

Voxel-Based modeling of the effect of non-uniform fiber distribution on the elastic properties of fiber-reinforced composites

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Abstract

This paper investigates the influence of non-uniform fiber distribution on the effective elastic properties of unidirectional fiber-reinforced composites. A methodology combining computer vision techniques and voxel-based numerical modeling is proposed for quantitative analysis of composite microstructures. Segmented microstructure images are processed to determine fiber centers, inter-fiber distances, and deviations from a regular arrangement. Based on the obtained statistical characteristics, regular and stochastic representative volume element (RVE) models are generated. The stochastic models reproduce the observed irregularity of fiber distribution through controlled random displacement of fiber centers. Finite element analysis and homogenization procedures are applied to evaluate the effective elastic properties of both microstructure types. The obtained results show that the introduction of spatial irregularity has a minor influence on the average elastic moduli and Poisson's ratios but leads to a statistical variation of the mechanical properties. The proposed approach can be used to improve the realism of micromechanical composite models and to assess the effect of microstructural heterogeneity on material behavior.

Keywords

fiber-reinforced composites, voxel modeling, representative volume element, homogenization, finite element method, stochastic microstructure, computer vision, elastic properties.

1. Introduction

Fiber-reinforced composites are among the most important modern structural materials and are widely used in aerospace, energy, transportation, and mechanical engineering applications. Their effective mechanical properties are determined not only by the characteristics of their constituents (the matrix and reinforcing fibers) but also by the features of their microstructure, particularly the spatial distribution of fibers within the material. In theoretical and numerical studies, fibers are commonly arranged in regular square or hexagonal arrays. However, experimental investigations and micrograph analyses have shown that real composite materials exhibit deviations from uniformity, including local fiber clustering, regions of increased porosity, and matrix-rich areas, all of which may alter the stress-strain state of the composite [1–3]. Such non-uniformities are especially common in materials manufactured using filament winding, resin injection molding, and fiber-reinforced additive manufacturing technologies [5]. They lead to variations in local stiffness and redistribution of loads between fibers and the matrix, which in turn affect the macroscopic elastic properties and strength of the structure. Therefore, assessing the degree of non-uniform fiber distribution is essential for developing more accurate and realistic composite material models and for optimizing their performance.

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This study proposes an approach that combines computer vision techniques with numerical modeling for the quantitative analysis of composite microstructures and the evaluation of the influence of non-uniform fiber distribution on the effective material properties. An algorithm was developed to process a set of microstructural image masks of a unidirectional composite, enabling the identification of fiber center coordinates, fiber radii, and deviations from a regular arrangement. Statistical analysis of the processed images is used to determine the average deviation from a regular distribution, which serves as a measure of non-uniformity for subsequent numerical simulations.

Based on the obtained data, two voxel-based representative volume element (RVE) models are generated:

1. A model with a regular fiber distribution;
2. A model with controlled non-uniformity, in which fiber centers are displaced by a percentage determined algorithmically from the statistical image analysis.

Subsequent simulations make it possible to compare the elastic properties of the two microstructure configurations. This provides a quantitative assessment of the influence of reinforcement non-uniformity on the mechanical behavior of composite materials and establishes a basis for the validation of micromechanical models that account for realistic microstructural features.

2. Related Work

Modeling the mechanical properties of fiber-reinforced composites is traditionally based on the use of representative volume elements (RVEs) and numerical techniques, particularly the finite element method (FEM). This approach enables the determination of effective material properties based on the underlying microstructure. In [5], micromechanical modeling of polymer composites reinforced with basalt and glass fibers was investigated, demonstrating the influence of fiber type and volume fraction on elastic properties. Similar approaches are widely used for evaluating the mechanical behavior of composite materials; however, the microstructure is typically predefined and is rarely analyzed from the perspective of its spatial organization.

