Indian Journal of Science and Technology, Vol 9(46), DOI: 10.17485/ijst/2016/v9i46/107492, December 2016
ISSN (Print) : 0974-6846
ISSN (Online) : 0974-5645

Optimization of Technological Parameters of Impregnation of Load-Bearing Rod Elements of Reflector made of Polymer Composite Materials by Transfer Molding Method

Dmitry Golovatov[1*], Maxim Mikhaylov[1] and Aleksey Bosov[2]

[1]The Bauman Moscow State Technical University, Moscow, Russia; gda.mgtu@mail.ru, mms.mgtu@mail.ru
[2]Materials Processing Technology Ltd bav.tpm@mail.ru

Abstract

Objectives: Actuality of the study is based on rapid development of polymer composite materials and their increasingly greater application in space industry. **Methods:** Consequently this work is focused on optimization of technological parameters of impregnation of load-bearing rods of transformable guy-roped type aerial reflectors made of polymer composites by transfer molding method. The main approach to the study of this problem is simulation of transfer molding process with computer-aided engineering system by the finite element analysis. **Findings:** Features of simplification of geometric models of power rod elements and simulation of transfer molding process are described. Calculations of impregnation velocity of perform model, impregnation time as well as fields of resin pressure distribution by volume of perform model are carried out. **Improvements:** According to results of the calculations, type of resin feeding into perform volume is selected.

Keywords: Polymer Composite Material, Transfer Molding, Finite Element Analysis, Technological Parameters

1. Introduction

Future development of radio astronomy, solar energy, space communication, investigation of the earth surface and other planets from space nowadays directly associated with possibility of space launch of large structures of different type and assignment: space telescopes and telecommunication antenna systems, energy and scientific platforms, solar cell batteries, etc. One of important and rapidly developing directions in area of space structures creation is a development of large transformable antennas for space communication, mounted on spacecrafts of different assignment.[1-4]

Load-bearing rod elements are included into the most of space communication antennas with high weight effectiveness and thermal stability. It is promising to produce such elements by transfer molding method from polymer composite materials (PCM) which have widespread application in space technology and support structures.[5,6]

Method of product producing from PCM by transfer molding is that pressurized resin is fed into enclosure of rigid die mould. This method of forming allows producing structures with high geometry fidelity, constant density in terms of volume and practically without voids or local lamination of material.[7-9]

Characteristics of product produced by transfer molding depend on the method of resin feeding (point or frontal). For the purpose of time minimization for impregnation of products made of PCM and reduction of void space occurrence probability in volume of preform model it is necessary to conduct analysis and subsequent optimization of technological parameters of impregnation process of load-bearing rod elements made of PCM by transfer molding.[10]

Investigations were conducted in that respect on

* Author for correspondence

reducing of preform filling time, definition of minimum amount of resin feed points and their positions. Investigations were conducted with the help of Voronoi diagram.[7,11] Investigations directed to reduction of incompletely impregnated parts of preform during transfer molding were also conducted through which calculated void spaces, their size and place of forming have coincided with experimental measurements.[12,13]In some works defining of the role of point's amount for feeding resin into preform under pressure is conducted with account of filling velocity, which in its turn adversely affects uniformity of resin distribution.[14,15]

2. Concept Headings

Optimization of technological parameters of impregnation process of load-bearing rod elements of reflector made of polymer composite materials by transfer molding is conducted with the help of engineering review by finite element analysis.

Engineering review represents a complex of tests, designed for assessment of ability of equipment, structures and also products produced to bear a project load and to work at rated duty.

In modern design various program packages of computer-aided engineering (CAE) are widely used, which allow to conduct engineering review of computer models without real experiments.

CAE is a common name for programs and program packages designed for solution of different engineering tasks: calculations, analysis and simulation of physical processes. Calculation part of program packages typically is based on numerical computation of differential equations (finite element analysis, finite volume method, finite difference method, etc.).

CAE systems represent a variety of program products, which allow assessing with the help of calculation methods how the product computer model will behave under actual operating conditions. These systems help to ensure product working capacity without heavy spending of time and money.

Most common and effective calculation method, applied in CAE systems is a Finite Element Analysis (FEA). Systems which use FEA as numerical analysis of technical constructions are called FEA systems.

Modern CAE are used together with CAD systems and often are integrated in them. In this case they are called hybrid CAD/CAE systems.

Overview of FEA

Analysis by FEA starts with digitalization of the region of interest (task area) and its compartition into cells of a mesh. Such cells are called finite elements (FE).

FE may have different shape. In contrast to real construction FE in discrete model are connected together only in isolated points (nodes) determined by finite amount of nodal parameters.

Selection of suitable elements with necessary amount of nodes from the library of accessible elements is one of the most important decisions for a user of FEA package. Designer also must set a total amount of elements (their size in other words).

FEA classical form is known as *h*-version. Piecewise polynomials of constant degrees are used in this method as a shape function and accuracy is increased through decrease of the cell size. The *p*-version uses a fixed mesh and accuracy is increased through increase of the shape function degree. Common rule is that the more amount of nodes and elements (в *h*- version) or the higher shape function degree (*p*-version), the solution is more accurate, but more expensive from calculation point of view.

