SPATIAL BRAIDING OF CYLINDRICAL SHAPE ARTICLES

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SUMMARY: Paper is devoted to analysis of effective deformative characteristics of 3-D composites formed by spatial braiding along the generatrices of a one-sheet hyperboloid. Relationships between geometric and technological parameters, which determine structure and properties of a braided composite, are derived. Elastic characteristics are calculated on the base of suggested elementary cell of the composite structure and method of orientational averaging. Dependencies of bending and torsional stiffnesses of thick-walled cylindrical rods made by the suggested method of spatial braiding and methods of winding on angle of braiding/winding are compared. Numerical estimations are obtained for rods of carbon (CFRP) and aramid (AFRP) fibre reinforced plastics.

KEYWORDS: spatial braiding, angle and degree of braiding, composite rods, torsional and bending stiffnesses.

INTRODUCTION

Thin- and thick-walled rod and tubular members of critical structures made from advanced composites are widely applied in the modern engineering. With respect to their technical application (ship shaftlines, deep-water risers for oil production, tendons and mooring lines for floating platforms, truss structures, etc.), they are designed for operation under different types of stress-strain states (tension/compression, bending, torsion and internal/external pressures) [1, 2]. Rational tubular shape of rods operating under the listed loading conditions are usually formed by filament winding [3]. Combination of various types of winding and different composites allows one to design the rod members of structures by means of rational selection of a reinforcing scheme according to the operating loads. Generation of significant system of technological residual stresses is a specific feature of the composite structures made by winding, especially closed to the circumferential winding. A multi-layered structure of wound articles causing a specific mode of their premature failure by delamination owing to availability of the planes of weak resistance to shear and transverse tension is one of drawbacks of winding technique.

Technology of spatial braiding developed in the framework of modern textile technologies [4] opens new possibilities to create composites with controlled deformative, strength and thermal-physical characteristics. Reinforcing preform of composite material is produced by spatial braiding only a single family of yarns enabling in the process achievement of very high volume content of reinforcement V_f, which is very close to unidirectional composites [4]. The next important stage of this technology is impregnation of the reinforcing preform with a binding material and subsequent consolidation of the composite to achieve a minimum degree of porosity. One of the principal advantages of spatially braided composites belonging to a class of spatially reinforced composites is lack of the planes of weak resistance to operating stresses. The internal yarn structure in 3-D braided preforms has a unique topology depending upon the braiding method applied. In the paper we consider the perspective method of spatial braiding of cylindrical articles by arrangement of reinforcing yarns/bundles along the generatrices of a one-sheet hyperboloid (Fig. 1).

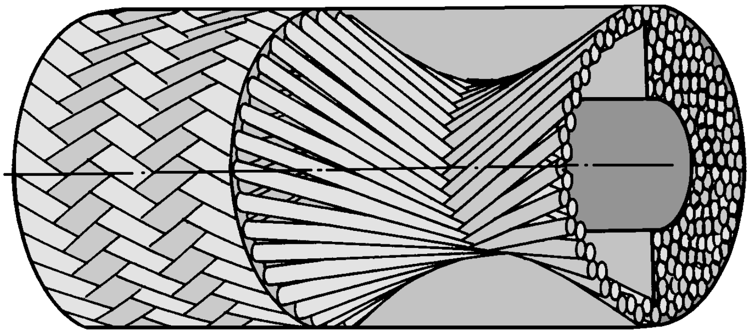

Fig.1. Model of spatially braided thick-walled cylindrical rod [4].

STRUCTURE AND ELASTIC PROPERTIES OF 3-D BRAIDED COMPOSITE

Single family of reinforcing threads placed along the directions of generatrix and having the same angle of slope θ may be described by the following geometrical and technological parameters: number of reinforcing bundles on the circle n, degree of weaving z_n, maximum diameter $D = 2b$, minimum diameter $d = 2a$, length L, height H, height of elementary cell of structure h, angle of slope θ, and angle of projection χ. Degree of weaving z_n in braiding is an analogue of the similar parameter in winding [3] and depends upon a number of shift positions of a bundle between the bottom and top planes $r\varphi$, which are distant each other on the length of H determined by a full kinematic cycle of actuating mechanism (Fig 2).

Degree of weaving may be only accounted by an integer number. Example shown in Fig.2 corresponds to the braiding of 36 reinforcing bundles placed through 10^o over the circle. Positions of these bundles also determine a possible shift of any bundle through the corresponding rotation of the actuating mechanism. As seen from Fig.2, degree of braiding z_n equals to 10, if the bundle from zero position of bottom circle comes to tenth position of the top circle. This parameter characterises the slope angle, braiding pattern and number of elementary cells through an article radius. Enlarged scale view of the elementary cell is also shown in Fig.2.