Analytical methods, particularly the Mori–Tanaka model, remain effective tools for the rapid estimation of composite properties. Recent studies have shown a growing tendency to combine analytical models with numerical simulations and machine learning techniques. In [6], a hybrid approach was proposed in which FEM results were employed to improve the accuracy of an analytical model through machine learning algorithms. This methodology significantly enhances prediction accuracy while maintaining reasonable computational efficiency.

An important aspect of composite modeling is the consideration of physical interactions between constituent phases. In [8], the influence of the interphase layer between fibers and the matrix on effective elastic properties was investigated. The study demonstrated that even a thin transition layer can substantially affect the mechanical response of the material, and that the relationships between microstructural parameters and effective properties can be described using nonlinear regression models.

A separate research direction focuses on the generation of stochastic microstructures. In [8], an algorithm for constructing RVEs with randomly distributed particles or fibers was proposed. The method enables the generation of statistically representative microstructures while maintaining a prescribed volume fraction. Statistical descriptors such as nearest-neighbor distances, pair-correlation functions, and Ripley's K-function are commonly employed to quantify the degree of randomness and spatial heterogeneity of the generated structures.

Further developments in stochastic modeling have investigated the influence of random generation techniques on simulation results. In [9], it was shown that the choice of random number generation algorithm affects the spatial arrangement of fibers within an RVE, which subsequently influences the statistical characteristics of the predicted mechanical properties. While the average elastic moduli remained relatively stable, significant differences were observed in their variance and distribution.

Recent studies have also advanced high-fidelity microstructure modeling techniques. In [10], machine learning methods were applied to generate stochastic RVEs capable of reproducing realistic microstructures of unidirectional composites with high accuracy. Such approaches aim to improve the correspondence between numerical models and actual composite materials.

Another important research area concerns the experimental and numerical validation of micromechanical models. In [6], short-fiber composites were investigated using RVE-based homogenization techniques and their averaged variants. The results demonstrated good agreement between numerical predictions and experimental observations. However, the proposed methodology was primarily focused on estimating average material properties rather than analyzing the influence of spatial microstructural heterogeneity.

A review of the current literature indicates that most approaches to modeling fiber-reinforced composites are focused on predicting effective average material properties using RVEs, analytical models, or hybrid combinations thereof. Considerable effort has been devoted to improving prediction accuracy and reproducing realistic microstructures.

Nevertheless, spatial microstructural characteristics such as inter-fiber distances, local fiber density, and the degree of non-uniform fiber distribution remain insufficiently investigated. Existing approaches generally do not incorporate these factors into the interpretation of simulation results, which limits the ability to fully describe the influence of microstructural heterogeneity on the mechanical behavior of composite materials.

Therefore, there is a clear need for methods that combine numerical modeling with quantitative microstructure analysis. In particular, the integration of computer vision techniques with micromechanical modeling provides a promising framework for evaluating spatial heterogeneity and its influence on the effective properties of fiber-reinforced composites.

3. Microstructure Modeling

3.1. Regular Fiber Distribution Model

The microstructure of a fiber-reinforced composite is considered at the level of a representative volume element (RVE), which consists of a matrix and a system of unidirectional fibers with circular cross-sections. Figure 1 illustrates a regular fiber arrangement in which the centers of the inclusions form a periodic lattice with a constant inter-fiber distance d .

Based on this configuration, a three-dimensional voxel model (Figure 2) of size $N \times N \times N$, where $N = 40$ voxels, is generated. Each element of the domain is assigned a corresponding material phase. The selection of the $40 \times 40 \times 40$ voxel size is based on the results of a previous study [12], in which the effect of voxel model size on the stability of effective elastic properties was investigated for polycrystalline copper. It was found that increasing the size of the representative volume reduces the statistical scatter of the obtained properties. For a model size of 20 voxels, the mean variance was 1.38, while the maximum deviation of the effective properties did not exceed 1.91%. Based on this observed trend, an RVE size of $40 \times 40 \times 40$ voxels was used in the present study as a compromise between the accuracy of microstructure representation and computational cost.