The next step is assembling. Assembling is a combination of individual elements into finite element mesh. From a mathematical standpoint assembling consists in assembly of rigidity matrixes of single elements into one global rigidity matrix of entire construction. In this case two numbering systems of element nodes are fundamentally used: local and global. Local numbering is a constant nodal numbering for each type of FE in accordance with introduced local coordinate system on the element. Global nodal numbering of entire construction may be absolutely random, as well as global numbering of FE. However one-to-one correspondence exists between local numbers and global numbers of nodes, on the base of which global system of finite element equations is formed.

Approximation

FEA refers to discrete analysis methods. However in contrast to numerical methods based on mathematical digitalization of differential equations, FEA is based on physical digitalization of object being examined. Real construction as continuous medium with a lot of infinite number of degrees of freedom is replaced by discrete model of interconnected elements with finite number of degrees of freedom. Since possible number of discrete models for continual region is infinitely large, the major task consists in selection of the model that approximate this region best of all.

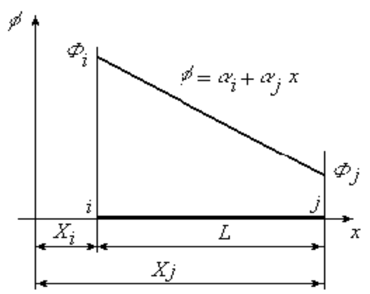
Subject matter of continuous medium approximation by FEA is as follows:

- Region of interest is divided into certain number of FE and family of elements across the region is named the system or FE mesh;
- It is expected that FE are connected together in finite number of points – nodes, situated along the outline of each FE;
- Polynomial approximant is set for each FE.

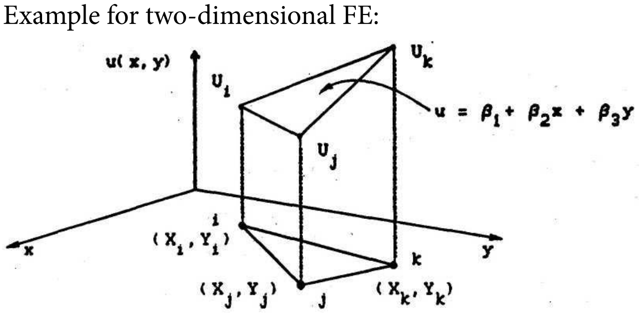
Approximating functions:
Polynomial approximant for one-dimensional FE:

$$u(x) = \sum_{i=0}^{r} a_i x^i$$

Example for one-dimensional FE:



Example for two-dimensional FE:



Polynomial approximant of the second order:

$$u^e(x,y) = \beta_1 + \beta_2 x + \beta_3 y + \beta_4 x^2 + \beta_5 xy + \beta_6 y^2$$

Polynomial approximant degree defines number of nodes for each element. It should be equal to the number of unknown coefficients α_i, included into polynomial.

Required functions within each FE (for example, distribution of displacements, deformations, strains, etc.) are expressed with the help of approximating functions through nodal values, which represent main unknown FE.

Required approximating function:

$$u(\bar{x}) = \sum_{i=0}^{r} h_i(\bar{x}) q^i$$

Where: $h(x)$ = co-ordinate /basic functions, so called shape function; q = unknown coefficients (nodal values).
In matrix view:

$$\overline{U}(\bar{x}) = \overline{H}\overline{U}$$

Approximation usually gives approximate but not exact description of real distribution of required values in the element. Because of that the results of structural analysis in the general case are also approximate. Naturally a question of accuracy, stability and convergence of solutions, obtained by FEA may be posed.

Accuracy is understood as deviation of approximate solution from accurate or true solution. Stability first of all is defined by error growth while performing certain computing operations. Unstable solution is a result of the wrong choice of approximating functions, "bad" region dividing, incorrect representation of the boundary conditions, etc. Convergence is understood as gradual approximation of successive solutions to ultimate solution as long as parameters of discrete model are determined, such as element dimensions, degree of approximating function, etc. In this regard the concept of convergence is similar to the meaning that it has in usual iteration processes. Therefore in converging procedure difference between consequent solutions is decreased, approaching zero at the extreme.

Above mentioned concepts are illustrated in Figure 1. Herein *x*-axis defines degree of clarification of parameters of discrete model, and *y*-axis defines approximate solution obtained at that clarification. In the figure the monotonic type of convergence is shown, at which solution accuracy is smoothly increased.

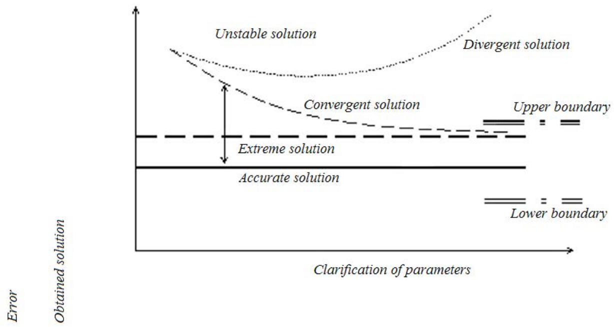


Figure 1. Dependence of solution from parameters.

Setting of boundary conditions and material

After task area approximation by the set of discrete finite elements we should define materials characterization and boundary conditions for each element. With the indication of different characteristics for different elements, we can analyze behavior of an object composed of different materials.

