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# Design on the driveshaft of 3D 4-Directional carbon fiber braided composites

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ABSTRACT

In this paper, the method of designing a drive shaft with a 3D 4-Directional braided composite structure is proposed. First, the tubular unit cell model of 3D 4-Directional braided composite is established for obtaining the engineering elastic constants and the strength values of the tubular braided composite. Also, the relationship among the shear modulus, the braided angles and the fiber volume fraction is analyzed. Second, an orthogonal anisotropic tubular model with a fiber volume fraction of 50% and a braided angle of 45° is established to predict the torsional strength, torsional stiffness and virbration modes of the 3D braided composite drive shaft. Finally, the parameterized design with the thickness of the tubular is used to calculate the ultimate torque of the drive shaft, also the optimal drive shaft size is given and the 60.18% weight loss is achieved. This work will play an important role in the lightweight design of the 3D 4-Directional braided composite drive shaft.

## 1. Introduction

The fiber reinforced composite shaft is widely used in aerospace and automobile [1] which has high specific strength, high specific modulus, corrosion resistance and low density [2]. The development of the early fiber composite shaft is mainly in the form of ply and winding, such as glass fiber composite drive shafts of Ford company in 1984 for the automotive applications; carbon fiber composite drive shafts of the United States Morrison company in 1985 for the automotive applications; carbon fiber composite shaft of the Guest, Keen & Nettlefolds Ltd (GKN) company in 1988 [3].

In order to improve the torsional performance of the drive shaft, a lot of researches on traditional carbon fiber composite drive shafts are investigated by means of theoretical, experimental and finite element analysis. Bert et al. [4] calculated the torsional buckling of the composite drive shaft by considering the non-axial stiffness and bending moment. Shokrieh et al. [5] and Badie et al. [6] investigated the torsional stability of composite shaft using different fiber orientation and layup sequences. Ercan Sevkat et al. [7,8] studied the residual torsional behavior of three different types of hybrid composite shafts under impacting load. Mutasher [9] and Misri et al. [10] studied the torsional behavior of the composite hybrid shaft showing maximum torsional strength at a winding angle of 45°.

Three-dimensional (3D) braided composites made up for the shortcomings of traditional laminated composite materials. Both determination of the elastic mechanical properties and failure behavior of braided composites are very important for guiding the design and application of drive shaft. Ayranci et al. [11] and Yu et al. [12] predicted the elastic properties of braided composites. Li et al. [13] proposed a post-buckling analysis of 3D braided composite cylindrical shells subjected to torsion in a hot environment based on the microscopic and macroscopic mechanical models. Jung et al. [14] investigated the curing behavior of 3D hybrid braided composites and the internal strain during the compression test using an embedded fiber bragg grating sensor. Harte et al. [15] studied the deformation and failure behavior of glass fiber/epoxy braided composite tubes under compression, torsion, tension-torsion and compression-torsion loads. Zhou et al. [16] studied the transverse impact response of a 3D circular braided composite tube with braiding angles of 15°, 30° and 45°. So far, three-dimensional braided composites have been widely used in engineering structures due to their integrity and good impact resistance, which can inhibit inter-layer cracks and delamination compared to laminated composites [17,18].

In this paper, the macro-meso-mechanics analysis is used to investigate the material properties, strength characterizations and mode behaviors of braided composite drive shaft, and the lightweight design of 3D 4-Directional braided composites drive shaft is described.

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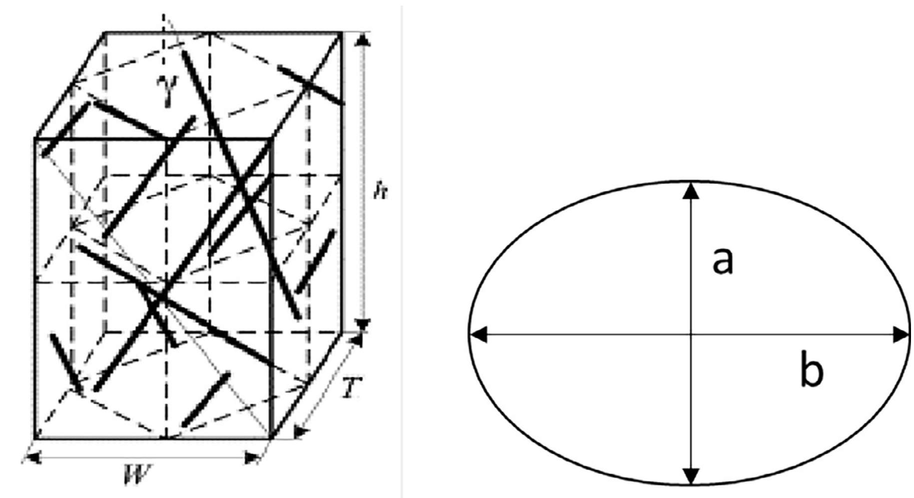


**Fig. 1.** Geometrical models of unit-cell and fiber section shape.

## 2. Mechanical analysis of tubular unit cell braided composites

### 2.1. Theoretical analysis of tubular unit cell model

In this study, a unit cell model of tubular 3D braided composites is established based on the four-step method [19]. Free-form deformation is a powerful method of shape change which has been widely used in computer animation and geometric modeling [20]. This technique shapes objects by embedding the objects inside an entity defined using the control grid. The lattice changes the solid deformation, so that the object deforms. In order to model a tubular unit cell, a rectangular unit cell is firstly created. The rectangular cell model is discretized into a grid, and the coordinates of each discrete point in the grid are mapped according to the derived mapping. Finally, the corresponding tubular subunit can be obtained by rebuilding the new mapping point set. Therefore, the braid angle γ and the fiber volume fraction $V_f$ can be defined according to the relationship between the cells and the fiber bundles [20,21].