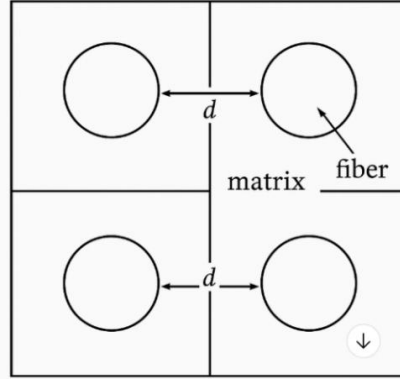


Figure 1: Schematic representation of the regular arrangement of fibers in a composite matrix.

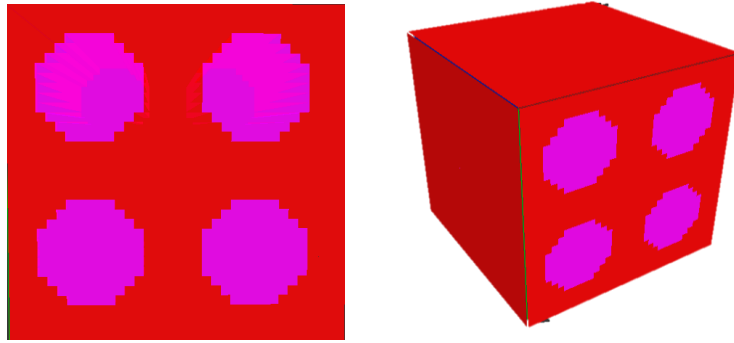


Figure 2: Numerical voxel-based composite model with a regular microstructure: 2D cross-section and 3D representative volume element (RVE) for subsequent FEM analysis.

Each voxel (x,y,z) is assigned a material phase using the following discrete function:

$$V(x, y, z) = \begin{cases} 1, & \text{matrix} \\ 2, & \text{fiber} \end{cases}, \quad (1)$$

where the values 1 and 2 are identifiers of the material phases and are used to assign the corresponding physical and mechanical properties within the numerical model.

The fiber volume fraction is defined as

$$V_f = \frac{N_{fiber}}{N_{total}}, \quad (2)$$

where N_{fiber} - is the number of voxels belonging to the fiber phase, N_{total} - is the total number of voxels in the model.

For the regular fiber arrangement, the fiber volume fraction is determined geometrically through the fiber radius. For stochastic models, the volume fraction is controlled by restricting the displacement of fiber centers and enforcing the non-overlapping condition between fibers.

3.2. Stochastic fiber distribution model

To represent the microstructure of real composite materials, which is characterized by deviations from a regular fiber arrangement, a stochastic fiber distribution model is introduced. The model is generated from a regular square packing configuration by applying random displacements to the fiber centers.

The coordinates of the fiber centers $x_i = (x_i, y_i)$ are defined as

$$x_i = x_i^{(0)} + \Delta x_i, \quad y_i = y_i^{(0)} + \Delta y_i \quad (3)$$

where $(x_i^{(0)}, y_i^{(0)})$ are the coordinates of the nodes of the regular lattice, and $(\Delta x_i, \Delta y_i)$ are random displacements determined according to a Gaussian normal distribution:

$$\Delta x_i, \Delta y_i \sim N(0, \sigma^2), \quad (4)$$

where σ is a parameter controlling the degree of microstructural heterogeneity.

To ensure the physical validity of the generated microstructure, a non-overlapping condition is imposed on the fibers:

$$\|x_i - x_j\| \geq 2r, i \neq j, \quad (5)$$

where r is the fiber radius.

