PREDICTION OF TEXTILE FABRIC REINFORCED COMPOSITE PROPERTIES BASED ON NODE INTERPOLATION CELL METHOD

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Abstract: Node interpolation cell method (NICM) is a micromechanics method employing the virtual displacement principle and the representative volume element (RVE) scheme to obtain the relationship between the global and the local strain. Mechanical properties of 2-D textile fabric reinforced ceramic matrix composites are predicted by NICM. Microstructures of 2-D woven and braided fabric reinforced composite are modeled by two kinds of RVE scheme. NICM is used to predict the macroscopic mechanical properties. The fill and warp yarns are simulated with cubic B-spline and their undulating forms are approximated by sinusoid. The effect of porosity on the fiber and matrix are considered as a reduction of elastic module. The connection of microstructure parameters and fiber volume fraction is modeled to investigate the reflection on the mechanical properties. The results predicted by NICM are compared with that by the finite element method(FEM). The comparison shows that NICM is a valid and feasible method for predicting the mechanics properties of 2-D woven and braided fabric reinforced ceramic matrix composites.

Key words: textile composites; mechanical properties; ceramic; node interpolation cell method

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INTRODUCTION

In past two decades, researchers have been showing an increase interest in textile fabric composites. The interlacing of fabric has several advantages, such as higher elastic and strength properties (especially through the thickness direction), better toughness properties, improved damage tolerance and impact resistance[1]. Those properties make the woven fabric composites attractive for many structural applications (aircraft, space, automotive, etc.). Since the advancement of woven technology, the performance of woven composite has been improved gradually.

However, the mechanical behavior of textile composite is complex due to the complicated microstructure. Many researchers have attempted to model the performance of textile fabric reinforced composites. These investigations are mainly dividing into three categories. The first category is analytical method that based on classical lamination theory (CLT). Ishikawa and Chou[2-3] developed mosaic, fiber undulation and bridging models. These three models are 1-D and only consider the undulation of the yarns in the loading direction. Naik[4] extended the models of Ishikawa and Chou to 2-D elastic models, considering undulations of both fill and warp yarns. Zhang and Dai[5] suggested a simplified 2-D model, in which the unit cell is modeled by using linear shape functions. Mital[6] developed a simplified model to simulate the complete thermo-mechanical behavior of plain weave composites. The second is finite element method (FEM) which is a powerful method for analysis of structures with complex geometry and configuration. It is firstly used by

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Whitcomb[7-8] to analyze the effect of assumed architecture on module and stresses in woven composites. After this work, many researchers use FEM to calculate the mechanical properties of woven composites[9-12]. Spring and solid elements are also used to constitute a parallelogram spring model to analyze braided composites. Because the analytical method based on CLT is simplified that could not be able to capture the complicated microstructures, it is computationally efficient. Moreover, the accurate finite element model of woven composites requires enormous elements so that the time of calculation is tedious. Therefore, another method, i. e. , the micromechanics model with homogenization is proposed, Tabiei[13-14] suggested a model of woven composites using the method of cells and four-cell.

Nowadays, micromechanics method that evaluates the effective mechanical properties of heterogeneous material is becoming a much more important method. Examples of micromechanics method is a high-fidelity generalized method of cells (HFGMC)[15] and finite volume direct average micromechanics (FVDAM)[16-17]. However, the subcells of HFGMC and FVDAM are limited to rectangles. The approximation of curvilinear inclusions through rectangular discretization increases the required number of subcells which makes the analysis more time-consumming[16]. In order to mitigate the impact of rectangular subcells, the quadrilateral subcell capability has been incorporated into the finite volume theory by Cattu[18] recently. In contrast with the parameter mapping method used by Cattu, Gao[19-20] developed a quadrilateral finite volume method by direct average approach and extended this micromechanics method to 3-D by using virtual work principle and node interpolation method, which is named as node interpolation cell method (NICM).

In this paper, NICM is employed to predict the elastic module of a 2-D textile fabric reinforced ceramic matrix composites. The fill and warp yarns are simplified with cubic B-spline and their undulation are mimicked with sinusoid. The results are compared with FEM. The effect of fiber volume fraction on the mechanical properties of woven and braided fabric composites is also investigated.

