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Predicting the Effective Properties of Unidirectional Composites Through Numerical Simulation

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Abstract

The Mechanical properties of composites are fundamental for the design of fiber composite structures. A new finite element analysis (FEA) technique is established to determine the effective properties of composite materials. The technique involves finite element analysis of Representative Volume Element (RVE). The boundary condition plays an important role in the analysis of composite RVE. It is important to predict the correct boundary conditions (BCs) to be applied on RVE before the analysis of composite RVE. In order for the deformation in RVE to accurately reflect the deformation within the composite structure, the BCs must be suitable. The appropriate boundary conditions to be applied are determined in this study using FE analysis of isotropic RVE. The composite RVE is subjected to the thusly acquired boundary conditions, and the resulting material property along that direction is given a unit displacement along the necessary direction. Averaging the stress - strain fields generated from the analysis yields the effective properties of unidirectional fibre reinforced composite material.

Keywords: *Representative Volume Element; finite element analysis; isotropic; Composites; Stress.*

1. Introduction

Modern technology requires materials with combined properties that cannot be met by conventional materials. In aerospace applications, the structural materials should be light weight and are required to be strong, stiff, low thermal expansion, impact resistant[9-11]. This requirement leads to the development of composite materials. Although direct study of composite structures is conceivable, it is time consuming and unrealistic. Material properties are fundamentals for any analysis. The properties of composite materials can be obtained by experimental tests[12-14]. In many practical cases, it is not possible to conduct an experiment for all possible reinforcement types and it's not economical. Predicting the effective properties plays a major role in any composite structure analysis[10-11, 16-26]. Many methods have been developed to predict the effective properties of composite materials like macro-mechanical analysis, micro-mechanics, meso-mechanics, experimental tests etc. Among all micromechanical models have been proven useful tool for design and analysis of composite materials.

The literature survey of existing micro-mechanical model has been done which involves complex mathematics, finite element methods, and continuum mechanics. The analytical result based on energy variational principles of Hashin and Rosen[1], Whitney and Riley's solution is based on the application of the energy balance approach with the help of classical elasticity theory[2], the result based on a mechanic approach involving the use of displacement continuity and force equilibrium conditions by Sun and Chenl and Chamis[6]. Tang, T prediction of effective properties is based on Variational method known as Variational Asymptotic

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Micromechanics (VAMUCH)[7]. C.T. Sun and R.S. Vaidya[9] estimated the effective properties through numerical method. The suitable boundary conditions to apply to the RVE for various load conditions are established using periodicity and symmetry conditions in their analysis. Gauss theorem is used to relate the non-homogeneous stress and strain fields to average the stress and strain fields.

In present work a new method is developed to predict the effective properties through numerical simulation. Numerical method usually involves analysis of RVE (Representative Volume Element). Micromechanics models based on the RVE fundamental principle are used to ease the analysis. Two important issues need to be followed during FE analysis of RVE.

The correct RVE with proper fiber matrix volume fraction as in the parent structure must be isolated. Second, the chosen RVE must have the appropriate boundary conditions applied to it. All the literature has mainly emphasized on these two issues which gave the path for the present work to develop a new method. In the present work the RVE is isolated with proper fiber-matrix volume fraction. Later the boundary conditions are found out by FE analysis of Isotropic RVE. The BCs thus obtained are imposed on composite RVE and unit displacement is given. The effective properties are computed by averaging the non-homogeneous stress and strain fields.

2.0 Representative Volume Element (RVE)

Experimental determination of effective properties of composite materials is difficult, especially when transverse shear moduli are involved. This means that the study of composites and the determination of the effective properties make the greatest use of finite element methods. Analysis of the RVE corresponding to the fiber packing sequence is typically required to estimate the composite properties using a numerical approach. There are several publications in the literature where the RVE is examined to ascertain the characteristics of composite materials. The composite materials represent statistical homogeneity i.e., periodic arrangement so that representative volume element (RVE) can be defined which is, as indicated by Hill[10], fundamentally typical of the entire mixture on average, with enough inclusions for the apparent overall moduli to be essentially independent of the boundary conditions. Due to the symmetry and periodicity of these arrays, only one array can be used to investigate the lamina at the micro scale in these idealizations. Furthermore, if this single array represents the general arrangement of fibres in relation to the matrix, as well as the interactions between fibre and matrix phases, it is referred to as a Representative Volume Element (RVE). Figure 1 shows the cross-sectional view of continuous fiber reinforced composite and arrays generally used for considering the RVE.

