UNIT CELLS FOR THERMAL CONDUCTION CALCULATION OF TEXTILE REINFORCED COMPOSITES

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ABSTRACT

The effective properties of composites can be calculated based on a representative volume element which can be called unit cell for a textile reinforced composite. A general approach of unit cell formulation for thermal conduction study of textile reinforced composites is proposed in this paper. The utilization of translational, reflectional and 180° rotational structure symmetries in the geometry formulation boundary conditions derivation of unit cells are clarified. Several typical two-dimensional textile reinforced composites including plain, 5-harness satin and 8-harness satin woven composites are studied. Unit cells of different sizes are established and corresponding thermal analysis are conducted.

1 INTRODUCTION

Textile reinforced composite is fabricated by a fiber textile preform solidifying with corresponding matrix. According to its preform architecture, textile reinforced composites can be classified as 2-dimensional (plain, twill and satin woven) and 3-dimensional (multi-directional braided, 3D needled, etc.) composites. Based on the symmetries indicated in the textile structure, a small element, the so-called unit cell is always formulated to represent the macro composite. There are two key steps, the identification of the symmetries and the derivation of corresponding boundary conditions.

The mechanical performance including effective elastic properties [1], failure behaviours [2, 3], fatigue properties [4] and even ballistic performance [5] of textile reinforced composites are widely studied. Thermal transport study of plain, satin woven and 3D braided composites can be found in [6-11]. However, study of thermal properties is still limited. A unit cell can be formulated according to the micro analysis of the composite structure and is often used to calculate the effective physical properties of the composite [12, 13]. Take the 8-harness satin woven composite as an example, a square unit cell has been developed in [14], and the unit cell has been used in the local strain and the damage analysis of the composite with appropriate boundary conditions[15, 16]. According the authors’ study experience in the unit cell formulations of different types of composite, we know that there must be some general rules can be summarized.

In this paper, unit cell formulation rules for thermal calculations are presented and can be widely used in the study of textile reinforced composite. Several examples of plain, 5-harness and 8-harness satin woven composites are analyzed. For each composite, unit cells of different sizes are established based on the rules introduced in this paper. The corresponding thermal calculations are conducted and effective thermal conductivities are studied.

2 UNIT CELL FORMULATION RULES

If the effective thermal conductivity in three directions of a composite is about to be measured, the experimental object should be a specimen which contains enough composite structure information, and the experimental boundary conditions should be a given heat flux or temperature gradient in the
measuring direction, and adiabatic conditions for other four boundary planes. The formulation process of a unit cell is shown in Fig. 1. In the figure, “Spec.” represents a model which has the same size and structure information with the experimental specimen. Based on the translational and 180° rotational symmetries, two unit cells UC1 and UC2 can be formulated. In the figure, BC0, BC1, BC2 are boundary conditions of the specimen model, UC1 and UC2 for thermal calculations, respectively. BC1 should be derived based on BC0, while BC2 should be derived based on BC1.

![Fig. 1 Formulation of unit cells](image)

Before the derivation, two rules which describe the relative temperature relations between symmetric nodes as shown in Eqs. (1) and (2) have to be defined.

Symmetric thermal stimulus: \( T_M - T_O = T_{M'} - T_{O'} \)  
(1)

Antisymmetric thermal stimulus: \( T_M - T_O = T_{O'} - T_{M} \)  
(2)

where nodes \( M \) and \( M' \), \( O \) and \( O' \) are symmetric nodes. The symmetric thermal stimulus (STS) is defined as heat flux that parallel to, while the antisymmetric thermal stimulus (ATS) is that perpendicular to the reflectional plane or the 180° rotational axis. For a translational symmetric structure, all the heat fluxes can be considered as a STS. Eqs. (1) and (2) are verified in Figs. 2, 3 and 4. Figures 2(a) and (b) show the temperature distribution in a reflectional symmetric structure under antisymmetric and symmetric thermal stimuli, respectively. As shown in the figures, the relative temperature relations between \( M \) and \( M' \), \( O \) and \( O' \) satisfy Eqs. (1) and (2). The same situation can be found for 180° rotational symmetric structure as shown in Fig. 3(a) and (b). For translational symmetric structure, all the heat fluxes can be defined as symmetric thermal stimulus, and hence the temperature contours in Figs. 4(a) and (b) show a distribution as described by Eq. (1).