1 NICM

In the framework of multi-scale theory, RVE and subcells of fiber-reinforced composites are shown in Fig. 1, the construction of displacement u_i in RVE is based on the two-scale expansion

$$u_i = \bar{\varepsilon}_{ij} X_j + \tilde{u}_i \tag{1}$$

where $\bar{\varepsilon}_{ij}$ is the symmetrical global or macroscopic strain which means equals to $\bar{\varepsilon}_{ji}$, X_j the global coordinate, and $\tilde{u}_i$ the fluctuating displacement which is the fundamental variable, $i, j=1,2,3$.

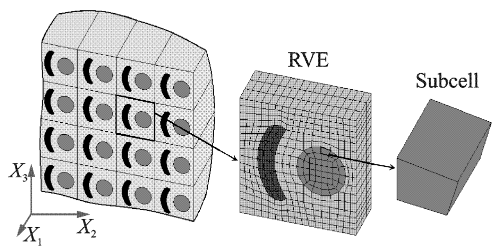

Fig. 1 RVE and subcells of fiber reinforced composites

In order to obtain the solution of $\tilde{u}_i$, some equations and conditions are employed, i. e. , the local stress equilibrium equations within the individual subcells, the traction and displacement continuity conditions between the individual subcells, and the periodic boundary conditions prescribed at the boundary of repeating unit cell.

The virtual displacement principle that has been used by many numerical methods can be expressed as

$$\int_{\Omega} \sigma_{ij} \delta\varepsilon_{ij} \mathrm{d}v = \int_{S_\sigma} T_i \delta u_i \mathrm{d}s \tag{2}$$

where $\delta\varepsilon_{ij}$ is the variation of strain at the point of stress σ_{ij}, and δu_i the variation of displacement at the point of application of external force T_i in the direction of the line of action of the force.

In the case of elastic analysis, the virtual displacement principle has the form of

$$\int_{\Omega} E_{ijkl} \varepsilon_{kl} \delta\varepsilon_{ij} \mathrm{d}v = \int_{S_\sigma} T_i \delta u_i \mathrm{d}s \tag{3}$$

where E_{ijkl} is the elastic module.

Linear geometric equation is

$$\varepsilon_{ij} = \frac{1}{2}(u_{i,j} + u_{j,i}) \tag{4}$$

Substitute displacement construction Eq. (1) into Eq. (4) gives the formulation of strain

$$\varepsilon_{ij} = \bar{\varepsilon}_{ij} + \tilde{\varepsilon}_{ij} \tag{5}$$

where $\tilde{\varepsilon}_{ij}$ is the local strain.

Substituting Eq. (5) into Eq. (3) gives

$$\int_{\Omega}(E_{ijkl}\bar{\varepsilon}_{kl}\delta\bar{\varepsilon}_{ij} + E_{ijkl}\bar{\varepsilon}_{kl}\delta\tilde{\varepsilon}_{ij} + E_{ijkl}\tilde{\varepsilon}_{kl}\delta\bar{\varepsilon}_{ij} + E_{ijkl}\tilde{\varepsilon}_{kl}\delta\tilde{\varepsilon}_{ij})\mathrm{d}v = \int_{S_\sigma}(T_i\delta\bar{\varepsilon}_{ij}X_j + T_i\delta\tilde{u}_i)\mathrm{d}s \tag{6}$$

Suppose $\delta\bar{\varepsilon}_{ij}=0$, the multi-scale virtual displacement principle is conducted as

$$\int_{\Omega}(E_{ijkl}\bar{\varepsilon}_{kl}\delta\tilde{\varepsilon}_{ij} + E_{ijkl}\tilde{\varepsilon}_{kl}\delta\tilde{\varepsilon}_{ij})\mathrm{d}v = \int_{S_\sigma}T_i\delta\tilde{u}_i\mathrm{d}s \tag{7}$$

The discretized form of Eq. (7) is

$$\sum_e\int_{^e\Omega}(E_{ijkl}\bar{\varepsilon}_{kl}\delta\tilde{\varepsilon}_{ij} + E_{ijkl}\tilde{\varepsilon}_{kl}\delta\tilde{\varepsilon}_{ij})\mathrm{d}v = \sum_e\int_{^eS}T_i\delta\tilde{u}_i\mathrm{d}s \tag{8}$$

The expression of local displacement $\tilde{u}_i$ by node interpolation function is

$$\tilde{u}_i = {}^eN^p\,{}^e\tilde{u}_i^p \tag{9}$$

where left superscript e is the number of subcell, right superscript p the local number in subcell, i the direction, ${}^e\tilde{u}_i^p$ the local displacement of node p in subcell e at direction i, ${}^eN^p$ the shape function of local displacement, and ${}^eN^p_{,j}=\frac{\partial\,{}^eN^p}{\partial x_j}$.