According to terminology of mathematical physics that considers various differential equations describing physical fields from unified mathematical point of view, boundary or edge conditions for given differential equations are divided into two basic types: essential and natural. Usually essential conditions are imposed on required function and natural ones are imposed on its spatial derivatives.

From the standpoint of FEA essential boundary conditions are such that shape the model degrees of freedom and are imposed upon components of global vector of unknown U (displacements). Alternatively natural boundary conditions are such that indirectly influence on degrees of freedom through the global system of finite-element equations and are imposed on right part of the system – vector F (applied forces).

As a rule essential boundary conditions in mechanical tasks are such that include displacements (but not deformations, representing space derivative of displacements). According to terminology of the theory of elasticity such boundary conditions are known as kinematic. For example, embedding and hinge support in rod tasks are essential or kinematic boundary conditions, imposed on a bend or longitudinal displacements of the rod points. Notice that in rod bending tasks essential boundary conditions are also conditions, imposed on a first derivative of the rod bending on axial coordinate that has mechanical sense of angle of the rod rotation. The same may be said about angle of rotation in the plate bending theory.

Natural boundary conditions in mechanical applications of FEA are conditions, imposed on different external force factors affecting points of the body's surface – concentrated forces and moments in rod tasks, distributed forces in two-dimensional and three-dimensional tasks. Such restrictions are called force boundary conditions.

Mixed boundary conditions are widely used in setting objectives of continuum mechanics particularly in the theory of elasticity. It means that some components of displacements and surface forces are simultaneously set in this point of the body's surface.

Three enumerated variants of boundary conditions are the most widespread in pure mechanical applications of FEA.

Besides boundary conditions for resolving of equations it is necessary to set characterization of material of which research object is made. For example, in stress-strain analysis parameters determine connection of tension and deformation.

System of equations forming

After set up of the boundary conditions and material, FEA program forms a system of equations, connecting the boundary conditions with unknowns, whereupon solve the system against unknowns.

Result generation

After finding of values of unknowns user gets a possibility to calculate value of any parameter in any point of any FE by the same required function that was used for system of equations forming. FEA program outputs are usually presented in a numerical form. However it may be difficult to get general picture about behavior of corresponding parameters from numeric data. Graphic images are more informative usually, because they give an opportunity to study behavior of parameters over the whole task area.

FEA formulation

By means of getting basic, i.e. resolving equations, there are four main kinds of FEA: direct, variational, weighted residuals and energy balance. Among enumerated kinds of FEA variational method and weighted residuals Galerkin method are particularly topical in structural mechanics.

Let us consider the variational method. This method is based on stationary principle of some variable that depends on one or more functions (such variable is named functional). In respect to mechanics of deformable solids this variable represents potential (Lagrangian functional) or additional (Castigliano's functional) energy of the system or is formed on the basis of these two energies (Hellinger-Reissner and Hu-Washizu functionals). If substitute approximating expressions of the required functions into functional and apply extremum principles (accordingly Lagrange principle, Castigliano's principle, etc.) to it, we will get the system of algebraic equation, the solution of that will be values of nodal unknowns.

Variational Lagrange principle: potential energy acquires stationary values on kinematically admissible displacements, which satisfy specified boundary conditions and force equilibrium conditions.

In contrast to direct method, variational method can in equal measure be successfully applied to both simple and challenging tasks.

So let us consider three-dimensional object of arbitrary shape, being in equilibrium condition affected by some stress load (Figure 2). Let us denote friction forces affecting the surface (surface forces) by p, and mass forces (volume forces) – by G. In general these forces are laid out on components parallel to the axes of coordinates:

$$G = \begin{bmatrix} G_x \\ G_y \\ G_z \end{bmatrix} \quad p = \begin{bmatrix} p_x \\ p_y \\ p_z \end{bmatrix} \tag{1}$$

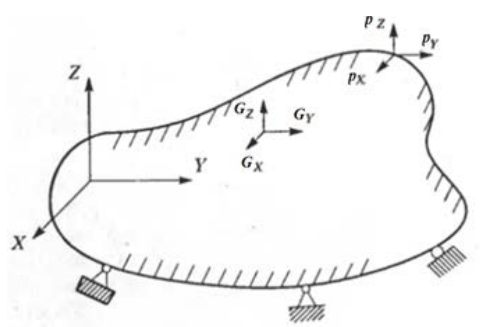


Figure 2. Three-dimensional object with external forces.

Let us denote displacement of arbitrary point of the object (X,Y,Z) in comparison with configuration in absence of stress load by symbol U. In this case

$$U^T = [U(X,Y,Z) \cdot V(X,Y,Z) \cdot W(X,Y,Z)] \tag{2}$$

Displacements U will lead to occurrence of deformation

$$\varepsilon^T = [\varepsilon_{XX} \cdot \varepsilon_{YY} \cdot \varepsilon_{ZZ} \cdot \varepsilon_{XY} \cdot \varepsilon_{YZ} \cdot \varepsilon_{ZX}] \tag{3}$$

and relevant strains.

$$\sigma^T = [\sigma_X \cdot \sigma_Y \cdot \sigma_Z \cdot \tau_{XY} \cdot \tau_{YZ} \cdot \tau_{ZX}] \tag{4}$$

It is necessary to calculate U, ε, σ in the point (X,Y,Z) with respect to preset external forces. Total potential energy of elastic body is described by expression:

$$\varPi = Э - A = \frac{1}{2} = \int_V \bar{\varepsilon}^T \sigma dV - \int_V \bar{U}^T G dV - \int_S \overline{U^S}^T p dS \tag{5}$$

Where $Э$ = energy of deformation;

A = work of applied mass and surface forces.