In Fig. 1, the relationship of geometrical parameters can be expressed as [21]:

$$a = \sqrt{3}\,b\cos\gamma$$
$$h = 8b/\tan\gamma$$
$$W = T = 4\sqrt{2}\,b \qquad (1)$$

where the fiber bundle is assumed to be an elliptical cross section, $a$ and $b$ are its long and short semi-axes of the fiber, $h$ represents the height, $W$ and $T$ represents the width of two bottom edges.

In addition, the fiber volume fraction $V_f$ is defined as [21]:

$$S = \pi ab = n_f \pi d_f^2/4\kappa$$
$$V_f = \sqrt{3}\pi\kappa/8 \qquad (2)$$

where $S$ is the yarn cross-sectional area, $n_f$ is the number of fibers in the fiber bundle, $\kappa$ is the yarn packing factor, $d_f$ is the diameter of a single fiber.

For the tubular unit cells, each unit cell in the circumferential direction establishes its own global coordinate system along the circumferential direction and the radial direction, respectively, and transforms the stiffness matrixes of different directional threads in each unit cell from their respective local coordinate systems to the global coordinate system, which can be obtained within each of the internal unity of the unit cell from the equivalent stiffness matrix. The total stiffness matrix [22,23] for all the yarns in the entire 3D 4-Directional tubular braided composites is:

$$\overline{\boldsymbol{C}}_{\mathrm{f}} = \boldsymbol{C}_{\mathrm{i}}\overline{\boldsymbol{C}}_{\mathrm{in}} + \boldsymbol{C}_{\mathrm{os}}\overline{\boldsymbol{C}}_{\mathrm{osn}} + \boldsymbol{C}_{\mathrm{is}}\overline{\boldsymbol{C}}_{\mathrm{isn}} \qquad (3)$$

where $\overline{\boldsymbol{C}}_f$ is the equivalent stiffness matrix of the fiber, $\boldsymbol{C}_i$ is the stiffness matrix of the entire interior region, $\boldsymbol{C}_{os}$ is the stiffness matrix of the outer surface cells, $\boldsymbol{C}_{is}$ is the stiffness matrix determined by the inner surface cells. The vector-superscript "—" is the corresponding equivalent stiffness matrix.

After filling resin, the total stiffness matrix of composite is expressed as [24]:

$$\boldsymbol{C} = V_{\mathrm{f}}\overline{\boldsymbol{C}}_{\mathrm{f}} + V_{\mathrm{m}}\overline{\boldsymbol{C}}_{\mathrm{m}} \qquad (4)$$

where $\overline{\boldsymbol{C}}_m$ is the stiffness matrix of the matrix, $V_m$ is the volume content of the resin, and $V_f = 1 - V_m$.

For the representative volume cell of the 3D braided composites, T300 carbon fiber and TDE-85 resin are selected as the braided yarns and the matrix, respectively. The material properties of the carbon fiber and the resin are of transversely isotropic and isotropic, respectively. Therefore, the material's flexibility matrix can be obtained by inverting the stiffness matrix, $\boldsymbol{S} = \boldsymbol{C}^{-1}$. Table 1 shows the properties of the component materials, including T300-6K yarn fibers and TDE-85 resin matrix [24]. The density of carbon fiber is 1.76 g/cm$^3$, and the density of epoxy resin is 1.16 g/cm$^3$.

This part of the work is mainly to explain that the 45° braided angle is the best in the pure torsional state for the strength and shear modulus. Because the drive shaft is mainly subjected to the torque in the shear state, a higher shear modulus of the braided structure is more favorable to bear the torsional loading. In this investigation, the longitudinal shear modulus of 3D 4-Dimensional tubular braided composites with volume fraction 50% of fiber and different braiding angles are firstly predicted in cylindrical coordinate system ($R$, $T$, $Z$).

As shown in Fig. 2, the longitudinal shear modulus $G_{ZT}$ first increases and then decreases with the increase of braid angle $\gamma$, which

**Table 1**
Mechanical properties of component materials.

| Material | $E_1$/GPa | $E_2$/GPa | $G_{12}$/GPa | $G_{23}$/GPa | $\mu_{12}$ | $E_m$/GPa | $\mu_m$ | $X_t$ or $S_t$/MPa | $X_c$ or $S_c$/MPa |
|---|---|---|---|---|---|---|---|---|---|
| T300-6K | 221 | 13.8 | 9 | 3.5 | 0.2 | – | – | 3528 | 2470 |
| TDE-85 | – | – | – | – | – | 3.5 | 0.35 | 83 | 83 |