Substituting local displacement $\tilde{u}_i$ into Eq. (1), the formulation of displacement becomes

$$u_i = \bar{\varepsilon}_{ij}X_j + {}^eN^p\,{}^e\tilde{u}_i^p \tag{10}$$

Then local stain $\tilde{\varepsilon}_{ij}$ of little deformation becomes

$$\tilde{\varepsilon}_{ij} = \frac{1}{2}\,{}^eN^p_{,j}\,{}^e\tilde{u}_i^p + \frac{1}{2}\,{}^eN^p_{,i}\,{}^e\tilde{u}_j^p \tag{11}$$

Substituting Eqs. (10,11) into Eq. (8) gives the basic equation of macro- and micro-constitutive model.

$$\sum_e{}^e\tilde{u}_k^{q}\,{}^eK_{kqip}\delta\,{}^e\tilde{u}_i^p + \sum_e\bar{\varepsilon}_{kl}\,{}^eC_{klip}\delta\,{}^e\tilde{u}_i^p = \sum_e{}^eT_{ip}\delta\,{}^e\tilde{u}_i^p \tag{12}$$

where

$${}^eK_{kqip} = \int_{^e\Omega}K_{kqip}\mathrm{d}v$$

$${}^eC_{klip} = \frac{1}{2}\int_{^e\Omega}(E_{ijkl}\,{}^eN^p_{,j} + E_{jikl}\,{}^eN^p_{,j})\mathrm{d}v$$

$${}^eT_{ip} = \int_{^eS}T_i\,{}^eN^p\mathrm{d}s$$

$$K_{kqip} = \frac{1}{4}E_{ijkl}\,{}^eN^q_{,l}\,{}^eN^p_{,j} + \frac{1}{4}E_{ijlk}\,{}^eN^q_{,l}\,{}^eN^p_{,j} + \frac{1}{4}E_{jikl}\,{}^eN^q_{,l}\,{}^eN^p_{,j} + \frac{1}{4}E_{jilk}\,{}^eN^q_{,l}\,{}^eN^p_{,j}$$

Periodic boundary condition is

$$\tilde{u}_i(X_j) = \tilde{u}_i(X_j + L_j) \tag{13}$$

where L_j is the characteristic length at direction j of RVE.

Combining Eq. (12) with periodic boundary conditions Eq. (13), we obtain the formulation of nodal displacement

$${}^e\tilde{u}_k^p = {}^eKC_{kpmn}\bar{\varepsilon}_{mn} + {}^eU_k^p \tag{14}$$

where ${}^eKC_{kpmn}$ is a four-order tensor that is related with shape of subcell and elastic property, and ${}^eU_k^p$ the two-order tensor which is related with boundary condition.

Based on the famous homogenized method, the global strain and stress are defined as the integral of corresponding local variable

$$\bar{\varepsilon}_{ij} = \frac{1}{V}\int_{\Sigma_W}\frac{1}{2}(u_in_j + u_jn_i)\mathrm{d}S \tag{15}$$

$$\bar{\sigma}_{ij} = \frac{1}{V}\int_V\sigma_{ij}\mathrm{d}v \tag{16}$$

where Σ_W is the outline of RVE, and V the volume enveloped by outline of RVE. u_i and n_j are displacement vector weight and normal vector weight of Σ_W.

Translating Eq. (16) to the discretized form, we have

$$\bar{\sigma}_{ij} = \frac{1}{V}\sum_e\frac{{}^eV\,{}^eE_{ijkl}}{{}^eV}\int_{^e\Omega}\varepsilon_{kl}\mathrm{d}v = \sum_e\frac{{}^eV\,{}^eE_{ijkl}(\bar{\varepsilon}_{kl} + {}^e\bar{\varepsilon}_{kl})}{V} \tag{17}$$

where ${}^e\bar{\varepsilon}_{kl}$ is the average local strain of subcell.

