms of the textile reinforcement and composite product, are of great importance. The models of flat warp-knitted fabrics and distance warp-knitted fabrics are well known [1 – 7]. Moreover similar structures of distance knitted fabrics can also be found in the technology of weft-knitted fabrics [8]. However, 3D warp-knitted fabrics are new structures, thus there are no references in literature describing their geometry or structural properties in the form of a model. The aim of this research is to describe 3D warp-knitted fabrics on the basis of a geometrical and structural model. This article is the first of the publications describing geometrical and structural models of solid knitted fabrics. In the next one, verification of these models and analysis of selected parameters will be presented.

Geometrical and structural model of spatial knitted fabrics

A spatial warp-knitted fabric is composed of at least three external layers, forming a triangle-shape cross-section of the product, and at least one internal layer [9 – 12]. The basic spatial structure of significant applicational potential in engineering constructions is a cuboid with the base of a rectangle. A knitted cuboid is one of the possible variants of geometrical and structural models of the spatial knitted fabrics group (***Figure 1***, see page 100).

The model of a knitted solid consists of external layers wz_i and $wz_{i'}$, and an internal layer *ww*. The external layers are formed from plain warp-knitted stitches, while the internal layer is a connecting link of the opposite loops of external layers of distance knitted fabrics' stitches. The external walls are the two opposing systems, in one of which the walls wz_1 and $wz_{1'}$ are arranged in parallel, while in the second wz_2 and $wz_{2'}$ are arranged perpendicularly. In the case of the knitted solid described, its construction can be referred to the architecture of distance knitted fabrics (***Figure 2***, see page 100). The resulting structure of knitted fabric C consists of two components: distance knitted fabrics A and B.

All the external layers in the spatial warp-knitted fabric can have an identical or diversified structure, depending on the configuration, or each wall may have an individual structure. Furthermore the whole product can be made of homogeneous or diversified materials. The thickness of the external layers g_{wzi} and $g_{wzi'}$ depends on the linear density of threads used, as well as on the number of component stitches. The internal layer is formed by introducing threads between the external walls, therefore the number of opposite arrangements of external layers determines the maximum number of thread configurations of the internal layer. The inner layer may also be formed as only one configuration of threads. There is also a possibility that in both arrangements, the I-I 'and II-II', threads are not introduced to the internal layer. In this case, the structure created will only have external walls (***Figure 1.a*** – segment of height h_2). Throughout the report of height H_{Rr} of the knitted solid, the internal layer can be of a segmental structure, meaning that at the height of the solid's report, there are smaller segments of identical or diversified height h_i. Parameter g_{pi} introduced describes the thickness of thebarrier, which is an arrangement of parallel threads running through the internal layer. In the case of the solid presented in ***Figure 1.a***, the barrier can be composed of threads placed between the two arrangements of the external walls wz_1-$wz_{1'}$ and wz_2-$wz_{2'}$. The thickness of individual barriers at the height of report H_{Rr} of the knitted solid can be identical or different. Barriers can be placed perpendicular to the external layers (perpendicular barriers), or at an angle $\beta_i \neq 90°$ (oblique barriers). At the height of H_{Rr} the angles β_i of the barrier arrangement can be identical or different (***Figure 1.b***). The geometry and arrangement of the barriers described above refer to the filled configurations, which means that all the barriers have a 'compact' structure. The use of incomplete thread-

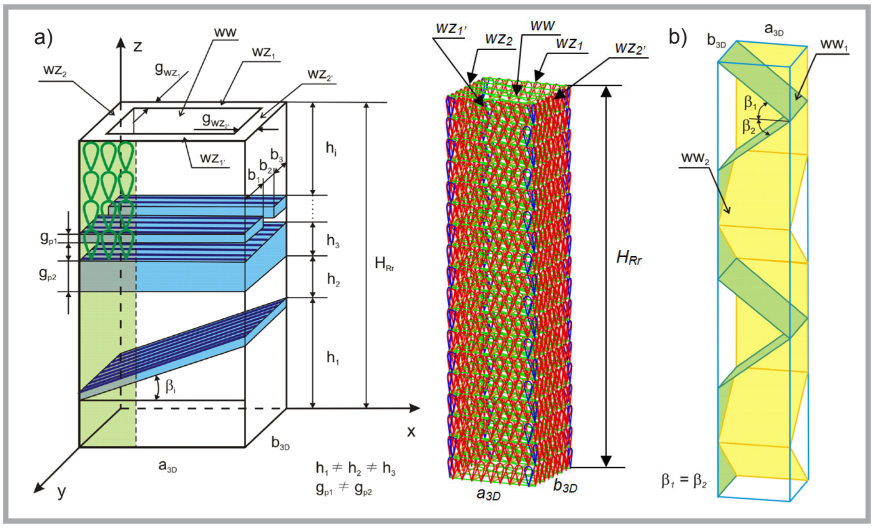

Figure 1. Spatial geometry designs of knitted solids: a) general structure of a spatial knitted solid, b) internal layer with oblique barriers.

