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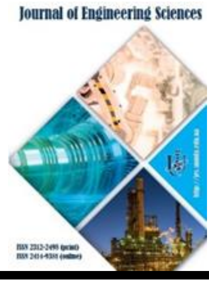

Object-Oriented Analysis of Frame 3D Textile Structures

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Abstract. The article applied an object-oriented approach to analyze complex mechanical and technological objects based on an example of frame 3D textile structure development for objects from composite materials. Based on the research, the principle of global class inheritance of objects was analyzed and summarized using the object-oriented approach for the mechanical-technological structure of 3D fabrics using mechanical technology of sewing, weaving, knitting, and knitting productions. The design scheme of a generalized topology of object-oriented design for mechanical and technological systems of 3D fabrics of sewing, knitting, weaving, and weaving productions was developed. Methods and equipment for manufacturing mechanical-technological frame structures of 3D objects from textile materials were presented. Novel concepts of object = 3D micro-model, object = 2D mini-model, and object = 3D macro-model for frame 3D textile structures were introduced. Principles of inheritance, encapsulation, and polymorphism were applied to applicable models. For anisotropic textile 2D models, typical diagrams are given in polar coordinates for dynamic modulus of elasticity and logarithmic damping decrement.

Keywords: complex system, inheritance, technological object, micromechanics, anisotropy.

1 Introduction

Standard mechanical technologies such as weaving production, knitting and weaving production, and sewing production can be used to produce framework 3D textile structures used in composite materials [1]. These technologies make creating structures with different densities and shapes possible, ensuring composites' high strength and stability. In addition, using mechanical technologies allows for automating the production process and reducing production costs, and, for example, usage of knitting production technology allows to get frame 3D structural knitwear with a large number of apertures, which ensures high adhesion with composite material.

One of the advantages of using 3D textile structures in composite materials is that they can provide greater structural strength and stiffness with minimal weight. In addition, such materials have high resistance to destruction and thermal and chemical influences. Various materials are used to produce 3D textile structures, such as polyester, kevlar, and carbon fibers [2, 3]. Such textile structures can be used as internal reinforcing elements in the production of composite materials or as external layers that protect from external influences, such as aircraft skins.

When using polymers, a standard method of obtaining the structure of quasi-fabrics using additive technologies is an example of 3D printing and other possible additive manufacturing methods.

Framework 3D textile structures are the basis for preforms made of thread or fiber objects as an internal framework of modern composite materials. The efficiency of usage and influence of reinforcement architecture significantly affect the mechanical properties of the textile-reinforced composite [4, 5].

Application of framework 3D textile structures in composite materials is widely used in the production of aircraft, automobiles, ships, equipment for sports and recreation, and other products that require high strength and rigidity [6–8], e.g., production of protective, military equipment (body armor, protective helmets, and armor pads) and other various non-metallic objects for people and machines.

In addition, composite materials allow the creation of more complex and ergonomic shapes, which expands the capabilities of designers and engineers when developing new products.

3D composite materials are fiber-reinforced polymers - commonly widely used name is fiber-reinforced polymer (FRP) composites. Production and usage of FRP composites are growing not only in traditional applications but also in new needs of biomedical devices and building structures.

2 Literature Review

An analytical review of 3-D fabrics and methods of their formation is performed in the work [9–11]. Simultaneously, the authors do not conduct a quantitative or qualitative analysis. The analytical review of 3-D fabrics and their formation methods performed in this work can be an essential contribution to relevant fields of science and technology. However, a lack of quantitative and qualitative analysis can complicate the possibility of practical use of research results.

Simultaneously, in the research works [12, 13], the diagram of the qualitative mechanism during delamination of Bato-layer composite polymer material stitched with shuttle stitches of class 300, the diagram of sliding and without sliding formation of single thread chain stitches of carpet type of class 100, the structural diagram of brand beam from three-layer composite-polymer materials of 3D shape are considered. Materials, working tools, and equipment for sewing 3D constructions from composite polymer materials for aviation equipment were selected.

The research [14] is dedicated to the fundamentals of developing 3D FRP materials from traditional approaches to their analysis and production using mechanical technologies of the weaving, knitting, weaving, and sewing industries.

The research works [15–23] are devoted to developing fibrous reinforcing structures for parts made of composite material, and existing patents for inventions are devoted to methods and technical means for forming 3D objects from FRP materials. Micro mechanical methods of analysis in problems of mechanics of solid environments with finite element method were also studied [24].

In the works [25, 26] proposed an object-oriented approach for automated design of working processes of knitting and sewing machines. In the work [27] topology of machine stitches and principles of their design were considered; the proposed method can be applied to determine heredity and 3D frame structure of packaging materials.

Simultaneously in the work [28, 29], CAD of light and textile industry objects is considered, but authors did not consider 3D frame textile structures. Along with this, in the work [30] modeling of two-dimensional and three-dimensional circular weaving process for creating objects of complex shape are considered. The proposed modeling algorithm is based on differential geometry and allows considering transient or stationary phenomena of the process, such as movement of weaving front, sliding on mandrel, and thread relaxation.