Relationships between the above-mentioned technological and geometrical parameters are determined by the following formulae derived:

$$\chi = \frac{\pi}{n} z_n, \qquad d = D\cos\chi, \qquad h = \frac{H}{2z_n},$$
$$L = \frac{H}{\cos\theta}; \qquad \theta = \operatorname{atan}\left(\frac{D}{H}\sin\chi\right) \tag{1}$$

Analysis of reinforcement directions in the spatially braided composite where yarns are placed along the generatrices of a one-sheet hyperboloid revealed four directions (see elementary cell of structure in Fig. 2). Elementary cell in a map has shape of an equilateral trapezoid with a length of middle line which may significantly differ from the trapezoid height. This leads to a cylindrical orthotropy of properties, which is characterized by nine independent characteristics of each physical-mechanical property of the material.

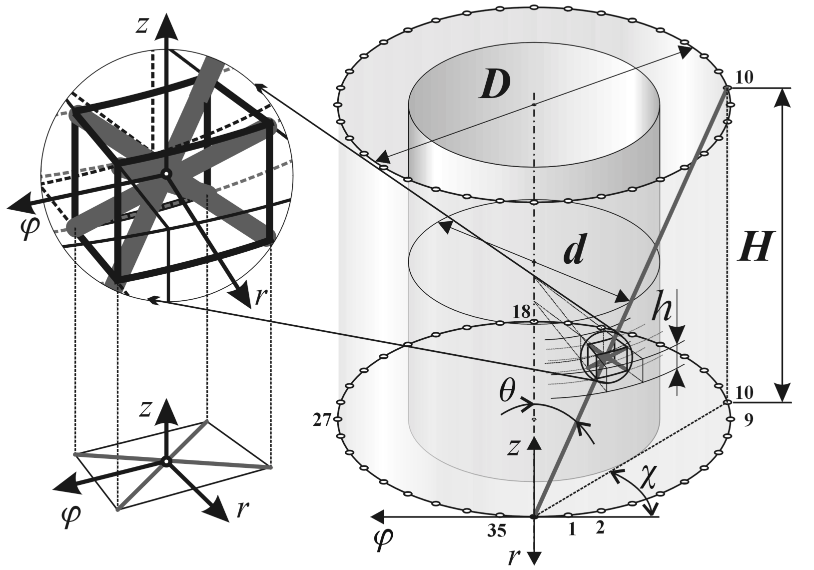

Fig 2. Geometric and technological parameters of structure of braided material.

Effective application of spatially braided rods in critical structures requires investigation of their elastic and strength characteristics. Theoretical strength calculation of spatially braided composites is very complex problem. It seems that experimental approach is really successful way to solve the problem now. Calculation of matrix of effective elastic properties $A_{\alpha\beta\eta\delta}$ of the 3-D braided composite schematically shown in Figs 1, 2 was carried out by method of orientational averaging, in which geometrical summation of the components of stiffness matrix of unidirectional composite fragments A_{ijkl} modelling all reinforcing directions in the 3-D braided composite is suggested:

$$A_{\alpha\beta\eta\delta} = \sum_{m=1}^{n} \frac{V_k}{V} \cdot \int_{L_m} A_{ijkl}^{(m)} l_{\alpha i} l_{\beta j} l_{\eta k} l_{\delta l} \frac{dL_m}{L_m} . \qquad (2)$$

where V_k and l_{pq} is volume content and direction cosines of the k-th unidirectional fragment, respectively.

Results of calculation of shear $G_{\varphi z}$ and axial E_z moduli of elasticity on a relative radius $\bar{r} = r / b$ and angle of braiding (θ = 5°…60°) for spatially braided composite on the base of aramid fibres and epoxy resin are shown in Fig. 3. It is seen that distribution heterogeneity for

