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Andrei Biziuk and Natalia Yasinskaya

A New Approach to Modeling Reinforcing Textile Structures for Composite Materials

Andrei Biziuk[1, a)] and Natalia Yasinskaya[2]

[1]Vitebsk State Technological University, Faculty of Information Technology and Robotics, Department of Information Systems and Production Automation, Moscow Av., 72, 210038 Vitebsk, Republic of Belarus
[2]Vitebsk State Technological University, Faculty of Manufacturing Technology, Department of Ecology and Chemical Technology, Moscow Av., 72, 210038 Vitebsk, Republic of Belarus

[a)] Corresponding author: biziuk.andrei@gmail.com

Abstract. The properties of composites largely depend on the properties of the reinforcing bases. When using woven textile materials as a reinforcing base for composites, it is necessary to pre-model the structure of this base. In this paper, the authors propose to use simulation modeling of textile materials to predict their properties. As a result, software for the simulation of textile materials has been developed, which can be used for industrial and scientific purposes. Three-dimensional models of textile materials can be used in modeling their impregnation with polymers.

INTRODUCTION

Polymer composite materials are the basis for creating a wide variety of household and technical products. Among modern polymer composite materials, reinforced (fiber polymer composites) are of great importance, the use of which provides significant advantages in terms of manufacturability, reducing the material consumption and cost of products, and improving their operational characteristics [1].

Fiber polymer composites consist of a reinforcing fiber filler and a polymer matrix. One of the main tasks of introducing a reinforcing fiber filler into a polymer material is to increase the mechanical or other functional properties. Reinforcing fiber fillers include a large number of different types of structures made on the basis of fibers and textile threads: braid and knitted fabrics, woven and voluminous structures, non-woven materials. The choice of the reinforcing structure is determined by the requirements associated with the various impacts to which the composite material product is subjected during operation. In recent years, fabrics and layered woven packets have been an integral part of the production of polymer composites. The woven base allows to make a variety of complex parts, the characteristics of which are incomparably higher than those of products based on fibers. In addition, the use of fabrics allows to reduce labor costs by eliminating manual laying operations and replacing sequentially laid layers in the product with an integrated system of reinforcing elements [2].

In reinforcing fabrics, the main (simple) weaves are most often used — linen weaves, twill weaves, atlas (satin) weaves, as well as other simple weaves — matting; crepe weaves [3]. A significant part of the reinforcing fabrics is produced by plain weave, as it provides the strongest connection between the warp and weft threads. The plain weave forms the same front and back sides. With the same linear density and density of the warp and weft threads, equally strong fabrics are obtained. Atlas and satin weaves include fairly long overlaps — straight sections of threads. This is essential for obtaining stronger composites, since the length of the overlaps is significantly longer than the critical length of the fibers or filaments in the finished composites. In addition, when producing layered plastics (textoliths), the direction of the threads more closely corresponds to the direction of the acting stresses in the finished material. Twill weave forms characteristic stripes on the surface of the fabric, located at an angle close to 45° to the direction of the base. In twill, the threads are less tightly arranged than in plain weave, and if all other things are equal, these fabrics are less durable than plain weave. Twill (satin) weave is characterized by the arrangement of one system of

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threads mainly on one (front) side — warp for atlas and the weft for satin, and on the wrong side — another system of threads. In addition, the front side has a more even, smoother surface. The connections of the threads in the atlas (satin) weave are less than in the fabrics of the plain or twill weave. Fabrics of atlas and satin weaves are widely used for reinforcement of composite materials.

In the manufacture of fibrous polymer composites, in particular, the implementation of the process of impregnating the fibrous base with a binder, one of the most important characteristics is the ability to absorb and retain a viscous liquid. This ability is due to the capillary-porous structure of the fibrous material, and achieving a high quality of impregnation is the most important condition for creating a composite material that guarantees its specified physical and mechanical characteristics [4], [5].

The purpose of this work is to develop a method for obtaining a spatial model of the structure of woven reinforcing bases, suitable for use in the study of impregnation with a polymer binder.