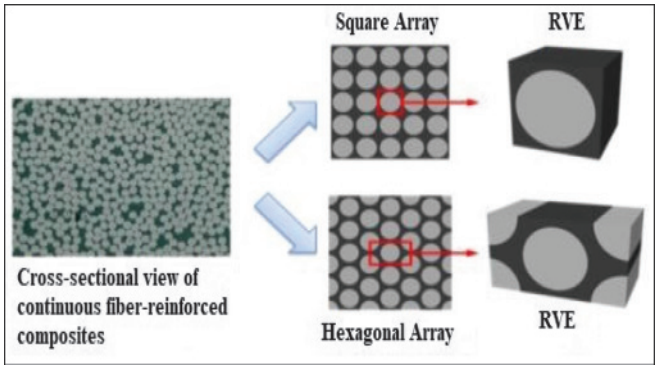


Figure 1: Cross-section of continuous fiber reinforced composite, arrays, RVE

2.1 Predicting the Effective Properties of Composite Material

Estimation of composite material properties through numerical method usually involves FE analysis of RVE. There are a few issues need to be considered during analysis. Firstly, the correct RVE with proper fiber matrix volume fraction as in the parent structure must be isolated. Second, proper boundary conditions must be applied to the RVE that has been chosen and then correct boundary conditions must be estimated before the FE analysis of composite RVE. Hence the boundary conditions are estimated through FE analysis of isotropic materials where properties are same along all the direction. The objective of this analysis is to find out the boundary conditions which give equal stress and strain throughout the RVE so that the material properties are same along all the directions. Later the boundary conditions obtained from the analysis are used to find the effective properties of composite materials.

2.2 Finite Element Analysis of Isotropic RVE

Before the FE analysis of composite RVE it is important to find out the appropriate boundary conditions to be imposed on RVE. Firstly, the RVE is modelled with isotropic material properties to find out the boundary conditions so that deformation in the RVE is uniform. Materials properties considered E=210 GPa and √=0.3. The RVE considered is 1x1x1 ¼m^3 cube as shown in the Figure 2. Hexa mesh is used for meshing the RVE. The RVE is subjected to initial displacement in various directions with corresponding boundary conditions so that the stress field in the RVE is uniform.

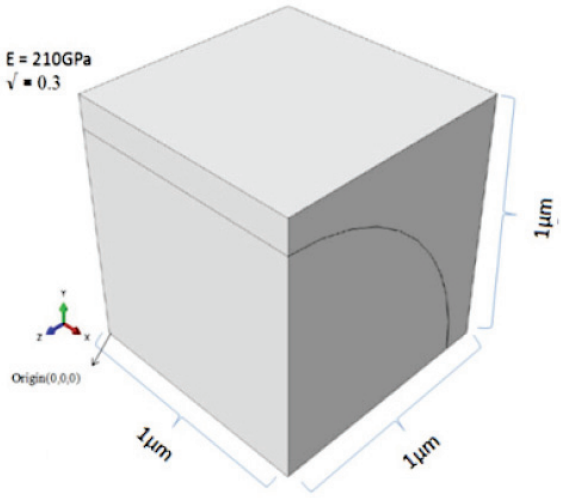
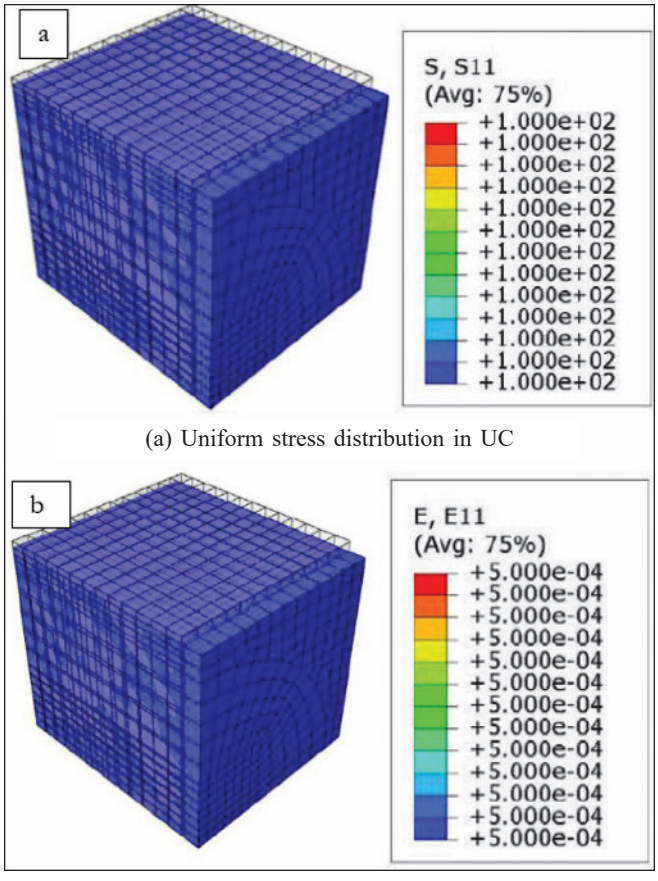


Figure 2: CAD model of RVE

2.3 Initial displacement along normal direction (normal deformation of RVE)

Initially, a unit displacement is applied on the face of RVE along X-direction at x=1µm. The stress and strain field in the RVE is as shown in the Figure 3 (a) and (b) respectively. To obtain a uniform stress and strain field, symmetric boundary conditions are applied along 3-directions. XSYMM boundary condition is applied along x-direction at x=0, YSYMM is applied along y-direction at y=0 and ZSYMM is applied along z-direction at z=0 as shown in Figure 4. Similarly initial displacement is applied along other two Y and Z direction imposing similar boundary condition.