Modeling of weaving process considering sliding of threads on mandrel is considered in the works [31, 32], process of friction between threads in convergence zone is considered in the works [33, 34].

In the works [35–37], finite element modeling is combined with experimental approaches. Mechanical properties of 3D frame structure are obtained by micromechanical modeling based on the microstructure of threads and repetitive geometry of unit cells.

In works [38, 39], viscoelastic properties of fabrics under cyclic loads were studied on a laboratory bench [40, 41] using special methods of analysis. These studies are important for understanding behavior of fabrics under constant loading and may have practical applications in design of materials subjected to cyclic loading. Results of these studies can be useful for further scientific and industrial activities in field of fabrics engineering.

Relevance of creating frame 3D textile structures using principles of object-oriented analysis and design is important for machine-building industry. Development of new technologies for creating frame 3D textile structures and possibility of their implementation based on existing mechanical technologies is possible on examples of mechanical technologies of fashion industry using basic principles of object-oriented design: principle of inheritance; principle of encapsulation; polymorphism principle and is relevant.

3 Research Methodology

Object-oriented analysis and object-oriented synthesis are the main stages of object-oriented design of complex mechanical and technological systems [22, 24] using modern computer design technologies due to object-oriented analysis (OOA).

The method of building a 3D model is obtained, and the result of object-oriented synthesis (OOS) is writing code or its implementation in a purpose-oriented software environment for object-oriented design. Therefore, the basic concept of OOA and OOS is “object” in the target instrumental sense. The object is an independent element of a designed mechanical and technological system, which is obtained and selected after decomposing such system into elements (components). The object contains encapsulated input data and algorithms, formulas, or methods for processing these data combined into a single entity.

Table 1 shows a set of methods and equipment used for the industrial production of mechanical and technological frame structures of 3D objects from textile materials.

The scientific novelty consists of applying the object-oriented programming (OOP) paradigm for the object-oriented design (OOD) of complex mechanical and technological systems to analyze 3D textile structures.

A generalized topology scheme of object-oriented design of mechanical and technological systems of 3D fabrics of sewing, knitting, and weaving industries is shown in Figure 1.

Structural diagrams of the topology of traditional structural design (Figures 1 a, c) and object-oriented design (Figures 1 b, d, e) of CMTS technological machines for manufacturing 3D textile structures are shown in Figure 1.

Object-oriented analysis for implementing mechanical technology to produce 3D fabrics based on sewing, knitting, or weaving technological equipment begins with the decomposition of the mechanical and technological system of the target purpose into an “object”.

Table 1 – Methods and equipment for manufacturing mechanical and technological frame structures of 3D objects from textile materials

Way	Advantages	Disadvantages
Textile method: – looms; – weaving machines; – knitting machines	Possibility of using mechatronic modules for sewing equipment integrated with looms	1. Complexity of designing and operating mechanical and technological systems with computer control. 2. Traditional weaving processes have limitations for creating complex 3D shapes from textiles. 3. 3D form creation by weaving is limited by their length and complexity by the implementation of the weaving method
Sewing method: – special sewing machines; – automatic embroidery machines	Highly efficient usage of modernized existing technological equipment	When textile and garment industries are combined, there is a need to increase production areas
Forming method: – equipment for forming 3D preforms from fibers, threads, and non-woven materials	Simplicity and cost-effectiveness of manufacturing 3D preforms	There is no frame structure, and therefore low strength of 3D preforms
Round winding method of 3D pre-forms	High productivity	There is no frame structure and a limited range of 3D preforms variations
Method of laying out textile cut details for 3D preforms of different thicknesses: – manual layout; – robotic layout	Possibility of manufacturing complex 3D preforms for composite parts of general and special mechanical engineering	High cost of hardware and software of robot technological systems with technical vision sensors
Additive technologies in combination with loom, knitting, and weaving methods	Possibility for creating objects of complex 3D preforms with the simultaneous formation and fixation	Limited usage of material types and their cost

Simultaneously, implementing the work process according to the cycle diagram of a sewing machine, knitting machine, or loom is considered. That is, the order-temporal interaction of all object = working tool of target purpose with each other, object = threads (yarn), and object = 2D-textile is formalized in terms of delegation of functions (messages) from parent object to descendant object according to principle of inheritance [42, 43].

In traditional 3D CMTS design of textile structures, metric synthesis is performed first, and then kinematic and dynamic analysis of the technological machine, that is, the mechanical component of the CMTS.

The technological component of SMTS begins to be developed from the analysis stage and ends with the synthesis stage of the 3D textile structure.

The structural diagram of the topology of the traditional CMTS design is shown in Figures 1 a, c. It is reduced to the design of separate mechanisms and the cyclogram of their interaction in the formation of 1 stitch (sewing technology), one report of the interweaving of loops, strokes, or sketches of threads or yarn (knitting technology), and the cycle in other mechanical technologies in the production of 3D textile structures.