MATERIALS AND METHODS

The problem of modeling the structure of textile materials is actively studied and there are several methods for solving it [6], [7], [8], [9]. Finite element modeling is often used. When using the finite element method, modeling is usually done at the thread level, rather than at the level of individual fibers. If it is necessary to use the model in the simulation of impregnation, it is necessary to take into account the relative position of the fibers inside the threads. In this paper, the authors propose a method for obtaining a model of a textile material based on the simulation of the interaction of individual fibers.

When designing composite materials based on textiles, it is necessary to choose the type of weave. Textile weaves can be encoded using a special scheme called "rapport". Rapport sets a repeating sequence of interweaving the warp and weft threads. In the Figure 1(a) the rapport of a plain weave is depicted.

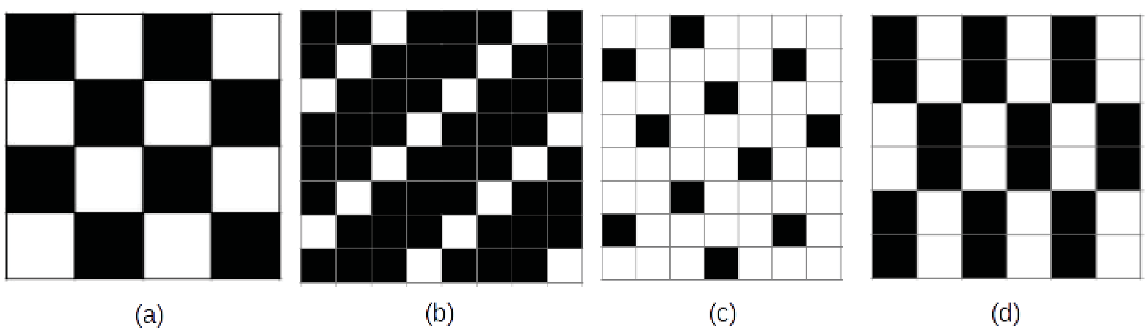

FIGURE 1. Rapports of textile weaves: (a) — plain; (b) — twill; (c) — satin; (d) - reps.

When modeling textile weaves, it is necessary to describe the trajectory of each thread using formulas. For a plain weave, the thread path will be well described by a periodic function based on the sine or cosine function. This method of modeling thread trajectories was used by the authors in [10]. If it is needed to model weaves other than plain, this method of modeling the thread trajectory will not work, since the trajectory behaves in a more complex way. In this paper, the authors propose a universal method for modeling the trajectories of threads set by an arbitrary rapport. In the figure 1(b, c, d) the rapports of other commonly used textile weaves depicted.

If we consider the trajectory of the thread in a weave other than plain, we can see that it is periodic, but the length of the sections on the front side and on the back side is different. To model such a trajectory, we need a function in which we can set the ratio between the length of the sections on the front and back sides. Such functions are known in physics and electronics and this relationship is called "duty cycle". Figure 2 shows a pulse periodic function with a period T and a pulse duration τ.

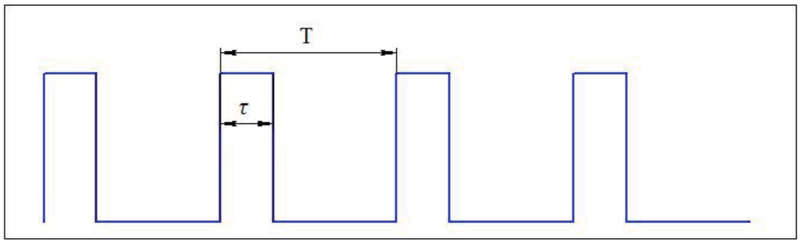

FIGURE 2. Pulse periodic function.