(a) Uniform stress distribution in UC

Figure 3: (b) Uniform strain in UC

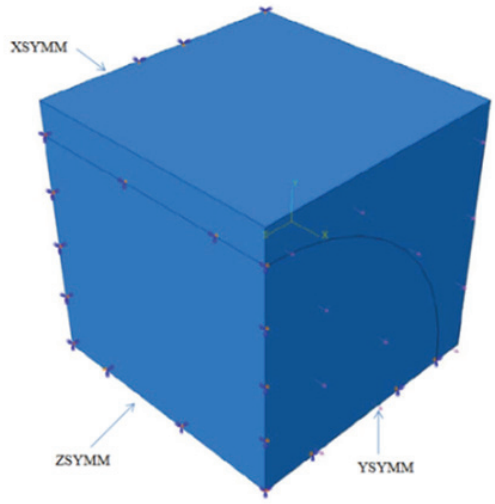


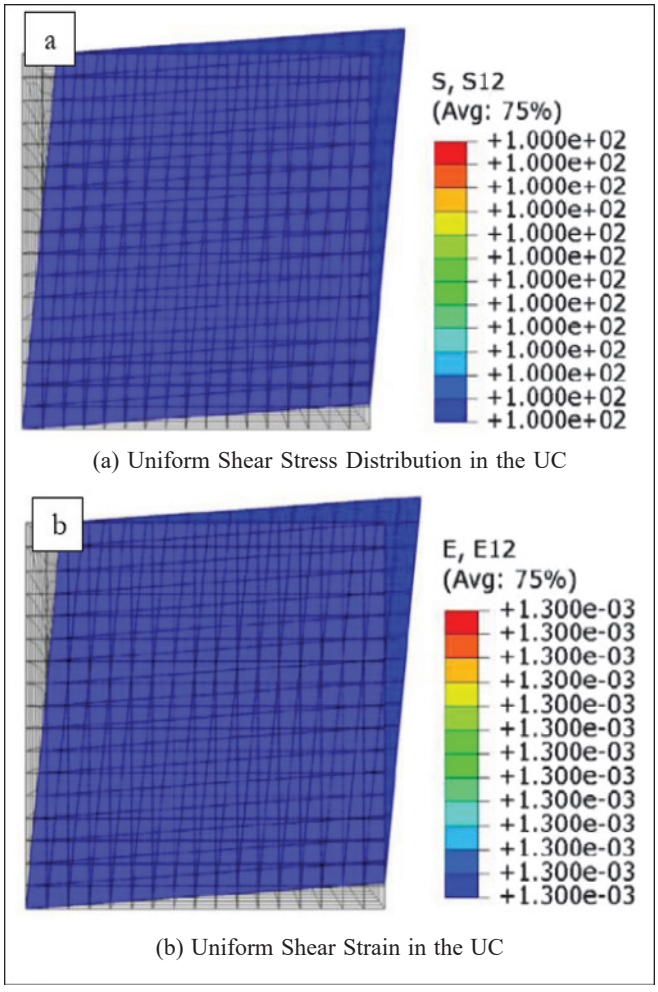
Figure 4: Boundary Conditions applied for Normal Loading

2.4 Initial displacement along transverse direction (shear deformation of RVE)

For a uniform shear deformation, a unit displacement is applied along two perpendicular directions. That is along x-direction at y=1µm and along y-direction at x=1µm. The stress and strain field in the RVE is as shown in the Figure 5 (a) and (b) respectively. To obtain a uniform stress and strain field, symmetric boundary conditions are applied along 3-directions. In this case XSYMM boundary condition is applied along y-direction at y=0, YSYMM is applied along x-direction at x=0 and ZSYMM is applied along z-direction at z=0 as shown in Figure 6. Similarly for a displacement along YZ-direction, XSYMM boundary condition is applied along x-direction at x=0, YSYMM is applied along z-direction at z=0 and ZSYMM is applied along y-direction at y=0. For ZX-direction loading, XSYMM boundary condition is applied along z-direction at z=0, YSYMM is applied along y-direction at y=0 and ZSYMM is applied along x-direction at x=0.

