Design and process for production of spacecraft structures using radial braiding and transfer molding

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Abstract. The paper presents the results of research dedicated to design and development of spacecraft structures using radial braiding and transfer molding. Experience in development, optimization and manufacturing of structures with closed section and biaxial and triaxial reinforcement is described for bearing rod, X-fitting, support platform, transformable lattice structure and ‘capillary’ tube.

1. Introduction
Generally, new material processing technologies offer a promising potential for improvement of the quality of structural design. As for composite parts, it is achieved via efficient reinforcement, promotion of integrity of the structure and sometimes via new structural design. As a result, there is a mass-efficient structure. These days radial braiding is state of the art trend in composite industry [1, 2, 3]. Experience of its application in composite structures production is rather small, and still there is a wide range of capabilities to explore.
The aim of the study, presented in this paper, is to explore the potential of radial braiding and transfer molding (Figure 1) to improve spacecraft structures.
Radial braiding is used to produce preforms from dry reinforcement material that later will be impregnated using one of transfer molding methods: infusion, RTM, Light RTM or RFI [4]. First of all, it is efficient to use braiding for production of parts with closed section. And from this point of view, braiding is an alternative to winding with additional range of options.

2. Thermally stable tubular structures
Main advantage of radial braiding is, first of all, a possibility to produce preforms with biaxial and triaxial reinforcement (Figure 1 (b), (c)). An angle of reinforcement about the x-axis of the part may vary in a wide range. Besides, various weave patterns in the nodes may be organized (Figure 1 (d)). Complex design and processing challenges may be dealt with owing to these processing capabilities, such as production of thermally stable structures. Figure 2 (a) shows tubular rod of a subreflector that has to meet stringent requirements when it comes to mechanical properties and minimization of deformation in a wide temperature range.
According to strength, stiffness and thermal stability requirements a set of rods was designed and produced (Figure 2 (b)). Essentially, these rods are thin-walled tubes with integrated flanges. Mechanical properties were achieved via adjustment of components of the composite material and mainly by selected reinforcement pattern. Loading simulation and simulation of the structure under
temperature were performed analytically and using finite element method to determine required properties [5, 6].

Figure 1. Radial braiding scheme (a), biaxial (b) and triaxial (c) braiding patterns: 1 – mandrel; 2 – spindle; 3 – reinforcement material (roving).

Figure 2. Thermally stable rods: (a) subreflector support (b) bearing rods.

Coefficient of thermal expansion ($\alpha_x$) and mechanical properties ($E_x, G_{xy}, E_y, M_{xy}$) as functions of braiding pattern (biaxial or triaxial), longitudinal to spiral fibers volume ratio as well as braiding angles $\omega$ were determined (Figure 3).

As a result of a compromise between strength, stiffness and thermal stability requirements an efficient reinforcement pattern was used: M46J 0° (96.3 %) / 16x1K T300 ±60° (3.7 %) (called quasi-unidirectional).

Next step was process simulation to determine equipment adjustment parameters. In particular [7, 8, 9] it is necessary to calculate spindles rotation velocity, axial advance velocity of the mandrel and actual reinforcement angle. Besides, it was necessary to predict and eliminate porosity [10].

The rods were molded using RTM, so molding process was simulated in PAM-RTM (ESI Group software) first, and the tool was manufactured (Figure 4).
Figure 3. Lengthwise coefficient of thermal expansion (CTE) (a) and lengthwise Young’s modulus (b) as a function of braiding angle.

Figure 4. Simulation of resin transfer (a) and design of the mold (b).

3. X-fitting
The other variant of support structure assumes intersection of the rods that is implemented using the X-fitting (Figure 5). If a preform of the X-fitting is manufactured by lay-up, the reinforcement template turns out to be chaotic. In this case ply book contains a large amount of patterns that leads to discontinuities in reinforcement fibers. As an alternative, kinematics of movement of the braiding equipment as well as reinforcement pattern for X-fitting radial braiding followed by RTM were developed.
4. Support platform

Based on the requirements of reinforcement pattern regularity and a possibility to simulate mechanical properties and thermal stability, a technology of spacecraft support platform manufacturing was developed (Figure 6).

The preform was braided using Rohacell® inserts. After the inserts were assembled in the mold, the whole structure was impregnated in a single-shot RTM. Figure 6 (e) demonstrates a fragment of circular support demonstrator. Considering the fact that the mandrels of the subpreforms have rectangular section and curvature, it is needed to develop technique for processing parameters calculation, and reinforcement angles in particular (equation (1)).

\[
\alpha' = \arctan\left(\frac{a}{(a+c)\tan(\pi l^{-1}\tan(\frac{\gamma}{l}))}\right).
\]

Here, \(\gamma\) is mandrel curvature angle, \(l\) is the length of curved mandrel with rectangular cross-section and \(a, c\) and \(\varphi\) are parameters of mandrel cross-section (Figure 7).