The duty cycle is the ratio between the period of the function and the duration of the pulse. To simulate a pulsed periodic function with a given duty cycle in electronics, the Fourier series is used, which allows us to approximate any periodic function with the necessary accuracy. The approximation of the pulse periodic function using a Fourier series looks like this:

$$f(t) = \frac{\tau}{T} + \frac{2}{\pi}\sum_{n=1}^{\infty}\left(\frac{1}{n}\cdot sin\left(\frac{\pi\cdot n\cdot\tau}{T}\right)\cdot cos\left(\frac{2\cdot\pi\cdot n\cdot t}{T}\right)\right) \quad (1)$$

In practice, it is impossible to calculate an infinite sum, so some few first terms are taken. The result of the approximation of the pulse periodic function with a duty cycle of $\frac{1}{3}$ using the first 40 elements of the Fourier series is shown in the Figure 3.

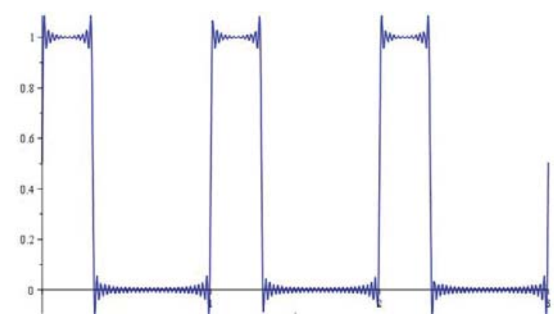

FIGURE 3. Approximation of the pulse periodic function.

As can be seen from the figure, there is high-frequency noise that will interfere with the further use of this approximation. We can also notice sharp outliers of the function up and down at the edges of pulse – the so-called "Gibbs phenomenon". In order to offset these negative approximation effects, we can apply the so-called "Cesaro Mean" or "Cesaro Summation". If we denote the sum of the first k terms of the Fourier series as a_k, then the Cesaro sum of this series can be written as:

$$\Phi_n(t) = \frac{1}{n+1}\sum_{k=0}^{n} a_k \quad (2)$$

Figure 4 shows the result of applying the Cesaro summation to the approximation of the pulse periodic function with a duty cycle of $\frac{1}{3}$ using the first 40 terms of the Fourier series.

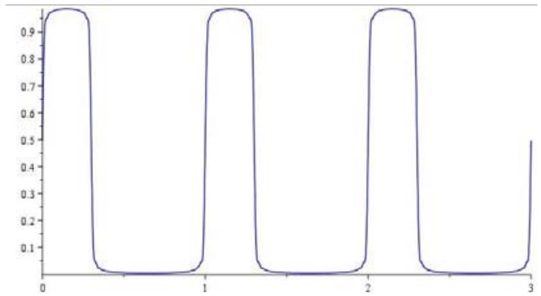

FIGURE 4. The result of applying the Cesaro summation.

By adjusting the duty cycle of the function, it is possible to approximate the thread path in the desired weaving pattern.

The method described above allows us to get a fairly accurate approximation, but the resulting function is too cumbersome for quick calculation during simulation. In addition, there will be problems when calculating the derivatives of this function at arbitrary points, which will be required in the future.

Another way to approximate the thread path in a textile weave is to use rectangular functions. A rectangular function is a function described by the following expression:

$$\Pi(t) = \begin{cases} 0, & if\ |t| > \frac{1}{2} \\ \frac{1}{2}, & if\ |t| = \frac{1}{2} \\ 1, & if\ |t| < \frac{1}{2} \end{cases} \tag{3}$$

The graph of the rectangular function is shown in Figure 5.

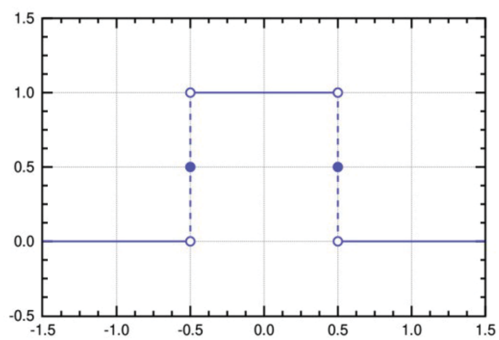

FIGURE 5. Rectangular function.