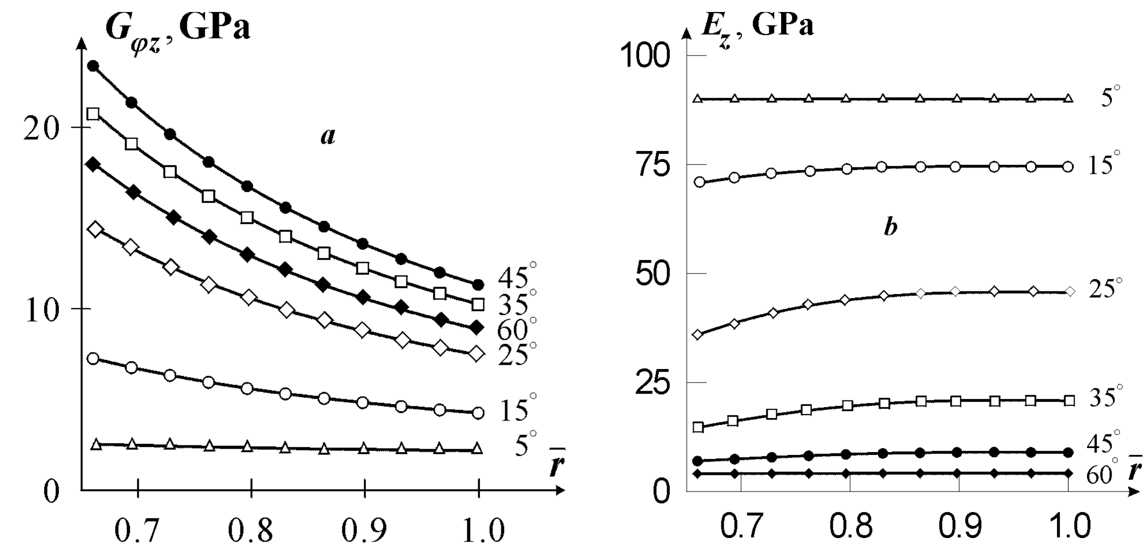

Fig.3. Dependencies of shear modulus $G_{\varphi z}$ (a) and modulus of elasticity E_z (b) on relative radius $\bar{r}$ =r/b and angle of braiding θ (figures at the curves).

these moduli with the radius of braided article depends upon the angle of braiding, especially for shear modulus $G_{\varphi z}$. Other elastic and thermal characteristics being calculated demonstrate an analogous heterogeneity of their distributions with the radius.

BENDING AND TORSIONAL STIFFNESSES OF SPATIALLY BRAIDED RODS

Bending C_b and torsional C_t stiffnesses of composite rods are important characteristics of these structural members in engineering applications. These characteristics, in the case when shear $G_{\varphi z}$ and axial E_z moduli are functions of the relative current radius $\bar{r}$ of rod, may be estimated by the following formulae:

$$C_t = 2\pi b^4 \int_m^1 G_{\varphi z}(\bar{r}) \cdot \bar{r}^3 d\bar{r};$$

$$C_b = \pi b^4 \int_m^1 E_z(\bar{r}) \cdot \bar{r}^3 d\bar{r}, \quad (3)$$

where $m=a/b$ is relative thickness of rod. Let us compare these characteristics for spatially braided cylindrical rods formed by the suggested technology of braiding and rods created by helical winding with constant angle $\pm\theta$ and varying angle θ. Angle θ is angle between axis z of the rod and direction of fibre lay-up. In the latter case, which is realized by using of simplest winding equipment (with constant speeds of mandrel rotation and motion of fibre-laying mechanism), winding angle varies with the relative current radius as follows:

$$\theta(\bar{r}) = \operatorname{atan}\left[\frac{\bar{r}}{m} \cdot \tan\theta(m)\right]. \quad (4)$$

We carried out the experiments with rods made of glass-fibre reinforced plastic (GFRP) wound with varying angle of winding θ (which practically linear changes from $\theta=37^o$ at inner radius of rod to $\theta=59^o$ at its outer radius) loaded in torsion. Volume content of reinforcing fibres in the fabricated rods was about of 65%. The experiments revealed that load carrying capacity of the rods in torsion τ^{ult} depends on degree of winding z_n and increases significantly in the range of small values of z_n (z_n = 1…7):

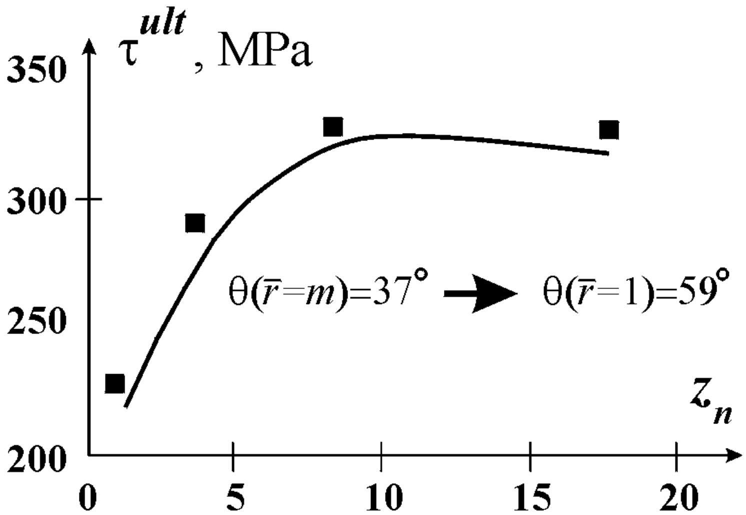

Fig. 4. Dependence of load carrying capacity in torsion τ^{ult} of GFRP rods wound with varying angle of winding θ on degree of winding z_n. Symbols ■ are experimental points, solid line is calculation on the model [3].