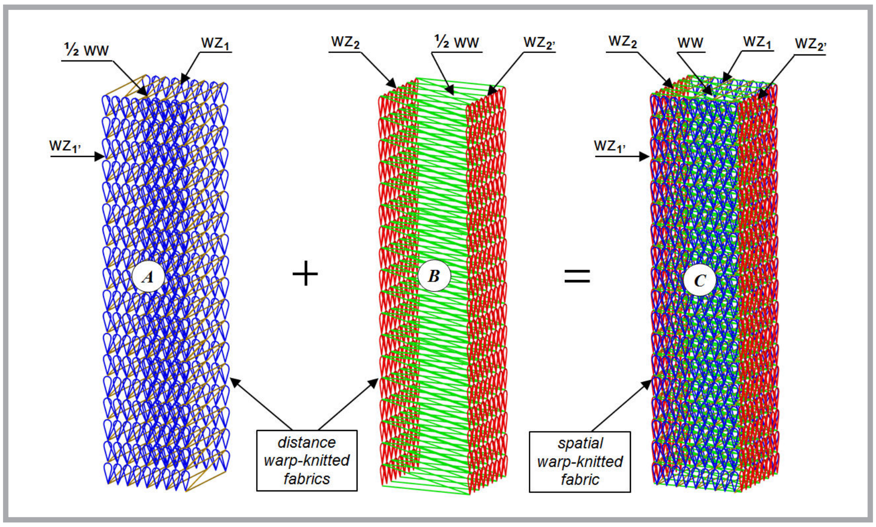

Figure 2. Design of spatial warp-knitted fabric on the basis of distance warp-knitted fabrics.

ing of guide bars introducing threads to the internal layer leads to obtaining a-jour knitted structures. A segment of thickness g_{p1}, shown in ***Figure 1.a***, was formed from the elements of width b_1 and b_3 filled with threads and an area without threads of width b_2.

However, it should be noted that the model developed, when referring to the 3D knitted fabric in the form of an angular solid, is of a general character in assumptions on the spatial structure of knitted fabric as well as in the relationships describing structural parameters of knitted fabric and knitted composites. The model, using an example of a specific geometric solid – a rectangular prism, can be used to describe the construction of other types of 3D knitted fabrics, including knitted products of a triangular cross-section, in the shape of a T-bar, C-bar, or a solid in the form of a spatial arc, among others.

Geometrical model of knitted fabric

The geometrical model of a knitted fabric in a spatial configuration describes the structure of warp-knitted fabrics in the form of a solid, taking into account the size of a solid, types of stitches, and spatial configuration of threads.

In modelling the geometry of the knitted fabric, the following assumptions were made: constant cylindrical cross-section of threads, the lack of friction between threads, and the orientation of threads in the stitch designed corresponds to the actual arrangement in the structure of the knitted fabric [13 – 15].

Hi-tech computer software ProCAD warpknitt 5 was used for modelling the spatial architecture of external and internal layers of a knitted solid.

An important element in designing knitted fabrics, besides the selection of yarns of relevant properties, specific technology and the finishing process, is the possibility of spatial visualisation of the knitted fabric structure at the very first stage of its development. The program used enables to realistically reproduce the structure of the product, both in the stretched state and after relaxation.

Algorithm for designing the geometry of the spatial architecture of a knitted fabric

A designing algorithm is presented in the scheme (***Figure 3***) [16], consisting of the following seven main blocks: determination of the basic group of warp-knitted stitches (plain and distance warp-knitted stitches), selection of the stitch type, determination of the number of component stitches (number of guide bars), definition of geometrical parameters of knitted fabrics, that is the width of wales, height of courses and length of yarn in the loop; selection of yarn by determining the type of raw material, linear density of threads, number of filaments, surface type and colour; and analytical recording of component stitches for a triple acting drum and declaration of threading reports of guide bars. The last two blocks automatically lead to generating a schematic drawing of the stitch on the needles and enable to obtain a draft of the actual threads in the spatial arrangement. The algorithm designed also takes into account the possibility of making changes of previously declared yarn parameters, technological parameters, recording of pattern chains, as well as the threading of guide bars.