The structural scheme of the topology of OOD CMTS 3D textile structures on the examples of sewing, knitting machines, and mechatronic models is shown in Figure 1, b, d. OOD, like OOP, is a design technique based on decomposing the designed system into objects that interact with each other in the form of execution requests – program codes in a high-level language.

Thus, the object is a key concept of OOP and OOD. The object is an independent element of the designed CMTS with fully defined functional responsibilities. Each object encapsulates its data (fields) and methods or algorithms (formulas) for processing (calculating) these data or functions.

Inheritance, encapsulation, and polymorphism are the main principles of software construction of access and interface of objects of a related class and objects that do not have a common parent.

The article deals mainly with original micro-objects, mini-objects, and macro-objects of 3D textile structures. They are built on field inheritance and the OOD method for various industrial productions of 3D textile structures. Object-oriented analysis (OOA) is considered in the form of an algorithmic description of the objects of the target application, which generates object-oriented synthesis (OOS). OOS is the implementation of a program code algorithm.

OOA in the design of object = 3D-fabric using the mechanical technology of sewing production is considered when interacting with the “responsibilities – delegation (inheritance)” dyad.

To perform shuttle stitches or flat chain stitches [27] in the machine, there are the following typical working units (tools) that interact with each other, threads, and material: needle, shuttle (looper), thread tensioner (thread feeders), toothed rack, presser foot, needle plate, needle thread tension regulator, shuttle tension regulator (loop) thread and means of stitch length adjusting.

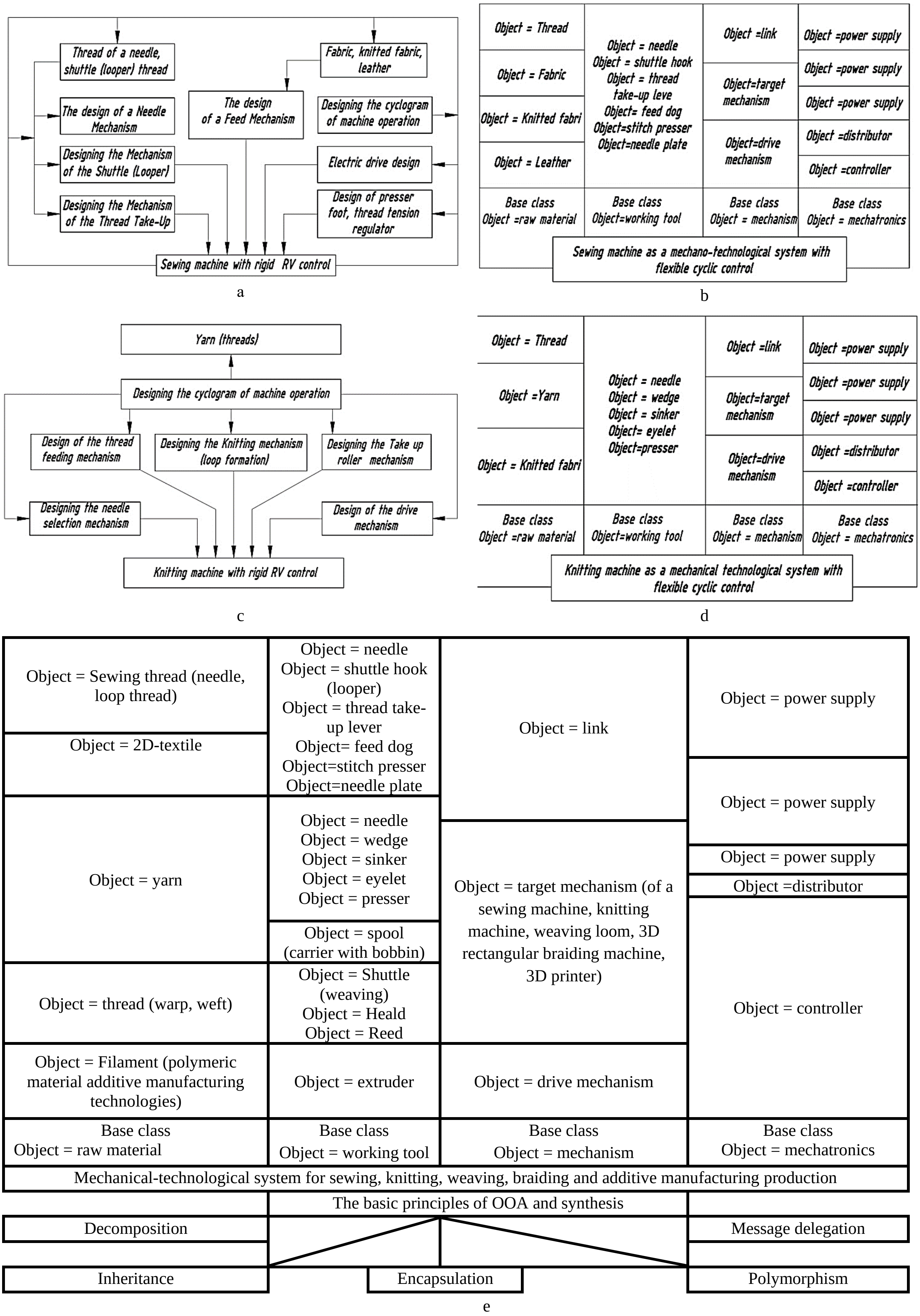

Figure 1 – Structural diagrams of the topology of traditional structural design (a, c) and object-oriented design (b, d, e) for CMTS technological machines for the manufacture of 3D textile structures

The first four working tools belong to forming stitches and are considered when constructing a cyclogram of machine operation because their position depends on the angle of rotation of the main shaft. Others ensure the quality of formation of shuttle stitches and seams, and kinematic connections with the main shaft are absent for them.