Three last items of equation (5) describe the external work, executing by real forces G, p on virtual displacements $\bar{U}$.

A superscript S of vector $\bar{U}$ means virtual displacement on the surface. Strains are calculated through deformations by relevant constitutive equations.

Let us obtain FEA equations from equation (5), starting with approximation of the object represented in Figure 2 by FE mesh. Elements are connected together in nodal points which are located on their boundaries. Displacement in any point with coordinates (x, y, z) in the local coordinate system of element is considered a function of displacements in nodal points.

So for the element T assumption is declared that

$$u^{(m)}(x,y,z) = H^{(m)}(x,y,z)\bar{U} \tag{6}$$

Where H = interpolation displacement matrix (shape functions), $\bar{U}$ = vector of displacement on all nodes. If total amount of nodes is equal N, vector $\bar{U}$ is written as follows:

$$\bar{U}^T = [u_1 v_1 w_1 u_2 v_2 w_2 \ldots u_N v_N w_N] \tag{7}$$

This expression can be rewritten as:

$$\bar{U}^T = [U_1 U_2 \ldots U_n] \tag{8}$$

Although displacements of all nodes are specified in equation (8) and therefore these displacements are also included into expression (6), for each certain element internal displacements are determined by displacements in its nodes only. All nodes have entered into expression (6) because it facilitates the process of combination of matrix of single elements into matrix of structure in whole, as it will be shown below.

Equation (6) allows calculating of deformations:

$$\varepsilon^{(m)}(x,y,z) = B^{(m)}(x,y,z)\bar{U} \tag{9}$$

Rows of a matrix deformations-displacements $B^{(m)}$ from equation (9) are obtained by differentiation and combination of matrix rows $H^{(m)}$.

Now we can also write expressions for strains inside each element:

$$\sigma^{(m)} = C^{(m)}\varepsilon^{(m)} + \sigma_0^{(m)} \tag{10}$$

Where C = flexibility matrix of element T (Hooke matrix), $\sigma_0^{(m)}$= initial strain inside the element. In structure of different elements it is possible to preset own flexibility matrix for each of them.

Let us rewrite equation (5) in view of sum of volume integrals and integrals over the surfaces of single elements:

$$\Pi = \sum_m \Pi^{(m)} = \frac{1}{2}\sum_m \int_{V^{(m)}} \overline{\varepsilon^{(m)}}^T \sigma^{(m)} dV^{(m)} - \sum_m \int_{V^{(m)}} \overline{u^{(m)}}^T G^{(m)} dV^{(m)} - \sum_m \int_{S^{(m)}} \overline{u^{S(m)}}^T p^{(m)} dS^{(m)} \tag{11}$$

Where element T varies from 1 to total amount of elements in the system.

Substitution of (6), (9) and (10) into (11) will give the next expression:

$$\sum_m \Pi^{(m)} = \frac{1}{2}\sum_m \int_{V^{(m)}} B^{(m)T}\overline{U}^T C^{(m)} B^{(m)} \overline{U} dV^{(m)} - \sum_m \int_{V^{(m)}} H^{(m)T}\overline{U}^T G^{(m)} dV^{(m)}$$
$$- \sum_m \int_{S^{(m)}} H^{S(m)T}\,\overline{U}^T p^{(m)} dS^{(m)} + \sum_m \int_{V^{(m)}} \sigma_0^{(m)} B^{(m)T}\overline{U}^T dV^{(m)} \tag{12}$$

Where surface interpolation matrixes of displacements $H^{S(m)}$ are obtained from volume interpolation matrixes of displacements $H^{(m)}$ by substitution of coordinates of element surface.

Let us denote

$$K = \sum_m \int_{V^{(m)}} B^{(m)^T} C^{(m)} B^{(m)} dV^{(m)} \tag{13}$$

$$R = R_B + R_S - R_0 \tag{14}$$

$$R_B = \sum_m \int_{V^{(m)}} H^{(m)^T} G^{(m)} dV^{(m)} \tag{15}$$

$$R_S = \sum_m \int_{S^{(m)}} H^{S(m)^T} p^{(m)} dS^{(m)} \tag{16}$$

$$R_0 = \sum_m \int_{V^{(m)}} \sigma_0^{(m)} B^{(m)^T} dV^{(m)} \tag{17}$$

Energy minimization Π results in equation:

$$\frac{\partial \Pi}{\partial U} = \frac{\partial}{\partial U}\sum_m \Pi^{(m)} = 0 \tag{18}$$

which with account of introduced notations will be written as:

$$KU = R \tag{19}$$

Note that summing of integrals taken over volumes of single elements in formula (14) expresses the fact that rigidity matrix of set of elements as a whole is obtained by addition of rigidity matrix of elements $K^{(m)}$. Similarly vector $R_в$ of volume force, affecting the whole body, is obtained by summing of volume force vectors, affecting separate elements. Vectors of other forces are calculated in the same way.