Results of modelling the spatial architecture of 3D knitted fabrics

A model of the structure of external and internal layers constituting the spatial knitted fabric was developed. The external walls were designed on the basis of plain warp-knitted fabrics, while the inner layer was modelled based on the internal layer of distance warp-knitted fabrics. Selected results of modelling the spatial knitted fabric are presented below.

Modelling the stitches of external layers

External layers of spatial warp knitted fabrics are made on the basis of plain warp-knitted fabrics. Due to the fact that the designs presented in the publication will be the components of spatial products of a technical purpose, it is important that the external walls of knitted solids are characterised by high stability in both the longitudinal and transverse directions, considering minimum values of elongation and, at the same time, high strength parameters. Three groups of plain warp-knitted structure intended for external layers were selected, i.e knitted fabrics on the basis of basic stitches - low stretchy, weft warp- knitted fabrics, and a-jour knitted fabrics reinforced with threads in the vertical and horizontal configuration.

An example of a fabric from the first group is illustrated in ***Figure 4***. This variant shows a basic configuration of a double-guide knitted fabric made of two tricot stitches lapping in opposition to closed loops. The Figure shows a 2D view of the knitted fabric's structure and cross-sections of products (1) and (2). Another example of the stitch configuration in this group can be the combination of a tricot and chain stitch. The use of a chain stitch reduces the longitudinal extensibility of the product. A slightly more stable arrangement is a double-guide plain warp-knitted fabric constructed with a chain and weft stitch introduced in the area of 2 t_u. The use of a weft stitch makes a product of high crosswise stability. Plain warp-knitted fabrics classified in this group are well-known structures of simple stitch configuration. These structures are included in the technology of new spatial knitted fabrics due to the simplicity of their production and ease of connecting two neighboring external layers of the fabric's solid in its corners (stitches with short laps).

The second group of plain warp-knitted fabrics included in the designs developed are weft structures with vertical weft threads, horizontal weft threads introduced across the width of the external wall, and knitted fabrics with both configurations of weft threads in their structure. This group is advantageous because of their strength parameters. A double-guide weft stitch of increased longitudinal strength is presented in ***Figure 5.a*** (see page 102). A knitted fabric is built on the basis of two stitches, i.e a stitch of vertical weft threads combined with a

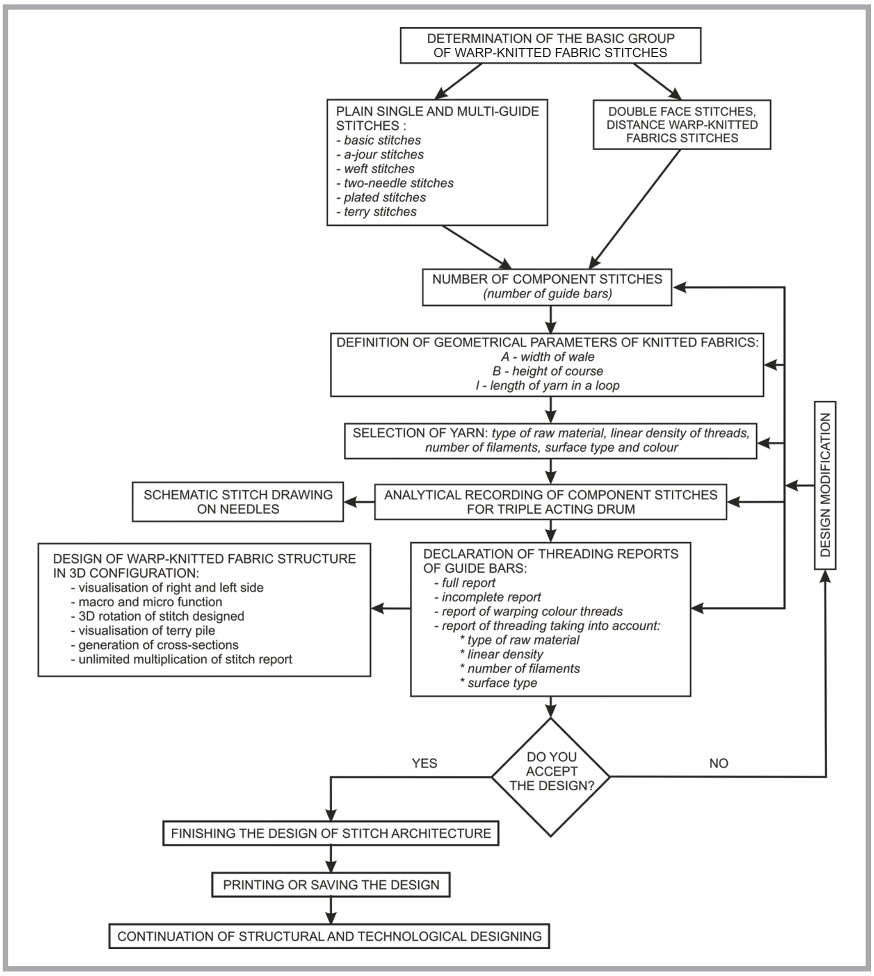

Figure 3. *Algorithm for designing the geometry of warp-knitted fabrics using ProCAD warpknit 5 software.*