It can be expressed in terms of the nodal fluctuating displacement as

$${}^e\bar{\varepsilon}_{kl} = \frac{1}{{}^eV}\int_{^e\Omega}\tilde{\varepsilon}_{kl}\mathrm{d}v = \frac{1}{2}\,{}^e\overline{N}^p_{,l}\,{}^e\tilde{u}_k^p + \frac{1}{2}\,{}^e\overline{N}^p_{,k}\,{}^e\tilde{u}_l^p \tag{18}$$

Therefore, the formulation of global stress is changed to

$$\bar{\sigma}_{ij} = \sum_e\frac{{}^eV}{V}({}^eE_{ijkl}\bar{\varepsilon}_{kl} + {}^eE_{ijkl}\,{}^e\overline{N}^p_{,l}\,{}^e\tilde{u}_k^p) \tag{19}$$

Substituting Eq. (14) into Eq. (19) and performing simplification, we obtain the relation between global stress and global strain

$$\bar{\sigma}_{ij} = \bar{E}_{ijkl}\,\bar{\varepsilon}_{kl} + \bar{T}_{ij} \tag{20}$$

where

$$\bar{E}_{ijkl} = \sum_e \frac{{}^eV}{V}({}^eE_{ijkl} + {}^eE_{ijmn}\,{}^e\bar{N}^{p}_{,n}\,{}^eKC_{mpkl})$$

$$\bar{T}_{ij} = \sum_e \frac{{}^eV}{V}({}^eE_{ijkl}\,{}^e\bar{N}^{p}_{,l}\,{}^eU^{p}_{k})$$

The variable $\bar{E}_{ijkl}$ is the component of homogenized macroscopic elastic tensor.

2 MICROSTRUCTURE MODELING

2.1 2-D woven fabric composites

The microstructure of woven fabric composites is shown in Fig. 2. We simulate the structure by a cubical RVE that is discretized by a set of hexahedron (Fig. 3), the mesh has 1 304 solid elements and 1 715 nodes. Assume that the parameter of fill equals to the parameter of warp and that the length of RVE equals to 1, i. e. $l=1.0$, and the height of RVE equals to 0.4. Sinusoid is used to simulate the undulation of fiber, the parameter is d, and the section of fiber is defined by cubic B-spline. Therefore, the expression of fiber volume fraction V_f is

$$V_f = \frac{10(4\lambda + 1)}{3}ab \tag{21}$$

where a and b are half of width and height of fiber respectively, and the height of $0.5a$ is λb, the value of λ is a constant in this paper.

Supposing $\lambda=0.75$ and $b=0.2a$, Eq. (21) is reformulated as

$$a = \sqrt{0.375 \cdot V_f} \tag{22}$$

According to Eq. (22), the geometrical parameter of a can be gained by fiber volume fraction.

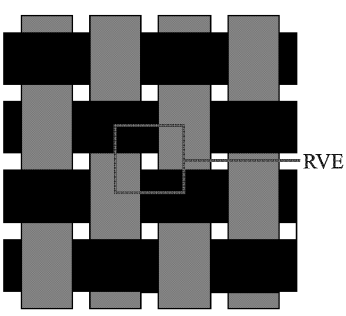

Fig. 2 RVE of woven fabric composites

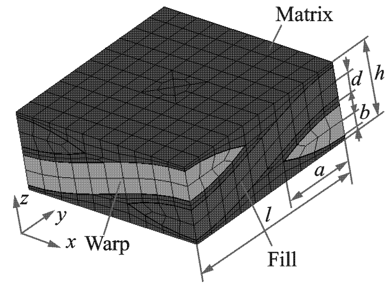

Fig. 3 Analytic model of woven fabric composites

2.2 2-D braided fabric composites

RVE of braided fabric composites is shown in Fig. 4. The model and the parameters of RVE are shown in Fig. 5. The model has 1 824 solid elements and 2 281 nodes. We assume the diagonal length of RVE is equal to 2, i. e. $l=1.0$. θ is braid angle, therefore, the length and width of RVE are $2l \cdot \cos\theta$ and $2l \cdot \sin\theta$ respectively.

The formulation of fiber volume fraction of braided composite is the same with woven composite as shown by Eq. (21).