Needle responsibilities are piercing materials, passing needle thread through materials, hinges forming, and delegation (inheritance) of the performed duties to shuttle, thread puller, and toothed rail, according to the cyclogram of the machine's operation.

Shuttle responsibilities are hinge capturing and expanding, the encirclement of the hinge around the bobbin holder with a bobbin with shuttle thread and bobbin cap, retention by the shank of overlay plate of hinge thrown from the nozzle of the shuttle, interweaving of needle and shuttle threads to form a knot, and delegation (inheritance) of performed duties to thread puller and rack, according to cycle diagram of machine operation.

Thread puller responsibilities are serving thread to the needle during its movement in the material until the moment of hinge formation, serving thread to shuttle from the moment when the hinge is captured by the nose until the moment of maximum expansion of the hinge, pulling needle thread from shuttle device and winding shuttle thread from bobbin, stitch tightening and winding needle thread from bobbin or coil, and delegation (inheritance) of performed duties of gear rack, according to cyclogram of machine's operation.

Gear rack or curb frame (ring with the material) responsibilities are moving the material to a specified stitch length with a stop when the needle is in the material, considering the task of automatic stitch length regulator, stitch length adjustment, and delegation (inheritance) of performed duties of the needle of the presser foot of needle plate according to cycle diagram of machine's operation.

Presser foot responsibilities are as follows:

– ensuring kinematic linkage in the mechanical-technological system: toothed rail – material – sole of presser foot when moving material to a given stitch length and in the mechanical-technological system (toothed rail – material – needle plate when the material is hanging);

– delegation (inheritance) functions of the machine servo control pedal to the main shaft at the beginning of sewing process when the presser foot is in a lower position;

– delegation (inheritance) of pressing microvolume of textile material to the toothed rail during the phase of moving material when the needle is above the material;

– delegation (inheritance) of functions to the main shaft, which means for all stitch-forming working units at the end of the sewing process when the presser foot is in the upper position.

Needle plate responsibilities are:

– delegation (inheritance) of keeping material under the presser foot when the needle is above material and in material, and there is a circular hole in the needle plate, which centers the needle axis.

– separation of teethes tops trajectory of the toothed rack into working and idle sets due to the presence of longitudinal slots in needle plate for passage of teeth of the toothed rack;

– delegation (inheritance) of necessary conditions of the presser foot and toothed rail for moving material when the needle is above material and conditions for material to stay when the needle is in the material.

The needle thread tension regulator and shuttle thread tension regulator's responsibility is delegation (inheritance) of the moment for needle and shuttle threads of free feeding of necessary thread length to form the next new stitches.

Thus, in a generalized form, using OOA at the entrance of mechanical technology, we have from 4 to 22 "ingredients" (ingredients of technological mode) – a sewing machine, needle threads (up to 15 needles when using an embroidery machine), one shuttle thread and, for example, 5 layers of textile material.

As an output of mechanical technology of 3D fabric formation, after getting the result of mechanical technology implementation. With each machine stitch performed, the difference between "ingredients" and the result of mechanical technology decreases. Furthermore, when this difference becomes equal to one, one new 3D object is obtained with new physical and mechanical properties, purpose, and operational properties.

Figure 2 shows an example of the inheritance principal scheme of a global class of objects during the object-oriented analysis of the mechanical and technological structure of 3D fabrics using the mechanical technology of weaving production.

By analogy, diagrams of the inheritance principle of a global class of objects were constructed during the object-oriented analysis of mechanical and technological structure using mechanical technology of sewing production (Figure 3) and 3D knitted fabric using mechanical technologies of knitting production (Figure 4) and knitting production (Figure 5).

According to the principle of OOP polymorphism, the 3D-micro-model has properties of related objects as objects with one common parent object, to which various OOA methods can be applied.

According to the principle of inheritance in OOP [1, 23–25], object = 3D-micro-model (Figures 1–3) of textile material element inherits its physical and mechanical properties to objects of the upper level of the object hierarchy, namely, warp threads, weft threads of 2D fabric or hinges of knitted fabric object 3D-macro-model from textiles.

Simultaneously, object = 2D-mini-model inherits all data (fields) and methods (algorithms or steps of calculating analytical functions) from object = 3D-micro-model, and the object=3D-macro-model inherits from object = 2D-mini-model all its data and methods.