The expression (19) describes static equilibrium. When applied forces are varying with time, this expression is applicable to any certain moment. However on rapid loading inertial forces must be considered. On the d'Alambert's principle inertial forces of single elements may be added to mass forces. If we assume that acceleration in any point of the element is connected to acceleration in nodal points by matrix $H^{(m)}$ alike displacements, input of mass forces into force vector K will be expressed as:

$$R_B = \sum_m \int_{V^{(m)}} H^{(m)^T}[G^{(m)} - \rho^{(m)} H^{(m)} \ddot{U}] dV^{(m)} \tag{20}$$

Where $\ddot{U}$ = accelerations in nodal points, and $\rho^{(m)}$ = mass density of element T.

Substitution of (20) instead of (15) into (19) will give a new equilibrium equation:

$$M\ddot{U} + KU = R \tag{21}$$

Where M = mass matrix.

Note that U and R in equation (21) are time functions.

Damping forces may be taken into account as additional input into mass forces, that allow describing damping effect (attenuation). In this case the equation (20) takes a new form:

$$R_B = \sum_m \int_{V^{(m)}} H^{(m)^T}[G^{(m)} - \rho^{(m)} H^{(m)} \ddot{U} - k^{(m)} H^{(m)} \dot{U}] dV^{(m)} \tag{22}$$

Where $\dot{U}$ = velocity vector of nodal points, and $k^{(m)}$ = damping coefficient for element T.

The equilibrium equation takes the form of

$$M\ddot{U} + C\dot{U} + KU = R, \tag{23}$$

Where C = damping matrix.

In practice matrix *C* is usually constructed from mass matrix and rigidity matrix on the grounds of experimental data on damping in material, because it is quite difficult to define damping parameters of single elements.[16]

Further the order of simulation of impregnation of load-bearing rod elements of transformable guy-roped reflectors by transfer molding is described.

For task of optimization of technological parameters of the process of impregnation of load-bearing rod structures made from PCM by transfer molding method it is necessary to develop a range of geometric models of exemplary three-dimensional composite constructions, conduct simulation of impregnation process, analyze findings and draw conclusions.

2.1 Geometric Model

In the process of the task solution of optimization a draft model of impregnated products from PCM was built. Product for impregnation represents tubular element of nominal size 100×40×20 mm with wall thickness 1.50 mm. For further calculations of the impregnation process it is necessary to simplify the model. Simplification consists in transformation of solid-state draft model into a sheet body, maintaining overall dimensions. This simplification is conducted because of small thickness of walls in relation to overall dimensions.

In the process of simulation two computational schemes are developed presented further (Figures 3, 4), where P_1 is a feed pressure of resin into the product, P_{-1} – pressure of pumping from the product.

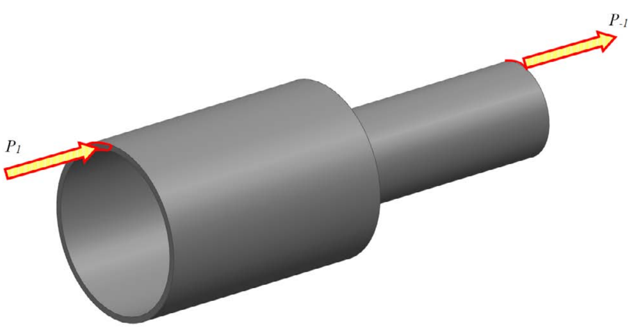


Figure 3. Computational scheme for tubular of nominal size 100×40×20 mm with point-feeding of resin.

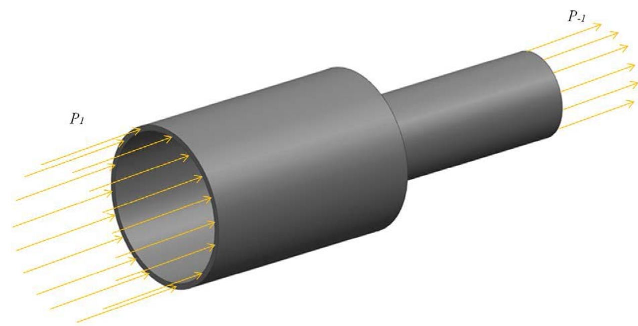


Figure 4. Computational scheme for tubular of nominal size 100×40×20 mm with frontal feeding of resin.

2.2 Simulation of Transfer Molding Process of Exemplary Three-dimensional Composite Constructions

In the process of simulation of transfer molding process two computational schemes are developed with point and frontal feeding of resin.

Point-feeding scheme is understood as feeding of resin into defined area, restricted by cross section of the tubular on cross-cut end of the impregnated product, and pumping of air and excess resin is produced from the opposite (symmetric) side of the model.

Frontal scheme of impregnation is characterized by feeding and pumping of resin from two different opposite ends of the product in the entire area of frontal cross-section. Thus, an impregnation passes frontally from one butt end to another.

In each computational scheme resin was fed under pressure P_1 equal to 102 kPa and temperature equal to 55°C. Pumping from the opposite end was performed under pressure of 10 kPa. During calculation of transfer molding process the next variants of weaving of layers were defined for the models:

- 4 layers ± 35˚;
- 1 layer 0˚/± 36˚/± 72˚;
- 2 layers 0˚/± 60˚.