tricot stitch. In this example, a key role is played by the vertical weft threads of considerable thickness Φ_w compared to those of binding yarn of thickness Φ_{pw} forming a tricot stitch. Assuming that $\Phi_w > \Phi_{pw}$, then the total thickness of the knitted fabric can be generalised to the sum of two thicknesses of the binding yarn and the diameter of weft yarn, which can be written in accordance with the formula: $g = 2\ \Phi_{pw} + \Phi_w$. A variant of knitted fabric in which vertical weft threads of diversified linear density were used is shown in ***Figure 5.b*** (see page 102). In this variant, due to the diversified diameters of weft threads, in the structure of the knitted fabric there are segments of variable thickness of the textile product (g_1 and g_2).

In order to reduce the surface mass of a knitted fabric in the case of threads of considerable thickness, yarns of a 'channel' (hollow) structure can be used.

A slightly different structure is presented by a woven-like warp-knitted fabric of increased longitudinal and transverse strength (***Figure 6***, see page 102). In this design the number of vertical weft threads placed in the area of one needle pitch was increased. Furthermore horizontal weft threads were introduced into the structure across the whole width of the product. The use of longitudinal and transverse thread configurations signifi-

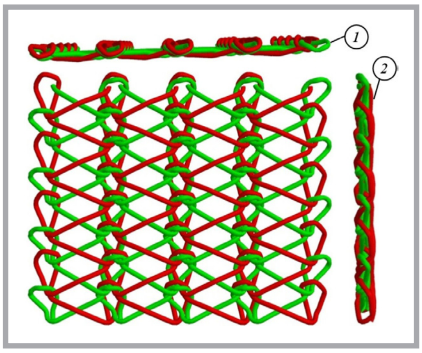

Figure 4. *Design of a basic structure of a warp-knitted fabric on the basis of tricot stitches lapping in opposition to the horizontal sections along courses (1) and wales (2).*

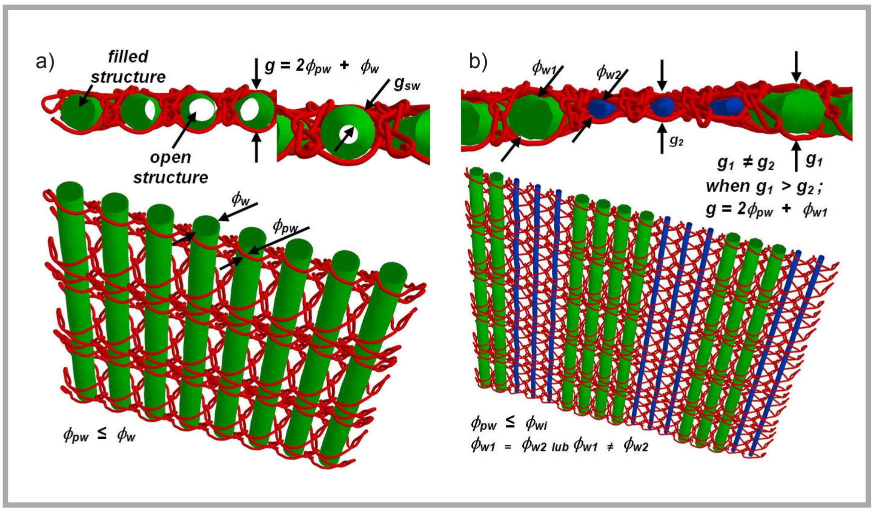

***Figure 5.** Designs of exemplary configurations of warp-knitted stitches of a spatial knitted fabric's external layers with increased longitudinal strength: a) of constant linear density of vertical wefts, b) of variable linear density of horizontal wefts.*