A rectangular function can be represented as the limit of a rational function:

$$\Pi(t) = \lim_{n\to\infty, n\in\mathbb{Z}} \frac{1}{(2\cdot t)^{2n}+1} \tag{4}$$

To approximate the trajectory of the thread in the weave, you can set some small n in (4). Figure 6 shows an approximation of a rectangular function at n=4.

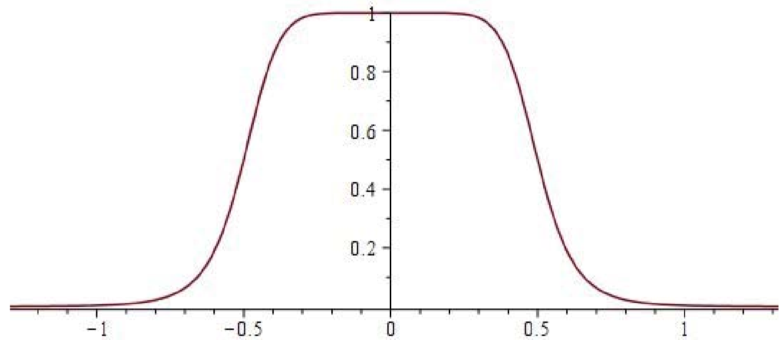

FIGURE 6. Approximation of a rectangular function

If we use a linear combination of approximations of the rectangular function, we can get the necessary trajectory of the thread in the weave. Figure 7 shows the graph of the function $\Pi(t-1) + 2 \cdot \Pi(t-3) + 0.7 \cdot \Pi(2 \cdot (t-5))$, which describes the trajectory of the thread with loops at the points with coordinates 1, 3 and 5.

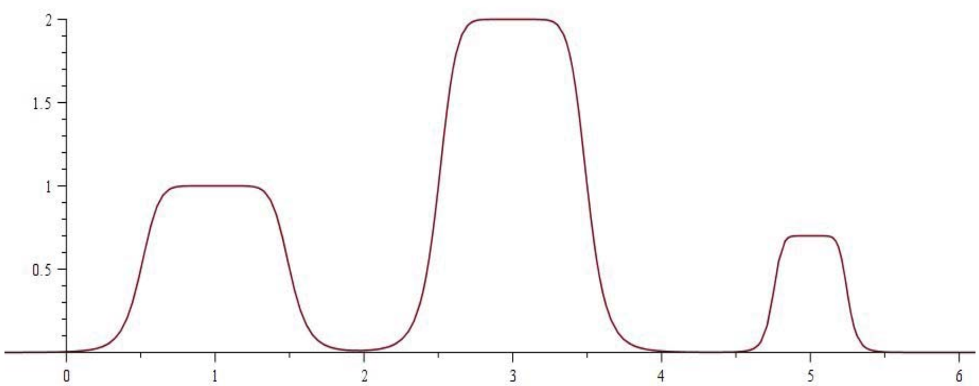

FIGURE 7. Combination of approximations of a rectangular function

The next stage of thread modeling is the description of the trajectories of individual fibers. The trajectory of each individual fiber in a twisted thread can be approximated by a helix. A helix with a rectilinear axis directed along the x-axis can be described by the following parametric equation:

$$\begin{cases} x = t \\ y = cos(t) \\ z = sin(t) \end{cases} \quad (5)$$

It is required to construct a helical line with an axis passing along the trajectory described by function (4) or a linear combination of such functions. To do this, we need to define a function that calculates the normal vector to the trajectory at a given point and a function that calculates the length of the trajectory from the starting point to the specified one. The function that sets the normal vector looks like this:

$$\mathrm{n(t)}=\begin{bmatrix} n(t)_x \\ n(t)_y \\ n(t)_z \end{bmatrix} = \begin{bmatrix} -\dfrac{f'(t)}{\sqrt{(f'(t))^2+1}} \\ 0 \\ \dfrac{1}{\sqrt{(f'(t))^2+1}} \end{bmatrix} \tag{6}$$

where f(t) — is a function of the thread path.