3.0 Finite Element Analysis of Composite RVE

From the obtained boundary conditions the FE analysis of RVE is carried out. The RVE is modelled with 0.36 fiber volume



(a) Uniform Shear Stress Distribution in the UC

(b) Uniform Shear Strain in the UC

Figure 5

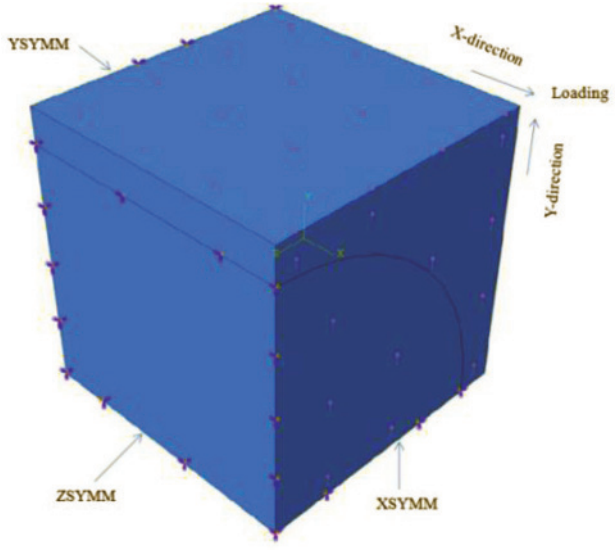


Figure 6: Boundary Conditions applied for Shear Loading

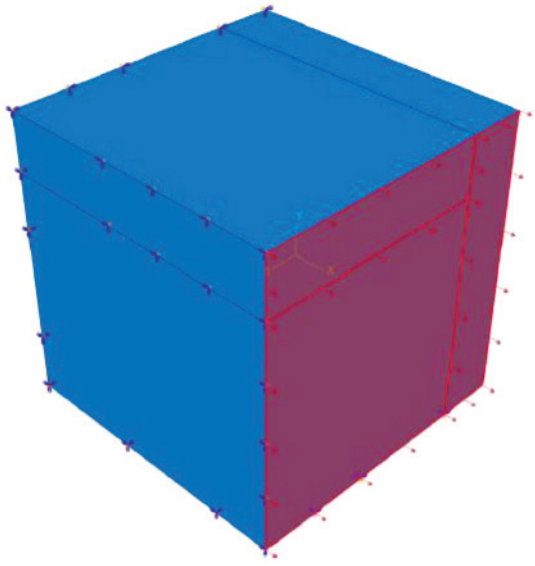


Figure 7: Initial displacement along fiber direction (X-direction)

fraction. The fiber considered is SiC with modulus 430GPa, 0.18 poison's ratio and a Ti-matrix with modulus 85.5GPa, 0.3 poison's ratio. The RVE is modelled as shown in Figure 7. The non-uniform stress and strain fields inside the heterogeneous medium are produced by the FE analysis of the composite RVE. According to average stress and strain are determined from the collected data. To calculate the average stress filed, the UC is given initial displacement along fiber direction as shown in the Figure 7. The corresponding stress quantities for each element are recorded and the average stress in fiber and matrix is calculated using Eq.1. With the average values, the average stress in the UC is calculated. For simplicity square fiber is considered.

$$\text{Average stress } \sigma' = \frac{\sum_{i=1}^{n} Si\ Ai}{\sum_{i=1}^{n} Ai} \quad \ldots (1)$$

Where S is the stress induced in each element, A is the cross-sectional area of the element, and i is the element number.

3.1 Validation Example

For validation purpose, the analysis of composite RVE is carried out. For analysis purpose glass/epoxy composite is considered with 0.64 fiber volume fraction and is compared to existing analytical method. The boundary conditions and the loadings are as mentioned in previous section. The stress and strain field induced in the RVE is as shown in the Figure 8(a) and (b) respectively. As initial equal displacement is given to RVE, the corresponding strain field is uniform throughout the RVE. The corresponding stress quantities for each element are recorded and the average stress in fiber and matrix is calculated separately using Eq.1. With the average values,

the average stress in the RVE is calculated using Eq. 2. The result is compared to theoretical value.

$$\text{Average Stress } \sigma' = \frac{\sigma' f \ A' f + \sigma' m \ A' m}{Af + Am} \quad \text{... (2)}$$