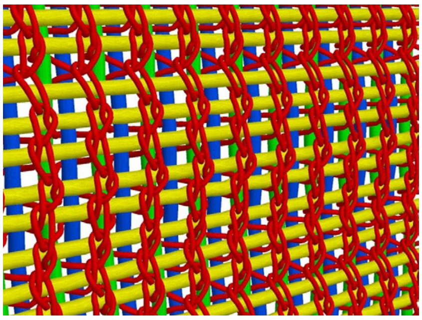

***Figure 6.** Design of woven-like warp-knitted fabric of increased horizontal and vertical strength.*

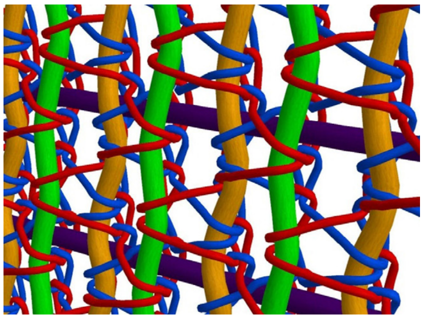

***Figure 7.** Design of a-jour warp-knitted fabric of increased vertical and horizontal strength.*

cantly limits the elongation of a knitted fabric and increases strength parameters of the composite constructed on the basis of the knitted fabric.

All of the above-mentioned structures of plain warp-knitted fabrics were fully-filled structures, therefore they were characterised by a high surface mass. Reduction of a 3D warp-knitted fabric mass can be achieved by reducing the surface mass of external walls. This effect can be obtained by the use of a-jour stitches (group III).

A-jour knitted fabrics are characterised by high structural deformability, therefore in order to eliminate this disadvantage, additional vertical and horizontal weft threads were introduced to the knitted structure, as shown in ***Figure** 7*. A different example is the design of the external layer of an a-jour structure based on a quadrangular grid, in the structure of which two sets of weft threads were also introduced.

Modelling the stitches of internal layer

Modelling the stitches of the internal layer of spatial warp-knitted fabrics was performed for distance warp-knitted fabrics – the components of the knitted solid. In the classic case, threads of the internal layer form approximately parallel planes in each spatial course of the knitted solid. One course of a spatial warp-knitted fabric is understood as loops in the external layers at height B and as links of both external layers as well as the internal layer at the same height. The thickness of warp-knitted fabric g_D is the sum of values of the thickness of the external layers g_{wz1} and g_{wz2} and the thickness of the internal layer g_{ww}, which can be written as $g_D = g_{wz1} + g_{wz2} + g_{ww}$. This thickness can be related to the cross-sectional dimensions of the knitted solid, that is $a_{3D} \times b_{3D}$ (***Figure 1***).

The structures of distance warp-knitted fabrics investigated were divided into three groups including plain distance warp-knitted stitches of compact structure, distance weft warp-knitted stitches of vertical and horizontal weft configuration and a-jour distance warp-knitted stitches. Due to the fact that the first group includes traditional structures of distance warp-knitted fabrics, while the second group includes only configurations of weft threads in external layers, their designs are not presented in this publication.

An important group are the a-jour distance warp-knitted stitches. ***Figure 8*** presents variants of distance warp-knitted fabrics, of which the external layer is of an a-jour architecture.

These a-jour structures are formed by knitting the threads of internal layers into one of the external walls of the product, forming free spaces. In the areas where threads of the internal layer are alternately knitted in both of the opposite external layers, a filled region is formed creating a barrier arranged at a right angle to the external layers of the product. When all the barriers are of equal height h_{pi} and distant from one another by a fixed value of h_{ki}, then the internal layer has a homogeneous isotropic structure over the whole height of the knitted fabric H_{Rr} (***Figure 8.a***). The height of individual barriers and the distance between them can be identical or different. Another variant of a warp-knitted fabric is shown in ***Figure 8.b***, which is characterised by heterogeneity along its height, therefore it is of an anisotropic character, which means that all the heights of the barriers as well as the distances between them are varied.

The variant of distance warp-knitted fabric illustrated in ***Figure 8.c*** shows an a-jour structure with oblique barriers. Depending on the type of stitch used, angles βi of the arrangement of barriers with respect to the external layers can be identical or different, which results in a homogeneous or heterogeneous structure of the knitted solid.

Model of structural and technological designing of a composite and spatial warp knitted fabrics

Structural and physical properties of knitted solids, their components as well as composites formed on the basis of these knitted fabrics were determined in the structural and technological modeling of spatial warp-knitted fabrics and a composite by defining the dependencies between basic parameters of the threads and knitted fabrics.

A computer program was developed by the authors in order to determine the parameters of both knitted fabrics and composites on the basis of the input parameters given.

Algorithm for structural and technological designing

An algorithm for the structural and technological designing of the structure of warp-knitted fabric described above and a composite built on its basis consists of the following four blocks:
- parameters of threads
- basic parameters of knitted fabrics
- structural and physical parameters of knitted fabrics
- parameters of knitted composites.

A general scheme of the algorithm's structure is presented in ***Figure 9***.