Increasing of the degree of winding leads to more homogeneous structure of wound composite with barriers in the way of microcracks and increasing the in-plane shear strength as a result. This effect for spatially braided composites should be more significant. Controlling by this technological parameter is the way to increase toughness of failure and impact strength of spatially braided composites.

Dependencies of shear $G_{\varphi z}$ and axial E_z moduli on angle of winding φ are calculated as follows:

$$G_{\varphi z}(\theta) = g_{66}; \qquad E_z(\theta) = g_{11} - \frac{g_{12}^2}{g_{22}}, \tag{5}$$

where g_{11}, g_{12}, g_{22} and g_{66} are components of effective stiffness matrix of angle-ply composite:

$$\begin{aligned}
g_{11} &= \overline{E}_L \cos^4\theta + \overline{E}_T \sin^4\theta + 2\left(\overline{E}_L \nu_{LT} + 2G_{LT}\right)\cdot \sin^2\theta \cdot \cos^2\theta \;;\\
g_{22} &= \overline{E}_L \sin^4\theta + \overline{E}_T \cos^4\theta + 2\left(\overline{E}_L \nu_{LT} + 2G_{LT}\right)\cdot \sin^2\theta \cdot \cos^2\theta \;;\\
g_{12} &= \left(\overline{E}_L + \overline{E}_T - 4G_{LT}\right)\cdot \sin^2\theta \cdot \cos^2\theta + G_{LT}\cdot\left(\sin^4\theta + \cos^4\theta\right) \;;\\
g_{66} &= \left(\overline{E}_L + \overline{E}_T - 2\overline{E}_L \nu_{LT}\right)\cdot \sin^2\theta \cdot \cos^2\theta + G_{LT}\cos^2 2\theta,
\end{aligned} \tag{6}$$

where $\overline{E}_{L,T} = \dfrac{E_{L,T}}{1 - \nu_{LT}\cdot\nu_{TL}}$, E_L, E_T are moduli of elasticity along and across reinforcing fibres, respectively; G_{LT} is shear modulus in the plane LT; ν_{LT} and ν_{TL} are Poisson's ratios.

Dependencies of reduced torsional $\overline{C}_T = C_T / b^4$ and bending $\overline{C}_b = C_b / b^4$ stiffnesses of spatially braided and wound rods on angle of braiding/winding θ are shown in Fig.4 (for AFRP rods) and Fig. 5 (for CFRP rods). The results demonstrate that torsional stiffness of spatially braided rods (curves 1) is about of 1.5 times less than wound ones (curves 2, 3). Torsional stiffnesses of the rods wound with constant (curves 2) and varying (curves 3) angles of winding differ little. Maximum of torsional stiffness in the case of winding with varying angle was realised when winding angle at inner radius was about ±40^o instead of ±45^o in the case of winding with constant angle.