3.1.1 Numerical solution

Total number of elements = 1000

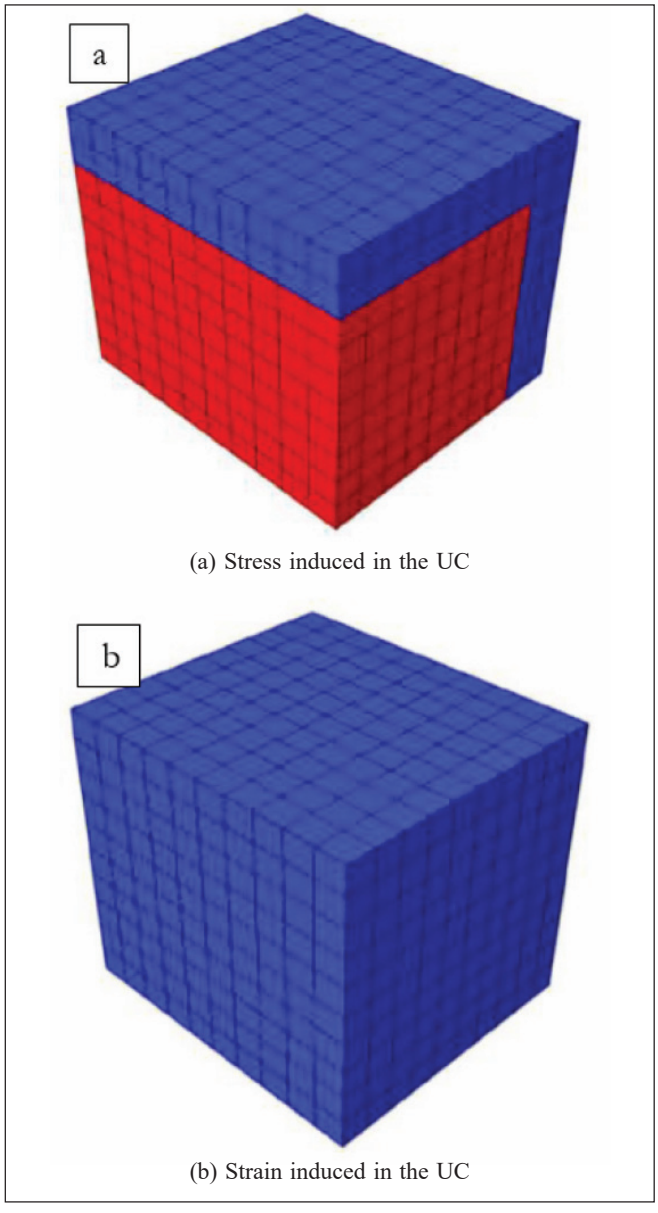
Total c/s area of fiber = 640 mm.

Total c/s area of matrix = 360 mm.

Average stress in the fiber and matrix is calculated using Eq.1.

σ' f = 8497.869844 MPa

σ' m = 345.6793333 MPa



(a) Stress induced in the UC

(b) Strain induced in the UC

Figure 8

Using the Eq. 2 the average stress in the UC is calculated.

σ' = 5563.08126 MPa

Average strain in the UC ∈' = 0.1

Effective property of composite material along fiber direction

$E_1 = \sigma'/\in' = 5563.08126/0.1 = 55630.8126$ MPa

3.1.2 Analytical solution

According to rules of mixture the Longitudinal Young's Modulus of the composite material is given by Eq. 3.

$$E_1 = E_f V_f + E_m V_m \quad \text{... (3)}$$

Material property – Composite material considered is glass/epoxy with 64% fiber volume fraction. Young modulus of glass fiber and epoxy is 85Gpa and matrix is 3.4GPa respectively. Poisson's ratio is 0.2 and 0.3 for fiber and matrix respectively.

From Eq.3 the effective property (longitudinal young's modulus) is calculated.

$E_1 = (85000*0.64) + (3400*0.36) = 55624$ MPa

The numerical value shows the small deviation from the analytical solution.

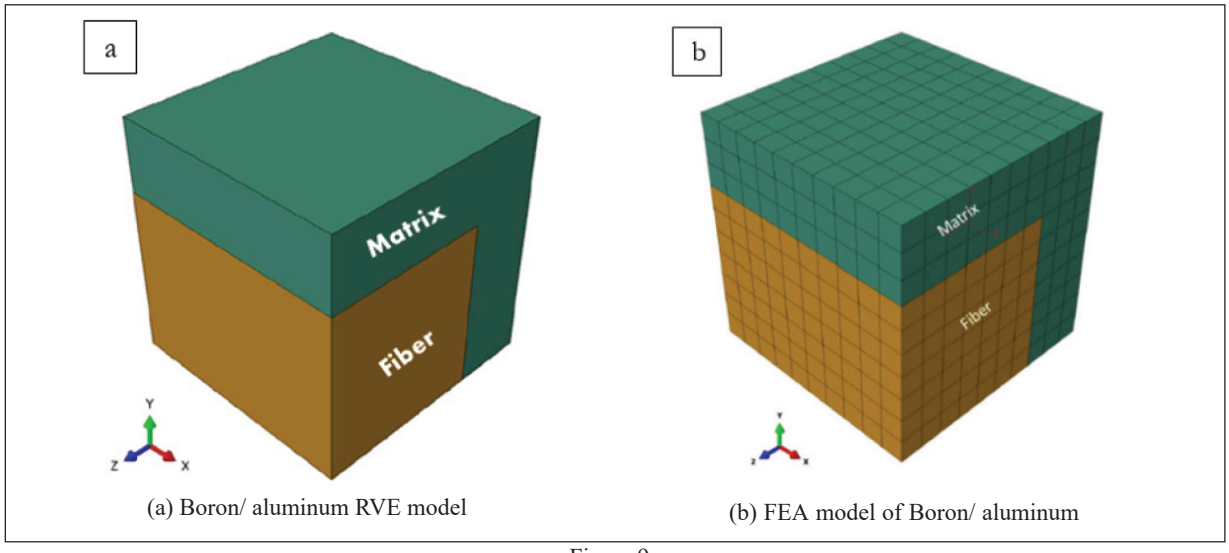
4.0 Finite Element Analysis of Boron/Aluminum Composite RVE (VF= 0.49)

Finite element analysis of boron/aluminum RVE is carried to check the validation of boundary conditions consider. The material properties along three directions are estimated and are compared to the existing literature values. The RVE of dimension $1\times1\times1\mu m^3$ is modelled with 0.49 fiber volume fraction as shown Figure 9 (a) and (b) shows FEA model of RVE which includes 1000 elements and 1331 nodes. The material properties are given in Table 1.