In the first block - PARAMETERS OF THREADS, the parameters of threads are declared referring to both the external and internal layers of the spatial product. Among the parameters declared are the linear density of threads forming the component stitches of external and internal layers, and the density of the material of threads forming the component stitches. The thickness of threads is a calculated value.

The second block - BASIC PARAMETERS OF KNITTED FABRICS presents in three separate segments the basic parameters of the external walls, internal layer and parameters of the spatial knitted solid. The most important parameters in this block are the height and width of the stitch report, the warp and weft density, the thickness of the knitted fabric, the thread length in a loop, and surface mass of the knitted fabric. For this and other blocks of the algorithm, only the parameters directly related to the structure of the spatial knitted fabric are described due to the limited size of this publication. The parameters declared directly related to the spatial knitted fabric are the dimensions of the cross-section of this structure, i.e a_{3D} and b_{3D} and the height of the report H_{Rr}, while the volumetric mass per one meter of spatial knitted fabric M_{3D} is a calculated parameter.

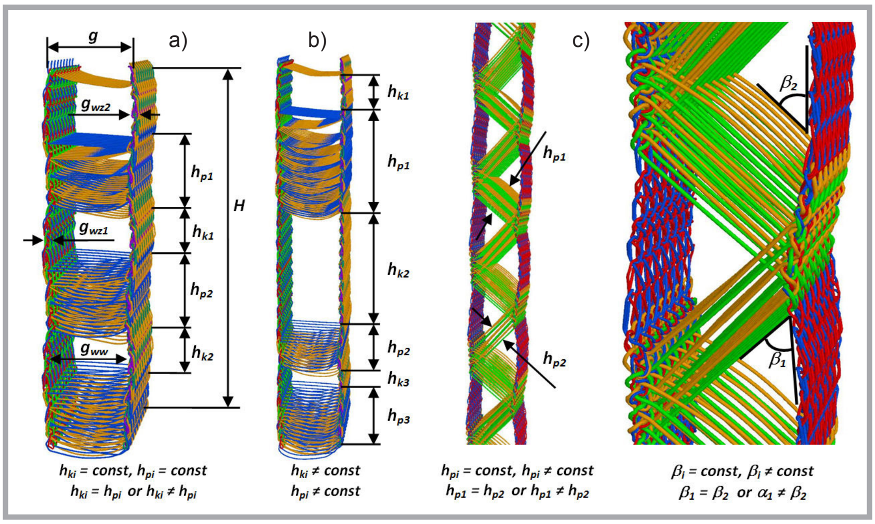

Figure 8. *Design of external layer of spatial warp-knitted fabric on the basis of distance knitted fabrics: a) of parallel barriers arranged evenly, b) of parallel barriers arranged unevenly, c) of oblique barriers.*

In the third block entitled STRUCTURAL AND PHYSICAL PARAMETERS OF KNITTED FABRICS, computational dependencies determining the structural parameters of knitted fabrics are defined. In the block directly related to the spatial knitted structure, the dependencies of the following parameters are taken into account:
- surface of threads at the height of one course and at the height of a course report of the spatial knitted fabric and the coefficient of the thread surface in the spatial knitted fabric,
- volume of threads at the height of one course and at the height of the course report of the spatial knitted fabric,
- volume of the spatial knitted fabric at the height of one course and at the height of the course report and volume coefficient of threads in the spatial knitted fabric,
- volume of threads, volume of knitted fabrics and volume coefficient of threads with respect to one meter of the spatial knitted fabric,
- void ratio of spatial knitted fabric,
- density of the knitted fabric per one square meter of a knitted composite.

The fourth block of the computational algorithm PARAMETERS OF KNITTED COMPOSITES describes the parameters directly related to composite structures made on the basis of knitted fabrics. The only variable input in this block is the density of the resin. According to the assumptions made, the composite can take three forms. In the first case, free spaces in the volume of the knitted fabric are completely filled with resin, forming a uniform solid. The second case is a composite constructed by filling the structure with foamed resin. The last and most effective variant, designed to reduce the volume weight of the textile composite, is a product obtained by coating the surface of threads with resin. Coating the threads with resin increases the thickness of threads of the external layer stitches. Analogous to the approach taken to fill the structure of a spatial knitted fabric with resin, the parameters connected with the composite were divided into three groups, that is a composite with the maximal filling of free spaces with resin, one with the filling of free spaces with foamed resin, and a composite obtained by coating the surface of threads with a layer of resin. *The computational parameters for all three types of composite structure are the following:*
- factor of volumetric filling with resin,
- volume, mass and density of the resin per one meter of composite knitted,
- mass and density of one meter of composite knitted,
- ratio of mass of the knitted fabric and mass of the resin to that of the composite.