For the calculation of impregnation performance properties of material were specified on the basis of M46J Torayca carbon fiber. Polymeric matrix of epoxy-

Table 1. Main properties of used materials

Material	Density, kg/m³	Dynamic viscosity, cPs	Permeability in directions of Cartesian coordinate system (Figure 3), m²		
			X	Y	Z
ECD-MD	1200.00	0.10	–	–	–
M46J Torayca	1800.00	–	$1.00\cdot10^{-10}$	$5.00\cdot10^{-11}$	$5.00\cdot10^{-9}$

chloro-diane modified resin ECD-MD was preheated to temperature of 55°C and fed isothermally under pressure of 102 kPa. The main selected materials and their properties are presented further (Table 1).[5]

2.3 Meshing

For calculation of impregnability of load-bearing rod element by transfer molding method, two-dimensional (2D) finite-element (FE) mesh is imposed on the model by adjustable Layer Mesh method. This method is that initially a certain amount of elements is set on each face of concerned model и and with the help of Layer Mesh function nodes of ready 2D mesh are formed between elements.

Characteristic dimension of the mesh element is 2.00 mm. Further (Figure 5) graphically represented a mesh constructed by adjustable method FE on the surface of the concerned model. Number of FE, included into model of load-bearing rod element is equal 13922.

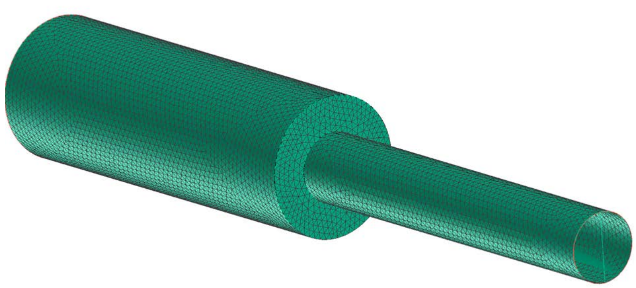


Figure 5. E mesh of the model of nominal size 100×40×20 mm. **Impregnation velocity of preform model of nominal size 100×40×20 mm**

2.4 Calculation of Impregnability of the Preform Model

Before the calculation of impregnability of load-bearing rod element by transfer molding method, characteristics of material are specified (Table 2) and pressure is set for feed of resin equal to 102 kPa and temperature equal to 55°C. Also pumping of air and resin excess are simulated on the opposite butt end of model (Figures 1, 2).

3. Results

The results of calculation are maximum and minimum impregnation velocities of products, probabilities of void space occurrence in the volume of preform model, fields of pressure distribution in the entire area of model in different variants of stacking of material layers and different schemes of impregnation of product models, values of maximum and minimum pressures of resin in preform during impregnation. Maximum and minimum values of impregnation velocities of products and maximum and minimum values of pressure distribution of resin flow in a model of load-bearing rod element are further (Table 2) presented. As a visual graphic presentation of resin distribution, velocity of resin propagation, pressure distribution of resin flow and void space occurrence throughout the volume of preform model, the model of tubular of nominal size 100×40×20 mm was chosen, represented further (Pictures 6-13).

Table 2. Comparison table of calculation data of impregnation of preform model of nominal size 100×40×20 mm

		Variants of preform laying					
		4 layers ±35˚		1 layer 0 ˚/±36˚/±72˚		2 layers 0˚/±60˚	
		Variants of computational schemes					
		Point feed-ing	Point feed-ing	Point feed-ing	Point feed-ing	Point feed-ing	Point feed-ing
Velocity of resin propagation, m/s	max	$4.01\cdot10^{-3}$	$1.22\cdot10^{-3}$	$3.98\cdot10^{-3}$	$1.28\cdot10^{-3}$	$3.96\cdot10^{-3}$	$1.16\cdot10^{-3}$
	min	$3.15\cdot10^{-7}$	$4.50\cdot10^{-6}$	$2.64\cdot10^{-7}$	$4.38\cdot10^{-6}$	$3.06\cdot10^{-6}$	$4{,}38\cdot10^{-6}$
Time of full impregnation of model, s		301,85	120.02	298.180	124.32	299.20	124.06
Pressure of resin distribution, Pa	max	1.00	1.00	1.00	1.00	1.00	1.00

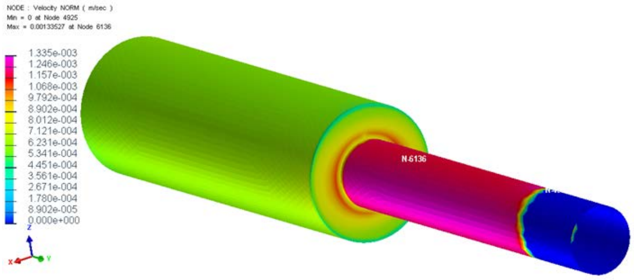


Figure 6. Distribution of resin velocities throughout volume of preform model of nominal size 100×40×20 mm in case of frontal feeding of resin (time t=96,01 s).