Descendant objects can supplement related objects with new data in program code and replace (overwrite) methods of parent objects or supplement them. During 3D geometric modeling, OOP data program code is "hidden" behind target menu icons, which users call when working with "object-sketches", "object-details", "object-assemblies", and "object-drawings".

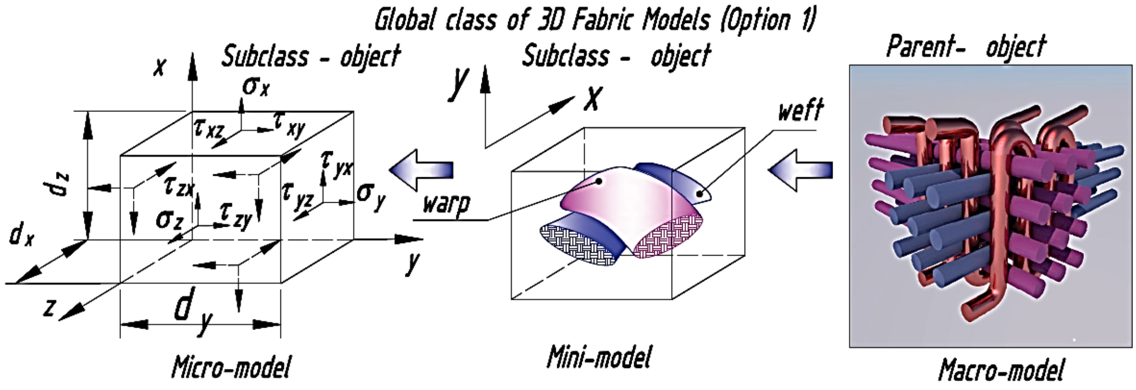

Figure 2 – Scheme of inheritance principle of a global class of objects in the object-oriented analysis of the mechanical and technological structure of 3D fabrics using mechanical technology for weaving production

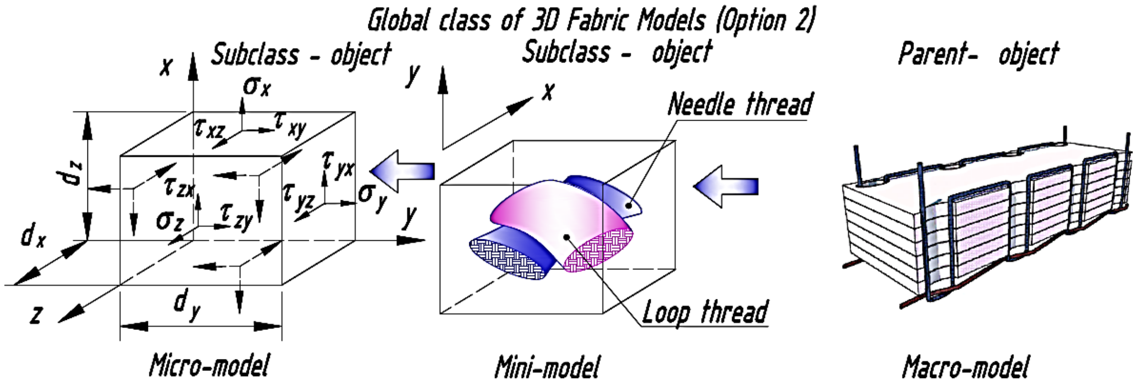

Figure 3 – Scheme of inheritance principle of a global class of objects in the object-oriented analysis of mechanical and technological structure of 3D fabrics using mechanical technology for sewing production

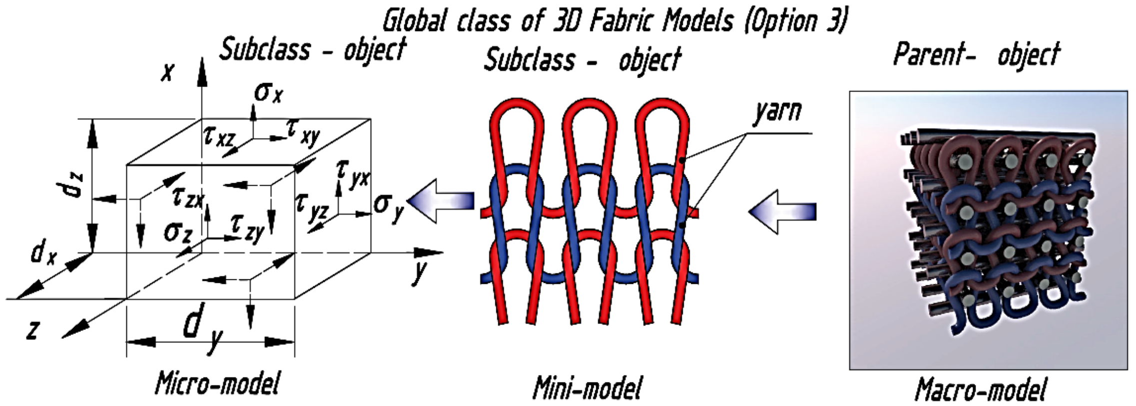

Figure 4 – Scheme of inheritance principle of a global class of objects in the object-oriented analysis of mechanical and technological structure of 3D fabrics using mechanical technology for knitted production

