ANALYSIS OF VISCOELASTICITY OF 3-D BRAIDED COMPOSITE MATERIALS*

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Keywords: 3-D braided composites; Periodic unit cell; Creep compliance; Relaxation modulus

1 General Introduction
Three-dimensionally braided composite materials are widely used in many industry areas, such as airplanes, space structures, ships, and building structures. Currently the research on the mechanical properties of 3-D braided composites is focused on their stiffness and strength behaviors [1-2]. Since time and temperature always play important roles in the working condition for 3-D braided composites, viscoelasticity is one of the most important mechanical properties. However, there is little research in this subject, especially theoretical analysis of 3-D braided composites. In this paper, viscoelasticity of 3-D braided composites is studied.

2 Mesomechanical Model
A mesoscopic geometrical periodic unit cell of 3-D braided composites is analyzed in details using a 45° unit cell division method (Fig.1). The structural parameters are determined from braiding processes. In the model, the cross-section shape of yarns and the contact between them are considered, and the geometrical structure of unit cells is established. The finite element method is employed to analyze the mechanical behaviors of 3-D braided composites. A tetrahedron element is used to discretize the three-dimensional model of a unit cell for the composites (Fig.2). The periodic boundary conditions for displacements are applied to the unit cell.

3 Constitutive Equations
By using the finite element model mentioned above, a step stress 200 MPa is applied on the unit cell along the braiding direction. The displacements of all nodes in the unit cell along the braiding direction are obtained (Fig.3), and the average strain along the
The relaxation modulus for the degradation time $t=200$ Mpa is 147.94 Gpa. The creep compliance along the braiding direction is calculated. The creep compliance for the periodic unit cell along the braiding direction is got according the following formula

$$J(t) = \varepsilon(t)/\sigma_0$$

(1)

An exponential function is used to fit a series of discrete creep compliances, and the expression for the creep compliances along the braiding direction is

$$J(t) = 0.137 - 0.0649 e^{-t/147.94}$$

(2)

where the unit for $J(t)$ is Gpa$^{-1}$, the unit for $t$ is hour. Along the braiding direction, the initial compliance $J_0$ is 0.0721 Gpa$^{-1}$, the final compliance $J_\infty$ is 0.137 Gpa$^{-1}$, and the retardation time $\tau$ is 147.94 h.

The constitutive equation for viscoelastic behaviors for the braided composites along the braiding direction is

$$\varepsilon(t) = 0.0721 \sigma(t) + 4.39 \times 10^{-4} \int_0^t \sigma(\tau) \exp(-t-\tau/147.94) d\tau$$

(3)

Through Laplacian transformation from the creep compliance the relaxation modulus for the composites is obtained as follows

$$Y(t) = 7.30 + 6.57 e^{-t/74.70}$$

(4)

It is shown that the initial modulus $Y_0$ is 13.87 GPa, the final modulus $Y_\infty$ is 7.30 GPa, and the relaxation time $\tau'$ is 74.70 h.

4 Numerical results

Three-dimensionally braided composite materials with fiber volume fraction 40% and braiding angles $30^\circ$, $35^\circ$, $40^\circ$, $45^\circ$, $50^\circ$, $55^\circ$ and $60^\circ$ are modeled using the finite element method for their viscoelastic properties. The viscoelastic parameters are listed in the table 1. The variation of creep compliances and relaxation moduli with time is shown in the figures 4 and 5, respectively. With the increase of braiding
angles of 3-dimensionally braided composites, the viscoelastic effects decrease and the anti-viscoelastic properties increase along the braiding direction. Thus a braided composite of small braiding angles should be adopted to avoid creep failure in engineering application. In the figures 6 through 11, it is shown that with the increase of braiding angles, the initial compliances, final compliances and retardation time increase, while the initial moduli, final moduli and relaxation time decrease with the increase of braiding angles. These viscoelastic
parameters are approximately linear with the braiding angle.

Three-dimensionally braided composites with the braiding angle 40° and fiber volume fractions 25%, 30%, 35%, 40%, 45%, 50% and 55% are also modeled using the finite element method for their viscoelastic properties. The viscoelastic parameters are listed in the Table 2. The variation of creep

Table 2. Fitting parameters for viscoelastic properties

<table>
<thead>
<tr>
<th>V_f (%)</th>
<th>J_1 (Gpa^-1)</th>
<th>J_∞ (Gpa^-1)</th>
<th>Y_0 (Gpa)</th>
<th>Y_∞ (Gpa)</th>
<th>τ'(h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>0.0819</td>
<td>0.1771</td>
<td>148.66</td>
<td>12.2110</td>
<td>5.6497</td>
</tr>
<tr>
<td>30</td>
<td>0.0788</td>
<td>0.1632</td>
<td>148.45</td>
<td>12.6902</td>
<td>6.1350</td>
</tr>
<tr>
<td>35</td>
<td>0.0755</td>
<td>0.1490</td>
<td>148.19</td>
<td>13.2503</td>
<td>6.7114</td>
</tr>
<tr>
<td>40</td>
<td>0.0721</td>
<td>0.1372</td>
<td>147.94</td>
<td>13.8699</td>
<td>7.2993</td>
</tr>
<tr>
<td>45</td>
<td>0.0688</td>
<td>0.1260</td>
<td>147.71</td>
<td>14.5302</td>
<td>7.9365</td>
</tr>
<tr>
<td>50</td>
<td>0.0655</td>
<td>0.1159</td>
<td>147.52</td>
<td>15.2698</td>
<td>8.6207</td>
</tr>
<tr>
<td>55</td>
<td>0.0625</td>
<td>0.1071</td>
<td>147.32</td>
<td>16.0000</td>
<td>9.3458</td>
</tr>
</tbody>
</table>

Fig.12 Creep compliances at different fiber fractions

5 Conclusions

The effects of braiding angles and fiber volume fractions on the viscoelastic properties are analyzed through the numerical simulation for 3-D braided composites. A 3-D braided composite with a smaller braiding angle and a higher fiber volume fraction has better creep-resistance ability.

6 References