Eqs. (1) and (2) can be used to derive the boundary conditions when \( M \) and \( M' \) come to boundaries of unit cells.
3 SEVERAL EXAMPLES

In this paper, several typical textile reinforced composites are studied. Figures 5, 6, and 7 show the unit cells formulated for the plain woven, 5-harness and 8-harness satin woven composites, respectively. All the UCs are formulated by translational symmetries, in which translational axes for plain woven composite are x-, y- and z-axis, while for other two types of satin woven composites are non-orthogonal x', y' and z-axis. For the plain woven composite UC2 is formulated by reflectional symmetries about $P_x$ and $P_y$, while UC3 is formulated based on 180° rotational symmetries about $X_1$ and $Y_1$. For 5-harness and 8-harness satin woven composites, UC2 is formulated based on 180° rotational symmetry about $Z_1$-axis. Accurate boundary conditions for the calculation of effective thermal conductivities for each unit cell are derived based on the rules discussed above. The detailed derivation process can be referenced in [9, 17].
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(a) Heat flux perpendicular to the translation axis

\[ T_M - T_O = T_{M'} - T_{O'} = T_{M''} - T_{O''} \]

(b) Heat flux parallel to the translation axis

Fig. 4 Temperature distribution of translational symmetric structure

Fig. 5 Unit cells of plain woven composites
With appropriate boundary conditions, the complete identical results including the temperature distribution and effective thermal conductivities can be obtained by unit cells of different sizes as shown in Fig. 8 (typical case about 5-harness satin woven composites) and Table 1. In the figure, the results obtained by UC1 and UC2 have the same temperature distribution. Table 1 shows the effective thermal conductivities calculated based on specific constituent volume fraction parameters. As clear presented in the table, unit cells of different sizes figure out the identical results. In addition, according to the calculation experience, we know that the smaller the unit cell size, the more complicated the boundary conditions, and the less the computational cost.
Table 1 effective thermal conductivities

<table>
<thead>
<tr>
<th></th>
<th>In-plane (W/m-K)</th>
<th>Out-plane (W/m-K)</th>
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<tbody>
<tr>
<td></td>
<td>UC1</td>
<td>UC2</td>
</tr>
<tr>
<td>Plain woven</td>
<td></td>
<td></td>
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<tr>
<td>(C/SiC, V_f=0.3, V_a=0.15)</td>
<td>33.39</td>
<td>33.39</td>
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<tr>
<td>5-harness satin woven</td>
<td></td>
<td></td>
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<tr>
<td>(C/resin, V_f=0.46)</td>
<td>2.043</td>
<td>2.037</td>
</tr>
<tr>
<td>8-harness satin woven</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(C/resin, V_f=0.46)</td>
<td>2.049</td>
<td>2.048</td>
</tr>
</tbody>
</table>

4 CONCLUSIONS

In this paper, some general unit cell formulation rules for thermal conduction study of textile reinforced composites are proposed. The rules can be widely used in numerical heat transfer of textile composites. The utilization of translational, reflectional and 180° rotational structure symmetries in the formulation of unit cells are clarified. Several typical composites including plain, 5-harness satin and 8-harness satin woven composites are studied. For each type composite, unit cells of different sizes are established and corresponding thermal boundary conditions are derived based on the rules discussed in this paper. The identical results can be obtained by unit cells of different sizes and verifies the accuracy of the boundary conditions. The smaller the unit cell size, the more complicated the boundary conditions, and the less the computational cost.

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