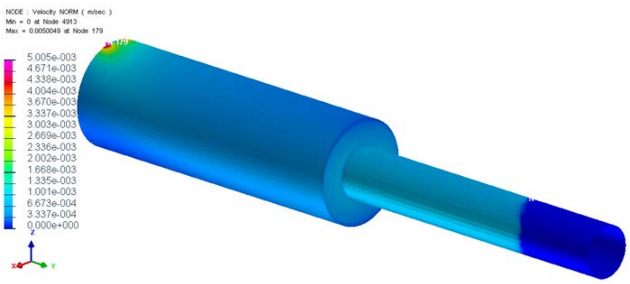


Figure 7. Distribution of resin velocities throughout volume of preform model of nominal size 100×40×20 mm in case of point-feeding of resin (time t=96,01 s).

Total impregnation time of preform model of nominal size 100×40×20 mm

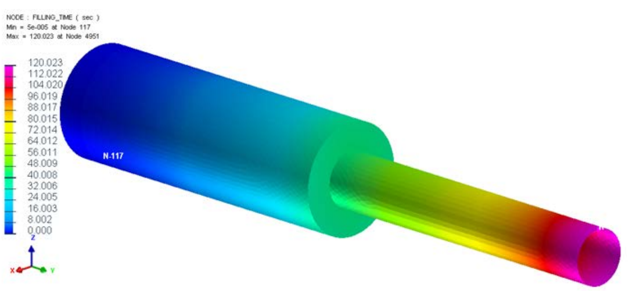


Figure 8. Total impregnation time of preform model of nominal size 100×40×20 mm in case of frontal feeding of resin.

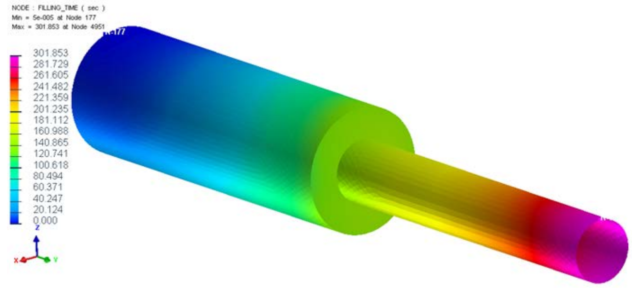


Figure 9. Total impregnation time of preform model of nominal size 100×40×20 mm in case of point-feeding of resin.

Distribution of resin pressure by volume of preform model of nominal size 100×40×20 mm

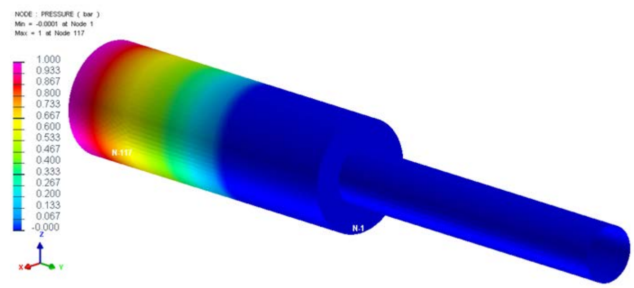


Figure 10. Distribution of resin pressure by volume of preform model of nominal size 100×40×20 mm in case of frontal feeding of resin (time t=20.01 s).

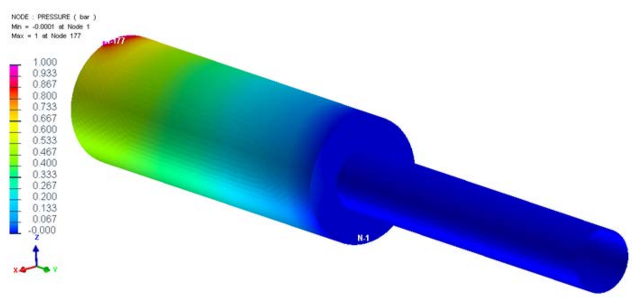


Figure 11. Distribution of resin pressure by volume of preform model of nominal size 100×40×20 mm in case of point-feeding of resin (time t=20.01 s).

Graphic presentation of resin distribution (impregnation front) by volume of preform model of nominal size 100×40×20 mm

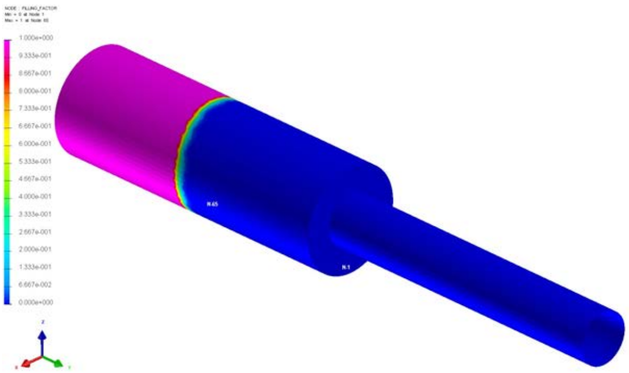


Figure 12. Distribution of resin front by volume of preform model of nominal size 100×40×20 mm in case of frontal feeding of resin (time t=20.0 s).