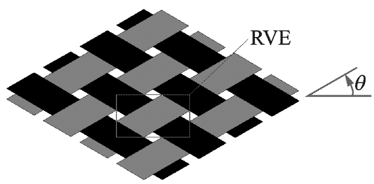

Fig. 4 RVE of braided fabric composites

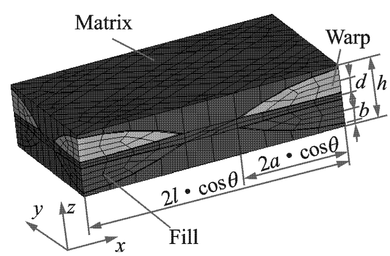

Fig. 5 Analytic model of braided fabric composites

3 NUMERICAL RESULTS

Ceramic composites have a high degree of porosity, and the porosity affects the mechanical properties seriously. In this paper, the elastic properties of fiber and matrix are reduced according to the volume of porosity, and the reduced elastic properties are used during the calculation of macroscopic mechanical properties of ceramic matrix composites. The formulation is

$$E'_s = E_s \frac{V_s - V_v}{V_s} \tag{23}$$

where E'_s is the reduced module, E_s the module before reduction, V_s the volume neglect porosity, and V_v the volume of porosity.

The constituent material properties and the value after reduction of the woven and braided fabric composites are shown in Table 1. The interphase is assumed to be 2% of the fiber diameter in thickness and the modulus of the interphase is assumed to be 3.5 GPa. The volume fraction of fiber and matrix are 40% and 60%, respectively, and the porosity in fiber and matrix are 11.5% and 8.5%, respectively.

Table 1 Material properties of fiber and matrix

Property	Original		Reduced	
	Fiber	Matrix	Fiber	Matrix
E_1/GPa	200	350	142.5	300.4
$E_2(E_3)$/GPa	200	350	142.5	300.4
$\mu_{12}(\mu_{13})$	0.25	0.2	0.25	0.2
μ_{23}	0.25	0.2	0.25	0.2

Based on RVE of woven and braided fabric reinforced ceramic matrix composites, NICM is used to predict the macroscopic mechanical properties. The results are compared with that of FEM.

The numerical results of woven fabric composites are shown in Table 2. The results show that the elastic properties predicted by NICM are in good agreement with the result of FEM and Ref. [6]. In the case of hexahedral discretization, the developed micromechanics method can use small mount subcells to describe the complicated microstructure of woven fabric composites primly and the results is close to FEM and measured values[6]. Therefore, NICM is an effective and accurate approach to predict mechanical properties of woven fabric reinforced ceramic composites.

For braided fabric composites, braided angle is 30 °, the results of NICM and FEM are shown in Table 3. The comparisons prove that the developed method can also applicable to braided fabric composites effectively.

Table 2 Results of woven composites

Property	NICM	FEM	Ref. [6]
E_1/GPa	214.377	213.155	214
E_2/GPa	214.493	213.155	214
E_3/GPa	122.733	113.106	—
G_{23}/GPa	53.057 5	46.209 9	—
G_{13}/GPa	53.117 5	46.209 9	—
G_{12}/GPa	87.401 3	87.031 8	—
μ_{23}	0.240 491	0.246 628	—
μ_{13}	0.241 446	0.246 628	—
μ_{12}	0.196 582	0.193 527	0.17

Table 3 Results of braided composites

Property	NICM	FEM
E_1/GPa	222.258	221.754
E_2/GPa	205.397	205.059
E_3/GPa	125.350	120.155
G_{23}/GPa	52.414 3	47.225 5
G_{13}/GPa	53.173 5	49.214 7
G_{12}/GPa	88.651 3	89.247 7
μ_{23}	0.246 116	0.247 703
μ_{13}	0.230 621	0.232 567
μ_{12}	0.210 243	0.210 705

Some other efforts are done to investigate the influence of micro-structural parameters on the macroscopic mechanical properties.

In the case of 2-D woven fabric composites, the variation of fiber volume fraction with elastic module, shear module and Poisson ratio are shown in Fig. 6. With the increasing fiber volume fraction, elastic module, shear module, Poisson ratio μ_{12} decreases, and Poisson ratio μ_{23} and μ_{13} increase. But μ_{12} has little difference with the diversity of fiber volume fraction. In addition, the most important is that the influence of fiber volume fraction on mechanical properties has little difference between NICM and FEM.