In addition, for the composite formed on the basis of coating the thread surface with resin, the following were determined:
- reduced width a_{3D}/depth b_{3D} of the spatial composite in the resin coating,
- volume of one meter of spatial knitted fabric in the resin coating,
- volume of resin around the thread of an internal layer stitch in one loop of

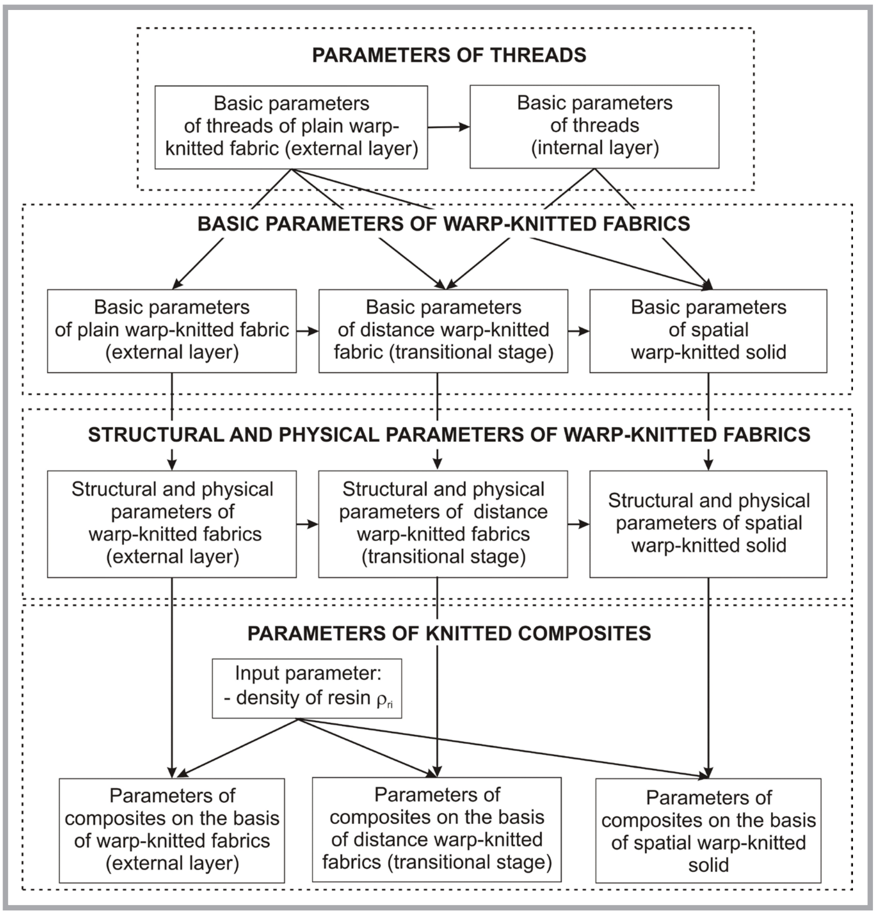

Figure 9. *Algorithm for the structural and technological designing of knitted fabrics and composites.*

the knitted fabric and at a height of one course.

Realisation of the algorithm for calculating the structural and physical parameters of knitted fabrics and composites required formulating about 450 calculation procedures.

Based on the algorithm developed for structural and technological designing of knitted fabrics and composites, as well as computational procedures formulated using the Microsoft Excel program, a computational program consisting of four blocks of algorithm described above was designed. For a deeper understanding of the relationship between the structural parameters of the knitted fabric stitches in the calculation program, it was divided into the following three parts : the parameters of plain warp-knitted fabrics (external layers), parameters of distance warp-knitted fabrics, parameters of spatial knitted solids and composites formed on the basis of the above knits.

The program is of a feedback structure. A change in any of the input parameters modifies the calculations in all three segments of plain warp-knitted fabrics, distance warp-knitted fabrics and spatial warp-knitted fabrics. This algorithm and the computer program elaborated is a tool for scientific research and the designing process for the properties of spatial knitted structures and knitted composites. A computer simulation of the properties of knitted fabrics and composites enables to optimise the construction of these structures.

Summary

A geometric and structural model of spatial warp-knitted solids was developed. The model was illustrated for a selected knitted structure in the form of a cuboid with a square base. This model can be used to describe other variants of spatial warp-knitted fabric structures.