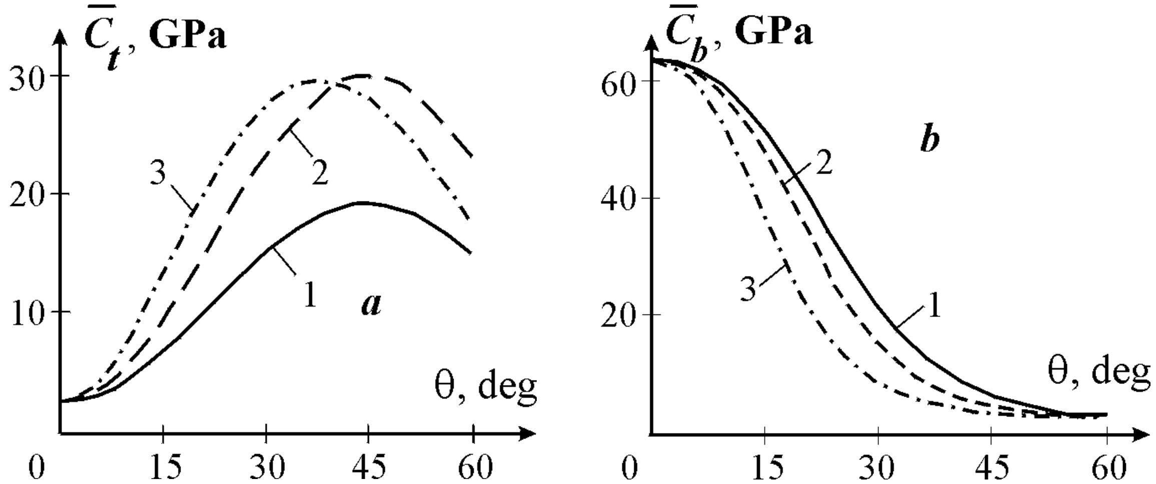

Fig. 4. Dependencies of reduced torsional (a) and bending (b) stiffnesses of AFRP rods formed by spatially braided (1), wound with constant (2) and varying (3) angles of winding.

Bending stiffness of spatially braided rods appeared high than wound ones, especially in comparison with rods wound with varying angle of winding in the range of about ±15^o…±30^o. Therefore, critical forces of buckling of spatially braided rods will be higher than wound rods. Torsional and bending stiffnesses of CFRP rods are about of two times higher than both spatially braided and wound AFRP rods.

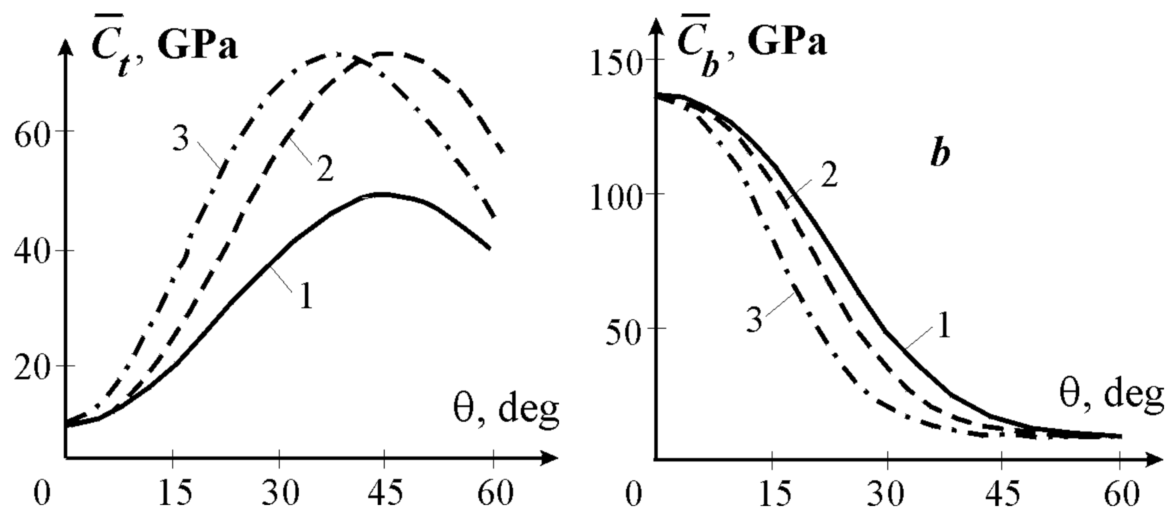

Fig. 5. Dependencies of reduced torsional (a) and bending (b) stiffnesses of CFRP rods formed by spatially braided (1), wound with constant (2) and varying (3) angles of winding.

Theoretical analysis carried out and models of composites fabricated showed good perspectives of the new method of spatial braiding. Future investigations will be include development of technology, fabrication of test specimens for studying the whole complex of mechanical and thermal-physical properties of composites, testing of prototypes of structural members. Special interest is investigation of toughness of failure and impact strength of these composites. Solution of these problems permits to determine rational fields of application of the developed technology.

CONCLUSIONS

1. New method of spatial braiding of cylindrical articles by means of reinforcement along the generatrices of a one-sheet hyperboloid is developed. This technology allows to create spatially braided composite without weak planes of resistance to operating stresses and realize very high volume content of reinforcement and produce articles without restriction of their length.

2. Controlling of angle and degree of braiding enables to create structural members with elastic, strength and thermal-physical properties which are changed though their thickness and length.

3. On the base of elementary cell of structure and method of orientational averaging, effective elastic properties of the composites made by the suggested method of spatially-braided are calculated. Torsional and bending stiffnesses of spatially-braided and wound rods are estimated.

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