An additional constraint is introduced to limit the maximum displacement of fiber centers, preventing them from leaving their local cells and avoiding excessive distortion of the original structure. The allowable displacement is defined relative to the characteristic cell size and is controlled by a parameter specifying the degree of stochasticity in the fiber distribution. In the present study, the displacement range of the fiber centers was limited to 15% of the characteristic dimension, providing a moderate level of microstructural heterogeneity for the numerical experiments. This approach enables the generation of microstructures with a controlled degree of non-uniformity, ranging from nearly regular arrangements to significantly random configurations. At the same time, the prescribed fiber volume fraction is preserved, and the condition of geometric non-overlap between fibers is maintained. The generated stochastic configurations are subsequently used for numerical simulations aimed at investigating the influence of spatial heterogeneity on the effective mechanical properties of composite materials.

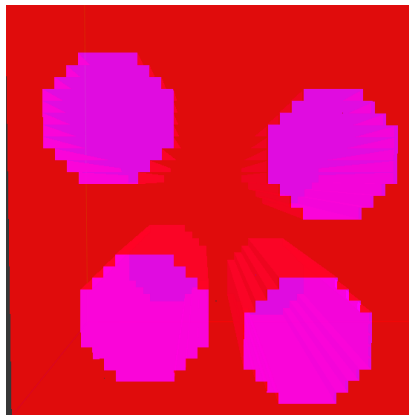


Figure 3: Example of a stochastic composite microstructure generated using Gaussian displacement of fiber centers.

4. Numerical Analysis and Homogenization

To determine the effective mechanical properties of the composite, a numerical analysis of the stress–strain state of the representative volume element (RVE) is performed using the finite element method (FEM).

The mechanical properties of the composite constituents are assigned according to their physical and mechanical characteristics (Table 1). The model consists of two material phases:

1. matrix - isotropic material;
2. fibers - orthotropic material with specified elastic.

Table 1
Mechanical properties of composite constituents

Component	Elastic Properties (GPa)	Poisson's Ratio	Density (kg/m ³)
matrix	E = 3	0.35	1200
glass fiber	E ₃₃ ≈ 76.5,	ν ₁₃ = ν ₂₃ ≈ 0.22,	2650
	E ₁₁ = E ₂₂ ≈ 10.1	ν ₁₂ ≈ 0.30	

The stress–strain analysis is carried out within the framework of linear elasticity:

$$\sigma = C\varepsilon, \quad (6)$$

where C is the material stiffness tensor determined through the homogenization procedure.

Macroscopic strain components are prescribed as boundary conditions to enforce uniform deformation of the RVE:

$$u(x) = \varepsilon \cdot x \quad (7)$$

where u is the displacement vector; ε is the prescribed macroscopic strain tensor.

All six independent strain components are considered: $\varepsilon_{xx}, \varepsilon_{yy}, \varepsilon_{zz}, \varepsilon_{xy}, \varepsilon_{xz}, \varepsilon_{yz}$. To construct a complete loading dataset, a combinational loading scheme consisting of 64 loading cases is employed, where each combination corresponds to a separate numerical simulation.

For each model, stress and strain fields are obtained and subsequently used to determine the effective material properties through homogenization.

The volume-averaged stress and strain tensors are calculated as

$$\langle \varepsilon \rangle = \frac{1}{V} \int_V \varepsilon \, dV, \quad (8)$$

$$\langle \sigma \rangle = \frac{1}{V} \int_V \sigma \, dV, \quad (9)$$

where: ε and σ are the strain and stress tensor components, respectively; $\langle \cdot \rangle$ denotes the volume-averaged value; V is the volume of the representative volume element.

The obtained averaged quantities are used in the homogenization procedure to determine the effective mechanical properties of the composite material.

5. Fiber distribution analysis and microstructure heterogeneity assessment

The input data for the study consist of segmented masks of fiber-reinforced composite cross-sections obtained from micrographs of the material. During data preparation, the reinforcing phase was separated from the matrix and represented as binary images, where each pixel corresponds to one of two phases: fiber or matrix.