Table 1: Material properties for boron/aluminum[6]

Composition	E (Gpa)	√
Boron (fiber)	379.3	0.1
Aluminum (matrix)	68.3	0.3

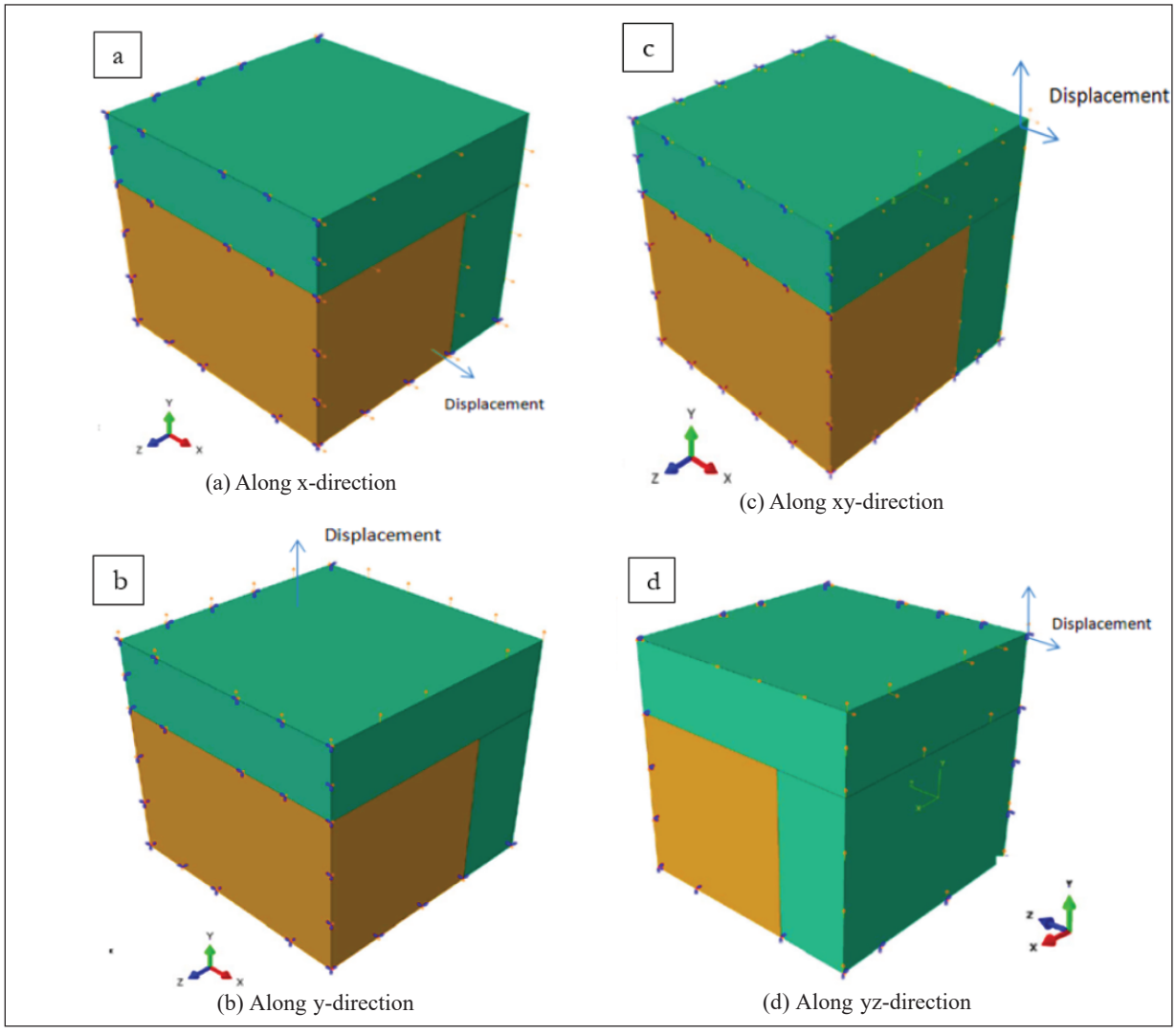
Similar to the case of finite element analysis of isotropic RVE, initial displacement and boundary conditions are imposed on boron/aluminum RVE. A unit displacement is applied on the face of RVE along X-direction at x=10mm to get modulus (E1) along x direction. Similarly, BC's and displacements are imposed along other direction as discussed in the case of isotropic material to get the properties along particular directions, that is to get E2, G12, G23, √12, √23. Figure 10 shows the application of boundary condition and initial displacement applied.