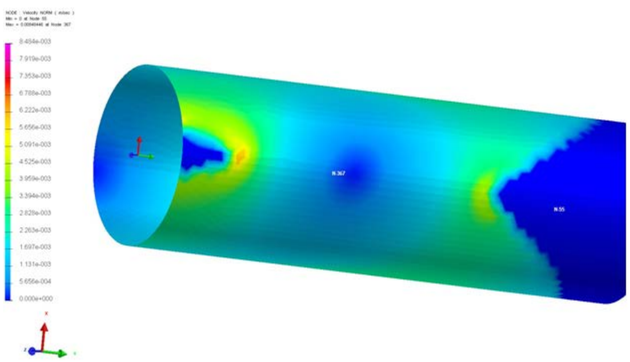


Figure 13. Distribution of resin front by volume of preform model of nominal size 100×40×20 mm in case of point-feeding of resin (time t=20.0 s).

4. Discussion

The uniqueness of this study lies not in determining the place of the supply and discharge of the resin, or impregnation velocity, but in the method of feeding. Two types of feeding were simulated: method of frontal feeding of resin and method of point-feeding of resin. The calculations determined the best course of resin injection at different carbon fiber weaves, namely: 4 layers ± 35^o; 1 layer 0^o/±36^o/±72^o; 2 layers 0^o/±60^o.

5. Conclusion

According to results of calculations the following conclusions were made:

- In case of frontal feeding of resin under pressure and symmetric pumping of of air and excess, average difference in impregnation velocity is equal to one order.
- In case of impregnation of the tubular element with a point feed, resin in the volume of the model is distributed unevenly, that causes formation of void space. Figures 12, 13 show nonuniform distribution of resin front throughout the volume of tubular element model of nominal size 100×40×20 mm.

Therefore, in case of frontal feeding of resin, impregnation of product is faster and the pressure of the resin flow is distributed throughout the volume of the preform uniformly, thus greatly reducing the probability of void space formation.

6. Acknowlegments

This work was supported in part by the Ministry of Education and Science of the Russian Federation, subsidy agreement no. 14.577.21.0130 of October 28, 2014, unique identifier of applied research investigations no. RFMEFI57714X0130.

7. References

1. Jie J, Tuanjie L, Xiaofei M, Pei W. A nonlinear equivalent circuit method for analysis of passive intermodulation of mesh reflectors. Chinese Journal of Aeronautics. 2014 Aug; 4 (27):924–9.
2. Li T, Jiang J, Deng H, Lin Z, Wang Z. Form-finding methods for deployable mesh reflector antennas. Chinese Journal of Aeronautics. 2013; 26 (5):1276–82.
3. Chugui Y, Khalimanovich V, Verkhogliad A, Skokov D, Nakrohin I. Mechanism of telescopic spokes extension of reflector and arms. Reshetnevsky readings. 2015; 1(19):141–3.
4. Gerasimov A, Zhukov A, Ponomarev S, Ponomarev V, Khalimanovich V. Simulation of large-scale transformable reflector with flexible spokes. Reshetnevsky readings. 2014; 1(18):68–69.
5. Mikheev P, Muranov A, Gusev S. Experimental definition of the module of interlayered shift of the layered carbon fiber reinforced plastic. Bauman Moscow State Technical University. 2015.
6. Muranov A, Aleksandrov I, Buyanov I, Chydnov I, Borodulin A, Mironov Y, Nelub V. Investigation of microstructure of nanomodified polymer composite materials. Science and education. The Bauman Moscow State Technical University. 2012.
7. Wang J, Simacek P, Advani S. G. Use of Centroidal Voronoi Diagram to find optimal gate locations to minimize mold filling time in resin transfer molding. Composites Part A: Applied Science and Manufacturing. 2016 Aug; 87, p. 243–55.

8. De Santis F, Pantani R. Development of a rapid surface temperature variation system and application to micro-injection molding. Journal of Materials Processing Technology. 2016 Nov; 237, p. 1–11.
9. Sozer E, Simacek P, Advani S. Resin transfer molding (RTM) in polymer matrix composites. Manufacturing Techniques for Polymer Matrix Composites. 2012. p. 245–309.
10. Aleksandrov I, Prosuntsov P. Determination of the Effect of Carbon Nanosized Particles on Thermophysical Characteristics of Polymer Composite Materials. Polymer Science. 2016; 9(4):377–81.
11. Smerdov A, Gusev S, Kulysh G, Rostovtsev M, Sokolov M. Elastic-dissipative characteristics of carbon fiber composite made by RTM technology. Composite structures. 2016; 2, p.21–25.
12. Bo Y, Tianguo J, Fengyang Bia, Yajun W, Jianguang L. Influence of fabric shear and flow direction on void formation during resin transfer molding. Composites Part A: Applied Science and Manufacturing. 2015 Jan; 68, p. 10–18.
13. Ravey C, Ruiz E, Trochu F. Determination of the optimal impregnation velocity in resin transfer molding by capillary rise experiments and infrared thermography. Composites Science and Technology. 2014 July. p. 96–102.
14. Shojaei A, Farrahinia H, Pishvaie S. Effect of system of initiators on the process cycle of nonisothermal resin transfer molding – Numerical investigation. Composites Part A: Applied Science and Manufacturing. 2010 Jan, 41, p. 138–45.
15. Laurenzia S, Grillia A, Pinnaa M, De Nicolab F, Cattaneoc G, Marchettia M. Process simulation for a large composite aeronautic beam by resin transfer molding. Composites Part B: Engineering. 2014 Feb, 57, p. 47–55.
16. Overview of Finite Element Analysis. http://www.npd-solutions.com/feaoverview.html.Date Accessed:2016.