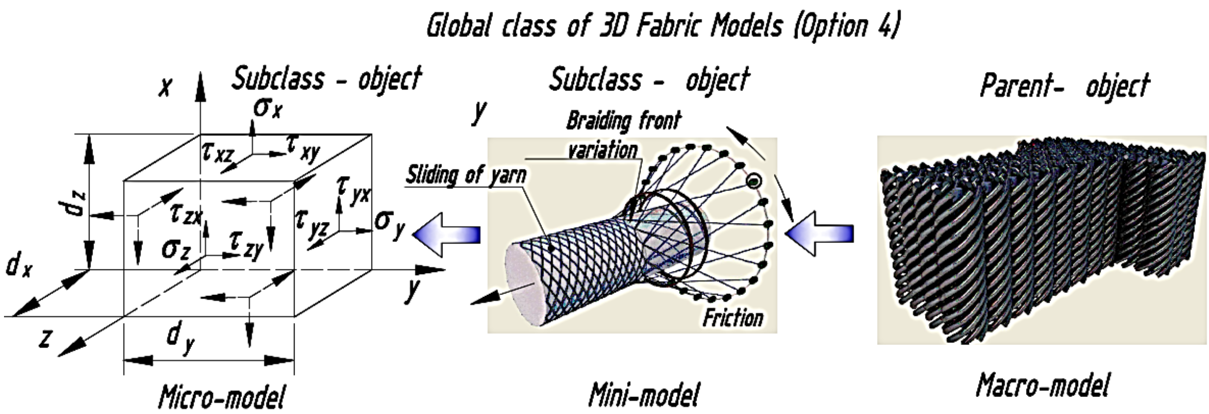

Figure 5 – Scheme of inheritance principle of a global class of objects in the object-oriented analysis of mechanical and technological structure of 3D fabrics using mechanical technology for weaving production

The program code of OOP methods is also hidden behind icons of the target menu when constructing a mesh of 3D-part or 3D-environment when studying deformations (displacements).

Object = 3D-micro-model in stretches and deformations for warp and weft threads of 2D-fabric and 2D-knitwear at OOA are considered as axially symmetric and plane-parallel problems when only two geometric coordinates are significant.

Micro-models of 3D-fabric and 3D-knitted-fabrics are a description of the 3D stress-strained state of micro-volume of material and require following mathematical formulation of the problem of static elasticity (or stress-strained state) that can be represented in vector form, includes three equations: equations of motion and balance, a geometric equation for the tensor of small deformations and physical equation in Hooke's generalized law form.

4 Results

Based on principles of micromechanics for elastic anisotropic material, Hooke's generalized law is a linear ratio between stress and strain defined as follows:

$$\{\sigma\} = [C]\{\varepsilon\}, \tag{1}$$

where $\{\sigma\} = \{\sigma_{11}\ \sigma_{22}\ \sigma_{33}\ \sigma_{23}\ \sigma_{31}\sigma_{12}\}^{\mathrm{T}}$ – stress component vector; $\{\varepsilon\} = \{\varepsilon_{11}\ \varepsilon_{22}\ \varepsilon_{33}\ \varepsilon_{23}\ \varepsilon_{31}\ \varepsilon_{12}\}^{\mathrm{T}}$ – deformation components vector; $[C]$ – matrix of elastic stiffness constants, which has 21 independent constants out of 36 parameters:

$$[C] = \begin{bmatrix} C_{11} & C_{12} & C_{13} & C_{14} & C_{15} & C_{16} \\ C_{21} & C_{22} & C_{23} & C_{24} & C_{25} & C_{26} \\ C_{31} & C_{32} & C_{33} & C_{34} & C_{35} & C_{36} \\ C_{41} & C_{42} & C_{43} & C_{44} & C_{45} & C_{46} \\ C_{51} & C_{52} & C_{53} & C_{54} & C_{55} & C_{56} \\ C_{61} & C_{62} & C_{63} & C_{64} & C_{65} & C_{66} \end{bmatrix}. \tag{2}$$

Expression (1) has the following inverse form:

$$\{\varepsilon\} = [\mathrm{S}]\{\sigma\}, \tag{3}$$

where [S] – the inverse matrix to $[C]$:

$$[S] = [C]^{-1} = \begin{bmatrix} S_{11} & S_{12} & S_{13} & S_{14} & S_{15} & S_{16} \\ S_{21} & S_{22} & S_{23} & S_{24} & S_{25} & S_{26} \\ S_{31} & S_{32} & S_{33} & S_{34} & S_{35} & S_{36} \\ S_{41} & S_{42} & S_{43} & S_{44} & S_{45} & S_{46} \\ S_{51} & S_{52} & S_{53} & S_{54} & S_{55} & S_{56} \\ S_{61} & S_{62} & S_{63} & S_{64} & S_{65} & S_{66} \end{bmatrix}, \tag{4}$$

where S_{ij} are the elastic malleability coefficients.