The function that calculates the length of the trajectory looks like this:

$$\mathrm{l(t)}=\int_0^t \sqrt{(f'(t))^2+1} \tag{7}$$

Now, using (4), (5), (6) and (7) we can define a function describing the trajectory of a single fiber in a thread described by its trajectory in the weave:

$$fib(t) = \begin{bmatrix} t + sin(l(t)) \cdot n(t)_x \\ cos(l(t)) \\ f(t) + sin(l(t)) \cdot n(t)_z \end{bmatrix} \tag{8}$$

In order to adjust the pitch of the turns of the helix and its radius, additional coefficients can be entered in the formula (8):

$$fib2(t,s,d) = \begin{bmatrix} t + s \cdot sin(l(t) \cdot d) \cdot n(t)_x \\ s \cdot cos(l(t) \cdot d) \\ f(t) + s \cdot sin(l(t) \cdot d) \cdot n(t)_z \end{bmatrix} \tag{9}$$

where d is the coefficient that regulates the number of turns of the helix per unit length of the thread; s is the coefficient that defines the radius of the helix.

Figure 8 shows the trajectory of a single fiber of the thread, the trajectory of which is given by the function $\Pi(t-1) + 2 \cdot \Pi(t-3) + 0.7 \cdot \Pi(2 \cdot (t-5))$.

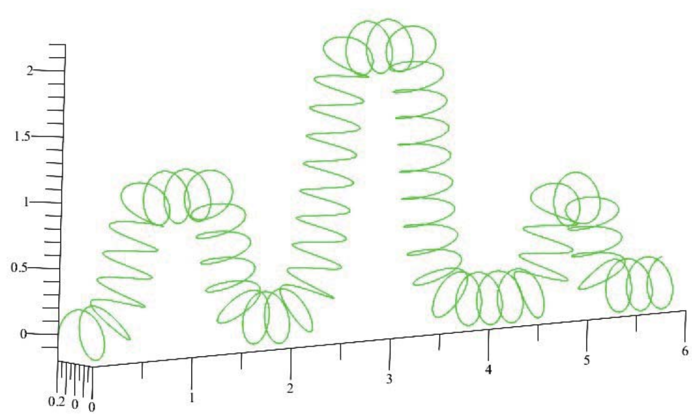

FIGURE 8. Trajectory of a single fiber

Each fiber in the thread has its own properties and the combination of these fibers forms a thread. The axis of the fiber does not have to coincide with the axis of the thread, so we can introduce parameters for the displacement of the helix along each of the coordinate axes into the formula (9):

$$fib2(t,s,d,r) = \begin{bmatrix} t + s \cdot sin(l(t) \cdot d + r_x) \cdot n(t)_x \\ s \cdot cos(l(t) \cdot d + r_x) + r_y \\ f(t) + s \cdot sin(l(t) \cdot d + r_x) \cdot n(t)_z + r_z \end{bmatrix} \quad (10)$$

where r — offset vector; r_x — offset along the x-axis; r_y — offset along the y-axis; r_z — offset along the z-axis.

In order to model a single thread, we need to model each fiber of this thread using the formula (10).

When simulating a section of fabric, each fiber of each thread is represented as a finite set of points in space, the coordinates of which are determined by the formula (10).

RESULTS AND DISCUSSION

To simulate a section of fabric with a given rapport software in the functional programming language Haskell was developed. Figure 9 shows a model of a section of fabric with a plain weave of threads, obtained with the help of this software.