A geometric model of spatial knitted fabric's architecture consists of two components: a model of the external layers made of multi-guide warp-knitted stitches and one of the internal layer of the knitted fabric, in which the straight sections of threads can be referred to the structure of spatial warp-knitted fabrics. A unique program - ProCAD warpknit 5 was used for designing the stitches of the knitted fabrics' components, while AutoCAD was used for modelling the spatial solid and composite. Models of the knitted fabrics' components were presented in a spatial arrangement taking into account the parameters of threads and their arrangement in knitted fabric stitches.

The basic parameters of the structure of knitted fabrics and the dependencies describing the structural characteristics of knitted solids with reference to the whole solid of a knitted fabric as well as their components were determined in the structural modeling. Physical properties of knitted fabrics and knitted composites were also determined for the three following structural variants: complete filling of the free spaces with resin and two unfilled cases (foam resin and resin coating). A structural algorithm for a knitted fabric consisting of four blocks: parameters of threads, basic parameters of knitted fabrics, structural and physical parameters of knitted fabrics and parameters of knitted composites was elaborated.

On the basis of the algorithm determined, a worksheet with a recording of about 450 calculation procedures formulating the relationship between the parameters of knitted fabrics and a composite was constructed using the Microsoft Excel program. The program developed enables to study the structure and technology of knitted fabrics as well as the properties of composites in the form of a computer simulation.

A description of the spatial knitted fabrics and composites presented in this publication is the first software of its kind, which aims to develop and analyse lightweight high-strength structures in the field of material engineering.

Acknowledgement

The study was financially supported by the National Centre of Science as a research promoter project entitled "Innovative technology of spatial warp-knitted fabrics - structure and properties".

References

1. Korliński W. *Podstawy dziewiarstwa.* Ed. WNT, Warsaw, 1977, p. 318.

2. Żurek W, Kopias K. *Struktura płaskich wyrobów włókienniczych*. Ed. WNT, Warsaw, 1983, p. 272.
3. Dalidovicz AS. *Osnowy teori wiazania*. Ed. Liogkaja Industria, Moscow, 1970, p. 432.
4. Mikołajczyk Z. *Identification of the process of knitting of the warp-knitted anisotropic structures on warp-knitting machines* (in Polish), Scientific Letters TUL 2009, Nr 1047, Dissertation z. 381, p. 234.
5. Helbig F. New dimensions for functional, regular 3D knitting. *Melliand English* 2006; 10: 153-155.
6. Helbig F. Geometrische Elemente reg-ulärer 3D-Gewirke. *Melliand Textilberichte* 2007; 3: 124-127.
7. Zhang L-Z, Jiang G-M, Miao X-H, Cong H-L. Three-dimensional Computer Simulation of Warp Knitted Spacer Fabric. *Fibres & Textiles in Eastern Europe* 2012; 20, 3(92): 56-60.
8. Kowalski K, Włodarczyk B. Modification of External Layers of Distance Knitted Fabrics with Elastomeric Threads and Its Effect on the Structural Parameters. *Fibres & Textiles in Eastern Europe* 2012; 20, 4(93): 62-66.
9. Mikołajczyk Z, Pieklak K, Golczyk A, Wiater Z. Spatial knitted product, patent application from 12.09.2008, P – 386074.
10. Mikołajczyk Z, Pieklak K, Golczyk A, Wiater Z. Spatial warp-knitted product, patent application from 12.09.2008, P – 386075.
11. Pieklak K, Mikołajczyk Z. New Generation of Structures in Warp-Knitted Distance Fabrics. In: *AUTEX International Conference 2009,* 26 – 28 May 2009, CESME – Turkey.
12. Mikołajczyk Z, Pieklak K. Innovative Structures and Technology of Spatial Warp-Knitted Fabrics. In: *45th International Federation of Knitting Technologists IFKT*, 27 – 29 May 2010, Ljubljana, Slovenia.
13. Neue Software für dreidimensionale Legungsdarstellung und – simulation. *Melliand Textilberichte* 2008; 11-12: 456 – 457.
14. Kyosev Y, Rahjens A, Renkens W. How clear is the boundary between reality and simulation? – Virtual and real warp-knitted – a comparative study between 3D simulation and actual fabrics. *Kettenwirk-Praxis* 2009; 4: 40 – 42.
15. ProCad warpknit Version 5- more than just 3D cinema for product developers - A new generation of software for simulating textiles in product development. *Kettenwirk-Praxis* 2010; 4: 34 – 35.
16. Pieklak K, Mikołajczyk Z. Architecture Designing of Warp-Knitted Fabrics. In: *XV Scientific Conference of the Faculty of Material Technologies and Textile Design at the Lodz University of Technology*, Łódź, 2012, p. 4.

Received 05.09.2011 Reviewed 15.05.2013