For small deformations in the Cartesian coordinate system, deformations can be defined as follows:

$$\varepsilon_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right), \tag{5}$$

where x_i – three coordinates in the Cartesian system; u_i – movements in directions of three Cartesian coordinates; $i = \{1, 2, 3\}$.

For the 3D-micro-model of orthotropic material that contains 3 orthogonal symmetric planes, where there are only 9 independent elastic stiffness constants, expression (1) assumes the form (6):

$$\begin{Bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{33} \\ \sigma_{23} \\ \sigma_{31} \\ \sigma_{12} \end{Bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ C_{12} & C_{22} & C_{23} & 0 & 0 & 0 \\ C_{13} & C_{23} & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66} \end{bmatrix} \begin{Bmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \varepsilon_{33} \\ 2\varepsilon_{23} \\ 2\varepsilon_{31} \\ 2\varepsilon_{12} \end{Bmatrix}. \tag{6}$$

Similarly, there are only 9 independent constants of elastic malleability and malleability matrix (7) for the 3D-micro-model of composite material is defined as follows:

$$[S] = \begin{bmatrix} 1/E_1 & -\nu_{12}/E_1 & -\nu_{13}/E_1 & 0 & 0 & 0 \\ -\nu_{12}/E_1 & 1/E_2 & -\nu_{23}/E_2 & 0 & 0 & 0 \\ -\nu_{13}/E_1 & -\nu_{23}/E_2 & 1/E_3 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1/G_{32} & 0 & 0 \\ 0 & 0 & 0 & 0 & 1/G_{31} & 0 \\ 0 & 0 & 0 & 0 & 0 & 1/G_{12} \end{bmatrix}, \tag{7}$$

where E_1, E_2, E_3, G_{12}, G_{31}, G_{23}, ν_{12}, ν_{13}, ν_{23} – engineering constants.

Frame 3D textile structures, defined as object=2D-mini-models in Figures 2 and 3, are single-layer preforms for parts and products manufacturing from composite materials. Physico-mechanical properties of frame 3D textile structures make it possible to predict their further behavior in 3D composite materials reinforced with 3D textile structures.

Physico-mechanical properties of synthetic and artificial fibers of warp and weft threads object = 2D-mini-models are anisotropic amorphous polymer materials, to which object = 3D-micro-models delegate (inherit) their physical and mechanical properties of object = 3D-macro-models.

The research works [39, 40] used the methodology and experimental machine to determine the dynamic modulus of elasticity E_d and attenuation decrement δ (phase delay angle of elastic deformations from mechanical tensions under established harmonic loads) of textile fibrous materials by resonance method for such materials.

Dynamic modulus of elasticity E_d (MPa) was determined as follows:

$$E_d = \frac{4\pi^2 ml}{ST_P^2}, \tag{8}$$

where m – the mass of holder and 2D-textile sample, kg; l – working length of sample, m; S – cross-sectional area of 2D-textile sample, m²; T_P – period of oscillations at the resonance, s.

The attenuation decrement δ was determined by the width of the resonant trough of the amplitude curve of exciting electromagnetic force at a constant amplitude of textile sample oscillations.

Resonance occurs when the textile sample's natural frequency coincides with the external electromagnetic force's oscillation frequency. The amplitude of continuous oscillations of the sample is established by changing the magnitude of the exciting force when resonance occurs.

Then the exciting electromagnetic force is increased N times, which leads to the proportional increase in continuous oscillations amplitude (resonance zone of oscillations):

$$N = \left(\frac{I_N}{I_P}\right)^2, \tag{9}$$

where I_N, I_P – the excitation current corresponds to the harmonic electromagnetic excitation force of the textile sample with excitation force increased by N times.

Then, changing the exciting force frequency achieves decreased oscillations and increased amplitude to a given value corresponding to a resonant one. Corresponding values of oscillation frequencies determine the width of the resonant cavity. The following formula determines the magnitude of logarithmic attenuation decrement:

$$\delta = \frac{\pi(T_1 - T_2) \cdot T_P}{T_1 \cdot T_2 \cdot \sqrt{N^2 - 1}}, \tag{10}$$

where T_P – period of resonance oscillations, s; T_1 – oscillation period at a given amplitude, lower than resonant one, s; T_2 – oscillation period at a given amplitude, higher than resonant one, s; N – number of increase in excitation force.

Figure 6 shows typical diagrams in polar coordinates [39] of static E_s and dynamic modulus E_d of elasticity (respectively, Figures 6 a, b) and typical diagrams of logarithmic attenuation decrement δ (Figure 6) loaded at different angles to warp threads of 2D-textile samples of different proportions and fiber composition.