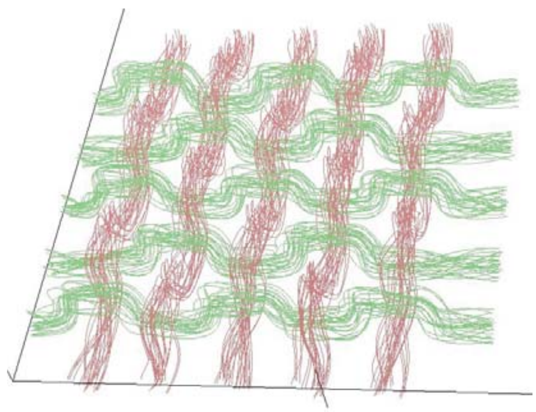

FIGURE 9. Fabric section model

The fibers in this model can intersect, since their parameters are set by a random number generator. For a more accurate representation of the structure of the fibers, a simulation of the interaction of the fibers with each other is applied, as a result of which the fibers are arranged in a more uniform structure. The result of this simulation is shown in Figure 10 (a).

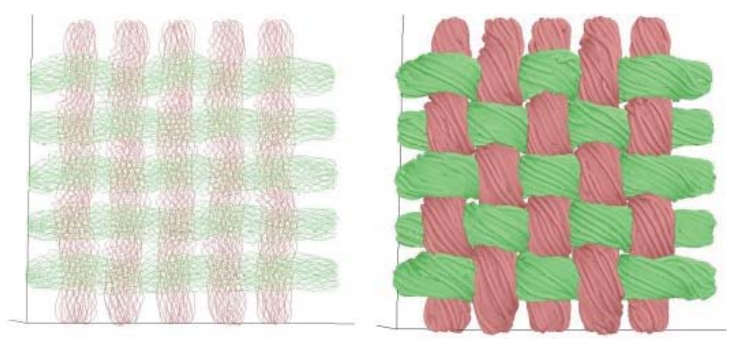

FIGURE 10. A section of fabric after modeling the interaction of fibers.
(a) - fibers in the form of lines; (b) - fibers in the form of tubes.

The software allows you to draw a three-dimensional model of each fiber in the thread in the form of a line, a set of points or a tube of a given diameter. Figure 10 (b) shows a model of a section of fabric with a display of fibers in the form of three-dimensional tubes.

Figure 11 shows the models of various non-plain weaves obtained using the developed software.

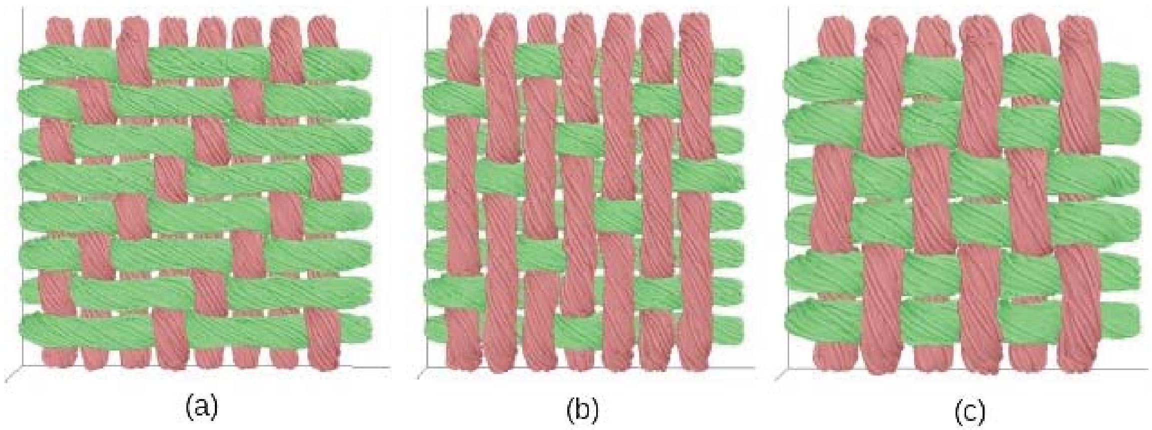

FIGURE 11. 3D models of textile weaves: (a) — twill; (b) — satin; (c) - reps.

CONCLUSION

As a result of this work, a method for modeling the trajectories of fibers and threads in an arbitrary textile weave using rectangular functions and helix equations is developed. The method was implemented in software that allows us to simulate a section of a woven reinforcing base with a given rapport for further use in the study of their impregnation with polymer binders.

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