Figure 5. Support structure with intersecting rods: (a) assembly; (b) X-fitting and the preform; (c) braiding process; (d) RTM mold.
5. Transformable lattice tubes

Another variant of ultra-light structure is a lattice tube (Figure 8) [11 - 13]. It has a braided preform that is impregnated by infusion.

One of the advantages of the said structure is an authentic weave of the fibers in the nodal areas (Figure 8 (c)) that ensures enhanced strength in these areas.

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**Figure 6.** Circular support: (a) ribbed structure; (b) integral braided structure; (c) spaced view; (d) braiding of subpreform; (e) complex preform; (f) fragment of an integral panel.

**Figure 7.** Position of roving on the curved mandrel.
Figure 8. Lattice tube: (a) lattice structure; (b) braiding process; (c) patterns in nodal areas.

To braid lattice preforms mass properties as well as kinematics of movements of the braiding equipment were simulated. The main calculated parameters are as follows:

Elastic modulus of braided fibers (equation (2)) that provides a possibility to determine elastic properties of nodal areas depending on the types of fiber and resin and braiding angle:

$$E_x = \frac{I}{A} \int \left( \frac{M \sin(\gamma)}{E} + \frac{f \cos(\gamma)}{AC} \right) dx.$$  \hspace{1cm} (2)

Here, $I$ is inertia moment of the cross-section, $E$ is elasticity modulus of the fiber, $f$ is the force acting in the direction of the fiber, $M$ is bending moment, $\gamma$ is the angle of fiber curvature, $bf$ is the distance between centers of rovings, $A$ is a constant.

Mass of the lattice structure (equation (3)):

$$m_s = 2 \frac{L}{\cos \phi} h_r \rho_m \frac{L}{a_r} \sin \phi + 2 \pi r \rho_m \frac{t_a}{a_a} h_a = 2 \pi r \rho_m \left( \frac{t_a h_r}{a_r} + \frac{t_a h_a}{a_a} \right).$$  \hspace{1cm} (3)

Here, $L$, $r$ are length and radius of the structure, respectively; $tr(a)$, $hr(a)$, $ar(a)$ are width, thickness and distance between spiral and lengthwise ribs, respectively; $\varphi$ is the angle between spiral and lengthwise ribs.

Mandrel feed rate $V_f$ for conical surface braiding (equation (4)):

$$V_f = \frac{\omega}{\pi \alpha \beta} \left( \frac{r_1 - r_0}{r_1 + r_0} \right).$$  \hspace{1cm} (4)

Here, $r_1$ is a radius of cone cross-section that changes along its axis; $\omega$ is angular velocity of the spindles; $\alpha$ is braiding angle; $x/L$ are parameters of conic surface.

Fiber volume fraction in nodal areas for biaxial and triaxial braiding (equation (5)):

$$V_f^\text{triaxial} = \frac{8 \pi b_1 b_2 (2a_2)^2 + \frac{b_f}{\pi \cos \alpha} \left( \frac{\pi}{b_f} + \frac{1}{b_f} \left( \frac{b_f}{2 \pi a_1 \cos \alpha} \right)^2 \right)^2}{2a_1 + a_2}.$$  \hspace{1cm} (5)

Here, $\xi$ is an elliptic line integral; $bf$, baxial is a distance between the centers of spiral and axial rovings; $b1$, $a1$ are semi-major and semi-minor axes of spiral roving cross-section; $b2$, $a2$ are semi-major and semi-minor axes of lengthwise roving cross-section.

This lattice structure was designed as part of self-deployable system. Its kinematic state is characterized not only by lengthwise folding, but also by lateral compression till the shape of a heavily oblong ellipse (Figure 9). The structure is transformed due to its intrinsic elasticity without any external actuators.

Figure 9. Deployment of the lattice tube.

6. ‘Capillary’ tube

Figure 10 (a) shows variants of tubes with multicell cross-section [14]. External shell has a rather large thickness compared to the tube elements inside. The structure is integral.
Manufacturing of ‘capillary’ tube has the following steps: braiding of preforms of the internal tubes using hexahedral mandrels; assembly of hexahedral mandrels in the single unit; braiding of the outer shell around the single unit. Then, the whole preform is impregnated using infusion or RTM technique. It is assumed that a thin-walled ‘capillary’ tube will be more light-weight compared to the usual tubular structure due to higher resistance to local buckling.

**Conclusion**

The study, including deflected mode and process simulation as well as an experiment, demonstrated that radial braiding together with transfer molding techniques provides the following possibilities:
- To generate lightweight thermally stable parts
- To design new, integral structures
- To ensure a proper level of automation and safety of production.

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