To accurately identify individual fibers, a combination of the Distance Transform and the Watershed algorithm is employed. This approach enables the separation of touching or partially overlapping fibers, which is particularly important for composites with a high reinforcement volume fraction. In the first stage, local maxima of the distance function are determined for each fiber region and used as markers for subsequent segmentation. As a result, each fiber is represented as an individual connected component.

For each identified region, its geometric characteristics, including area and centroid coordinates, are determined. In addition, area-based filtering is applied to remove small segmentation artifacts and regions that do not correspond to actual fibers. The coordinates of the centroid of the i -th fiber are calculated as

$$x_i = \frac{1}{A_i} \sum_{k=1}^{A_i} x_k \quad y_i = \frac{1}{A_i} \sum_{k=1}^{A_i} y_k \quad (10)$$

where A_i is the area of the i -th fiber and (x_k, y_k) are the coordinates of the pixels belonging to the corresponding region.

As a result, a set of fiber center coordinates is obtained:

$$P = \{(x_i, y_i)\}_{i=1}^N, \quad (11)$$

where N is the total number of fibers in the analyzed cross-section.

The obtained coordinates are used for further analysis of the spatial arrangement of the reinforcing inclusions. Based on these data, inter-fiber distances are calculated, their distributions are analyzed, and the real microstructure is compared with an idealized square-packing model. The resulting statistical characteristics are subsequently used for the generation of stochastic RVE models and for investigating the influence of microstructural heterogeneity on the effective mechanical properties of composite materials.

To construct the numerical model, it is necessary to quantify the degree of heterogeneity of the real composite microstructure and determine the allowable displacement of fibers relative to a regular arrangement. A square fiber packing model is adopted as the reference structure since it serves as the basis for the regular RVE model.

Using the obtained fiber center coordinates, a regular square lattice with the same number of fibers and the same average center-to-center spacing is generated. For each fiber in the real structure with center coordinates (x_i, y_i) , the nearest node of the reference lattice (x_i^0, y_i^0) is identified. The local displacement is then calculated as the Euclidean distance

$$d_i = \sqrt{(x_i - x_i^0)^2 + (y_i - y_i^0)^2}, \quad (12)$$

where d_i denotes the displacement of the center of the i -th fiber relative to the corresponding reference node.

The resulting set of values characterizes the deviation of the real microstructure from an ideal square packing arrangement.

To analyze the local arrangement of fibers, distances to the four nearest neighbors are additionally determined, corresponding to the number of neighboring fibers in a regular square cell. For each fiber, the average nearest-neighbor distance is calculated as

$$L_i = \frac{1}{4} \sum_{k=1}^4 d_{ik}, \quad (13)$$

where d_{ik} is the distance from the center of the i -th fiber to its k -th nearest neighbor.

The mean inter-fiber spacing is then defined as

$$L_{spacing} = \frac{1}{N} \sum_{i=1}^N L_i, \quad (14)$$

where N is the number of fibers in the analyzed cross-section.

To construct the reference square lattice, an automatic search is performed for the local microstructural region that most closely resembles a regular square packing arrangement. The selection criterion is based on minimizing the variation of inter-fiber distances and minimizing deviations of the angles between neighboring fibers from 90° . Using the identified cluster, the characteristic inter-fiber spacing and the orientation of the reference structure are determined.

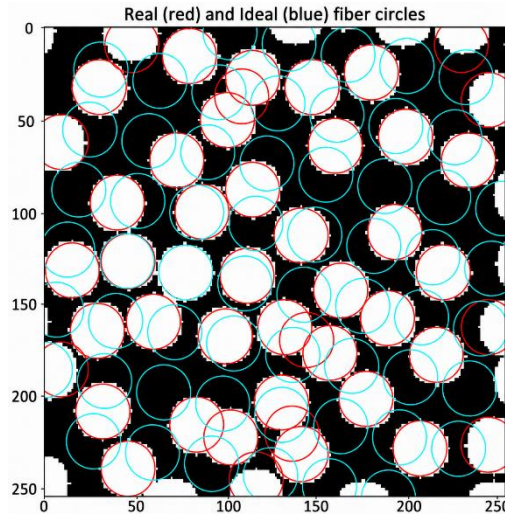


Figure 4: Comparison of the actual fiber arrangement with the regular square packing model.