(a) Boron/ aluminum RVE model

(b) FEA model of Boron/ aluminum

Figure 9



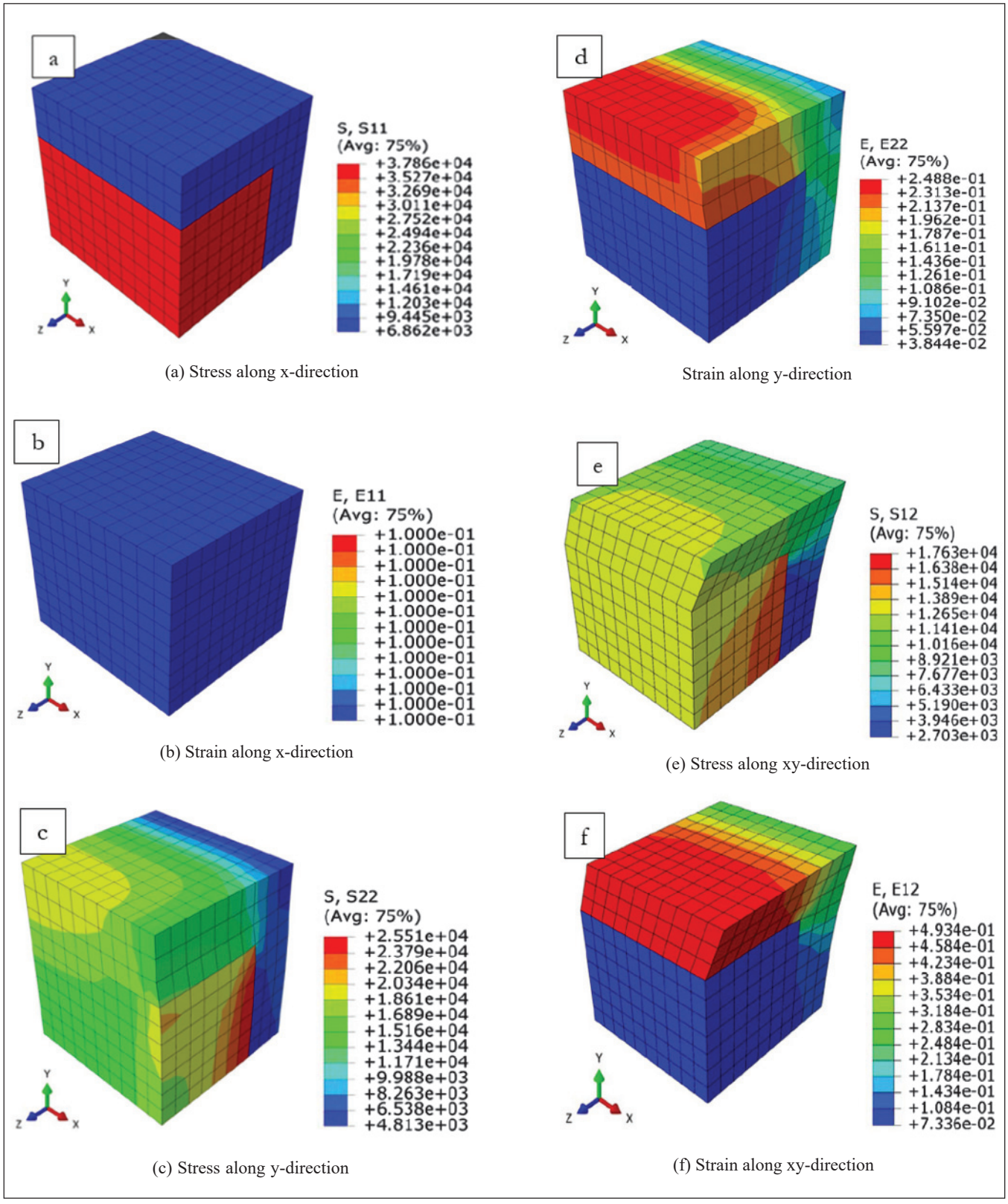
(a) Along x-direction

(c) Along xy-direction

(b) Along y-direction

(d) Along yz-direction

Figure 10



(a) Stress along x-direction

Strain along y-direction

(b) Strain along x-direction

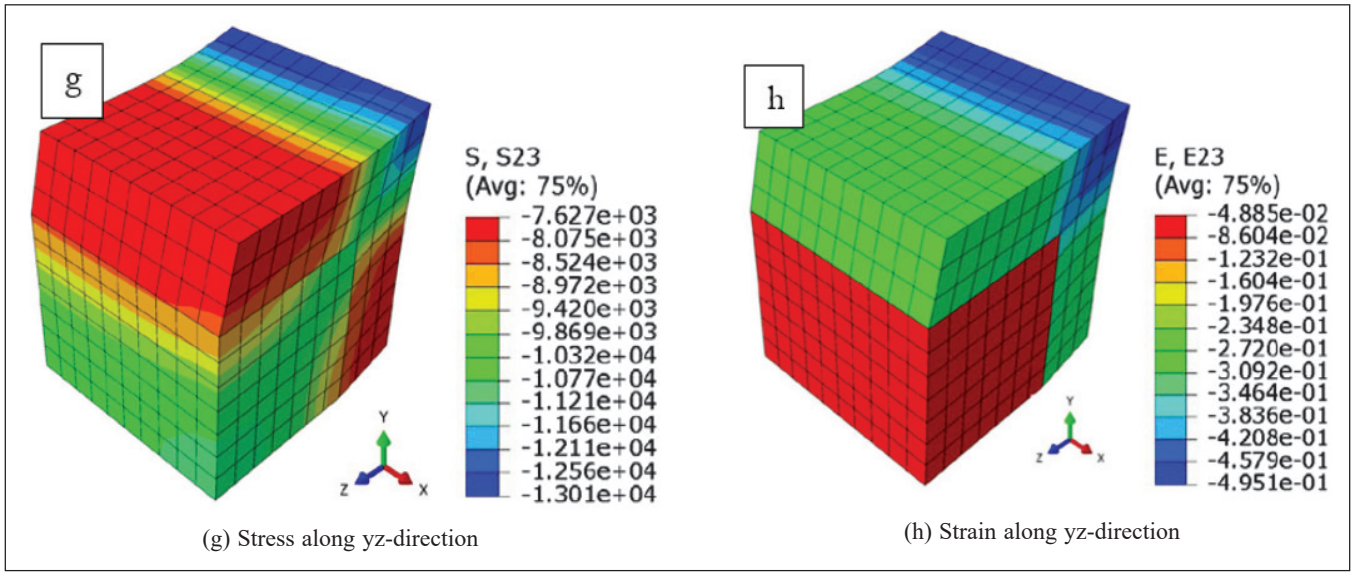
(e) Stress along xy-direction

(c) Stress along y-direction

(f) Strain along xy-direction

Figure 11: Stress and strain distribution in the Boron/Aluminum RVE

(Figure 11 Continued on next page)



(g) Stress along yz-direction

(h) Strain along yz-direction

Figure 11: Stress and strain distribution in the Boron/Aluminum RVE

Table 2: Material properties of Boron/Aluminum composite

Direction	Average Stress, σ'(GPA)	Average Strain, ε' (Longitudinal direction)	Modulus (Gpa)	Average Strain, ε"	(Transverse direction) Poisson's ratio
X	22.157	0.1	221.57	-0.019	0.19
Y	14.405	0.1	144.05	-0.0239	0.239
Xy	11.236	0.2	56.18	-	-
Yz	-9.304	-0.2	46.522	-	-

Table 3: Comparison of material properties for boron/aluminum composite (Vf =0.47)

Elastic Constants (Gpa)	FEA of RVE	Ref. 1	Ref. 2	Ref. 3	Ref. 4	Ref. 5	Experimental [8]
E1	215.02	215	215	214	214	215	216
E2	139.92	139.1	123	135	156	144	140
G12	54.69	53.9	53.9	51.1	62.6	57.2	52
G23	45.59	54.6	-	-	43.6	45.9	-
√12	0.192	0.195	0.19	0.19	0.2	0.19	0.29
√23	0.239	0.31	-	-	0.31	0.29	0.19

4.1 Calculations

The stress and strain in each element is tabulated and the average value is calculated using the formula.

$$\text{Average stress } \sigma' = \frac{\sum_{i=1}^{n} S_i A_i}{\sum_{i=1}^{n} A_i}$$

$$\text{Average stress } \varepsilon' = \frac{\sum_{i=1}^{n} \varepsilon_i A_i}{\sum_{i=1}^{n} A_i}$$

Where S is the stress in a single element.

A is the area of a single element.

ε is the strain induced in a single element.

The average stress and strain fields obtained from FE analysis and the material properties obtained from that average stress and strain fields along the x and y directions are as tabulated in Table 2.

The result obtained from the above analysis are compared to the existing literature values and are tabulated in Table 3.

The result shows a good correlation between the experimental and literature values.

5.0 Conclusion

The heterogeneous material is homogenized by effective properties which make the analysis of composite material more ease. A new method is developed to predict the effective material properties of composite materials. To find out the effective properties of composite material through the numerical method, appropriate boundary conditions under various loading have been determined through FE analysis of isotropic RVE. With the boundary conditions obtained FE analysis of composite material is carried out. The heterogeneous RVE properties are homogenized by averaging the stress and strain fields obtained from FE analysis of composite RVE. The finite element analysis predictions of a material's properties line up with actual theoretical and experimental values.

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