For 2-D braided fabric composites, the varia-

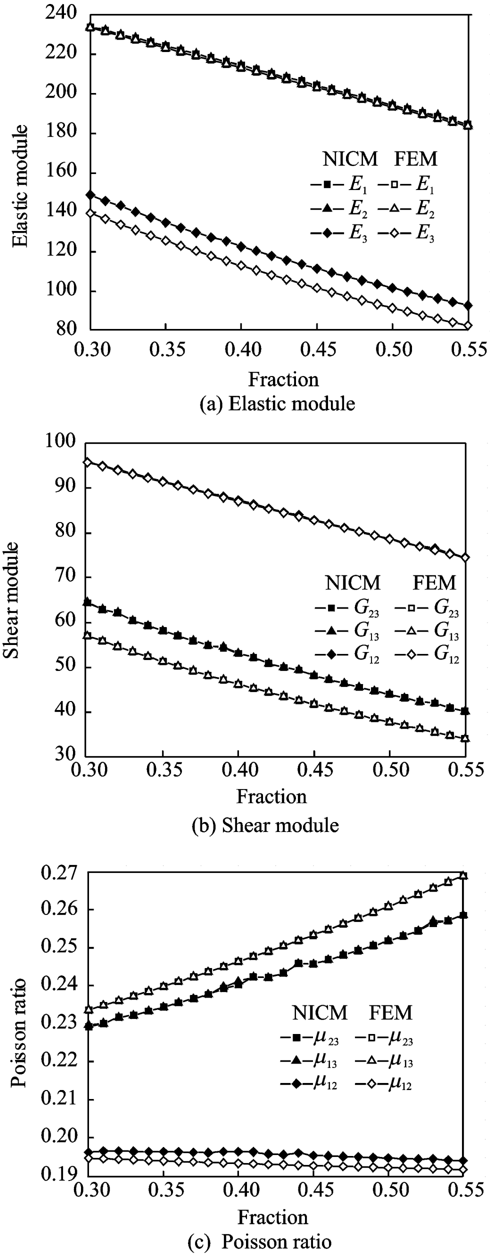

Fig. 6 Variation of mechanical properties with fiber volume fraction for woven composites

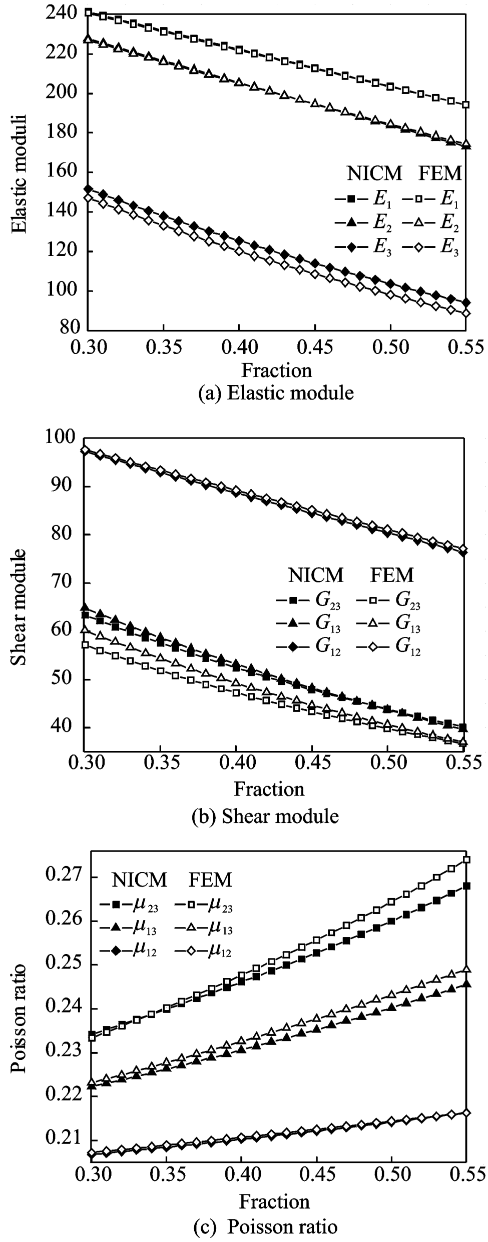

Fig. 7 Variation of mechanical properties with fiber volume fraction for braided composites

tion of fiber volume fraction with elastic module, shear module and Poisson ratio (Fig. 7) are similar with that in Fig. 6, so the effect of mechanical properties by fiber volume fraction is almost the same as woven fabric composites. Moreover, the variation of braided angle with mechanical properties is shown in Fig. 8. With increasing the braid angle, the difference of elastic module at directions "1" and "2" is decreased till the angle is equal to 45°, and there is similar trend between μ_{13} and μ_{23}.