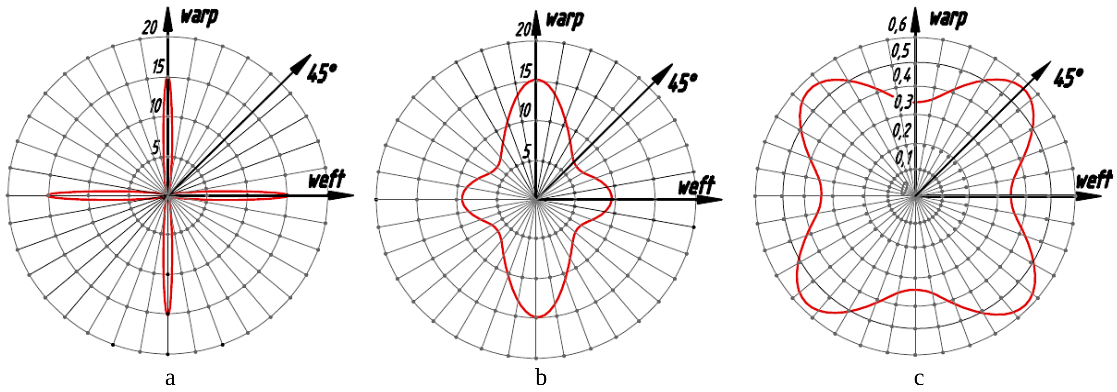

Figure 6 – Typical diagrams in polar coordinates of fabric's viscoelastic characteristics:
a – static modulus E_s; b – dynamic modulus of elasticity E_d; c – logarithmic attenuation δ

Using expressions (9) and (10), when moving to analysis from object = 2D-mini-model to object = 3D-macro-model of frame 3D-textile structures, obtained the following expressions for the dynamic modulus of elasticity E_d and for logarithmic decrement of attenuation δ for 2 layers (11) and (12), and 3 layers (13) and (14) of textile materials of composite preforms:

$$E_d^{II} := \frac{E_1 E_2}{E_1 + E_2} k_{MT}; \tag{11}$$

$$\delta^{II} = \frac{\delta_1 \delta_2}{\delta_1 + \delta_2} k_{MT}; \tag{12}$$

$$E_d^{III} = k_{MT} \prod_{i=1}^{3} E_i \sum_{i=1}^{3} [E_i(E_{i+1} + E_{i+2}) + E_{i+1}E_{i+2}]^{-1}; \tag{13}$$

$$\delta^{\mathrm{III}} = k_{MT} \prod_{i=1}^{3} \delta_i \sum_{i=1}^{3} [\delta_{\mathrm{i}}(\delta_{i+1} + \delta_{i+2}) + \delta_{i+1}\delta_{i+2}]^{-1}, \tag{14}$$

where k_{MT} – the mechanical and technological coefficient of frame 3D-textile structures:

1) k_{MT} = 0.9–1.0 – for frame textile 3D structures of knitting and weaving production methods;

2) k_{MT} = 1.0–1.1 – for textile 3D structures of sewing production;

3) k_{MT} = 1.1–1.2 for textile 3D structures of weaving production.

For textile 3D structures of weaving production, the mechanical and technological coefficient is calculated considering angle α of inclination of warp threads (Figure 7), which fasten layers of the 3D textile structure after weft threads are moved to the fabric edge by loom.

The binding threads of the base prevent the textile 3D structure from delaminating.

$$\alpha = arctg\left(\frac{h}{Nl_y}\right), \tag{15}$$

where h – height of the 3D textile structure; N – weft threads quantity on the projection of inclined section of fastening threads of the base; l_y – weft threads step.

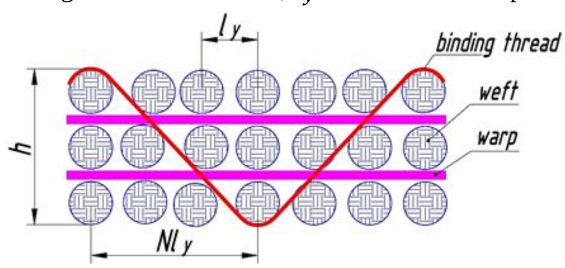

Figure 7 – Scheme for calculating the mechanical and technological coefficient of frame 3D textile structures

5 Discussion

For 3D geometric modeling and research of 3D textile frames, modern software products, such as SolidWorks or others, should be used.

At the final stage of OOP (OOA + OOS), visualization of fields (color fills) of stresses and deformations of 3D-macro-models of textile structure (Figures 2–5) is performed based on 3D-micro-model of textile structure using the principle of mathematical models' inheritance of Hooke's law in the form of its functionally-adequate numerical analog using methods of finite elements [24].

Such programmatic and logical cause-and-effect relationships occur at all stages of object-oriented analysis and object-oriented synthesis during the automated design of 3D macro-models of textile structures of various origins and applications.

6 Conclusions

A method of object-oriented analysis of frame 3D textile structures for composite materials using work processes of mechanical technology of weaving, knitting, and sewing industries was developed.

Cause-and-effect relationships in object = 3D-micro-model, object = 2D-mini-model, and object = 3D-macro-model of frame 3D textile structures were generalized in terms and principles of object-oriented design.

It was emphasized that matrix mathematical models (1) – (7) of micromechanics of elastic anisotropic textile materials (Figure 6) are inherited by the preprocessor, processor, and postprocessor during the automated design of frame 3D textile structures.

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