4 CONCLUSION

Because of hexahedral subcells, the developed method has strongly capability of simulating microstructures, it can simulate the complex characterization of woven and braided fabric composites. Micro-structural model of woven and braided fabric composites are built by RVE respectively. The fill, warp yarns are simplified to cubic B-spline, and the undulation is simulated as sinusoid. The relation between geometry parame-

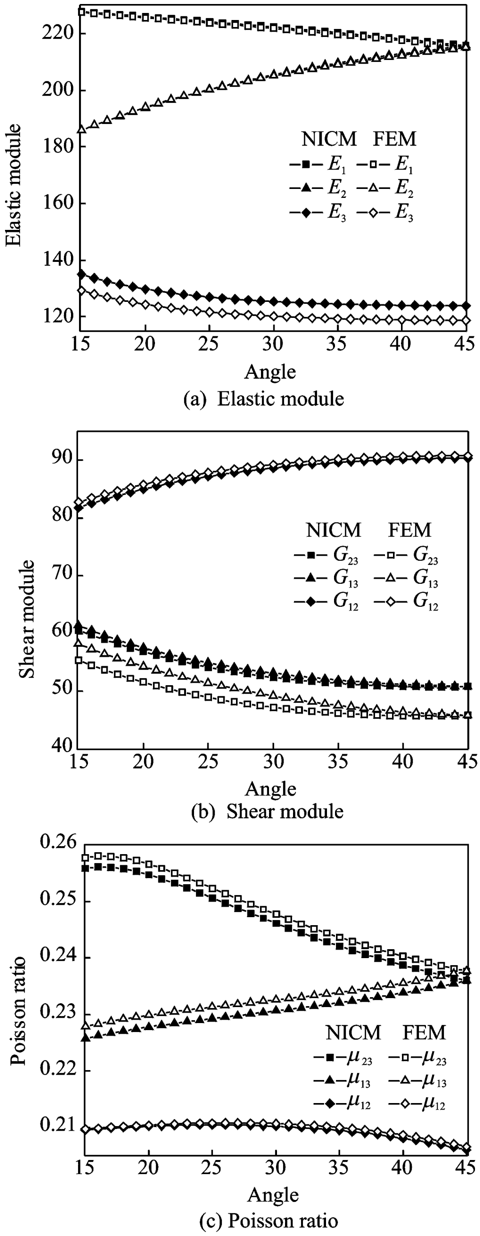

Fig. 8 Variation of mechanical properties with braided angle for braided composites

ters and fiber volume fraction is analyzed and NICM is used to predict the macroscopic mechanical properties. The influence of fiber volume fraction on the mechanical properties is also studied. The predicted results agree reasonably well with the predictions of FEM.

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基于节点插值子胞模型的纺织复合材料力学性能预测

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摘要:节点插值子胞模型是一种通过虚位移原理和代表性体积单元建立宏观和细观应变之间关系的细观力学方法。采用节点插值子胞模型进行二维纺织纤维增强陶瓷基复合材料的力学性能预测。分别建立二维平纹和交叉编织复合材料单胞的细观结构分析模型,分别采用三次B样条和正弦曲线来模拟经纱和纬纱的截面和弯曲形式,并根据纤维和基体中的孔隙含量对其模量进行折减,采用节点插值子胞模型进行宏观力学性能预测,并分析了细观结构参数和纤维体积含量对材料力学性能的影响。节点插值子胞模型的预测结果与有限元法比较表明:采用节点插值子胞模型进行二维平纹和交叉编织陶瓷基复合材料力学性能预测的有效性和可行性。

关键词:纺织复合材料;力学性能;陶瓷;节点插值子胞模型

中图分类号:TB332

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