To evaluate the spatial distribution of fibers, histograms of the average distances to the nearest neighbors were constructed. Unlike hexagonal packing, where each fiber has six nearest neighbors, a square packing arrangement is characterized by four nearest neighbors. Therefore, the primary analysis was performed for $k=4$.

Figure 5 presents the histogram of the average distances to the four nearest neighboring fibers. The histogram indicates that most fibers exhibit average neighbor distances in the range of 30–45 px. The peak of the distribution is located approximately between 38 and 42 px, corresponding to the

most characteristic inter-fiber spacing in the analyzed microstructure. At the same time, the finite width of the distribution indicates deviations of the real microstructure from an ideal square packing arrangement and confirms the existence of local regions with increased and decreased fiber density.

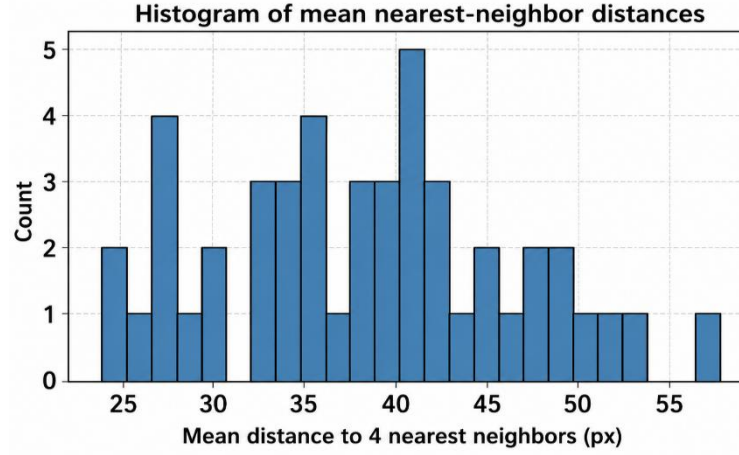


Figure 5: Histogram of the distribution of average distances to the four nearest neighboring fibers.

The obtained results indicate that the real composite microstructure is generally close to a regular square packing arrangement but exhibits local variations in inter-fiber spacing. These deviations were incorporated into the construction of stochastic RVE models for further investigation of the influence of microstructural heterogeneity on the effective mechanical properties of the composite material.

To reproduce the observed heterogeneity in the stochastic models, the fiber centers were displaced relative to the nodes of the regular square lattice according to a Gaussian probability distribution. Based on the obtained statistical characteristics and a series of preliminary numerical experiments, the maximum allowable displacement of fiber centers was set to 15% of the characteristic inter-fiber spacing. This value provides the formation of local regions with increased and decreased fiber density that are representative of the real microstructure, while preserving the prescribed fiber volume fraction and preventing geometric overlap between fibers.

6. Result and Discussion

To investigate the influence of spatial microstructural heterogeneity on the effective mechanical properties of the composite, a series of stochastic models was generated by randomly displacing the fiber centers relative to a regular square lattice. To obtain statistically stable estimates of the effective mechanical properties, 100 independent stochastic realizations were generated. This number of realizations provides a more accurate estimation of the mean mechanical properties, reduces the influence of random deviations in individual realizations, and allows for a more representative characterization of the statistical distribution of the composite properties. For each realization, a homogenization procedure was performed to determine the effective elastic moduli, shear moduli, and Poisson's ratios.

Figures 6–8 present the histograms of the effective properties obtained for the stochastic microstructures. The blue bars correspond to the results of individual realizations with randomly distributed fibers, while the blue curves represent approximations using a normal probability distribution. The orange bars indicate the corresponding values obtained for the regular model with a symmetric fiber arrangement.

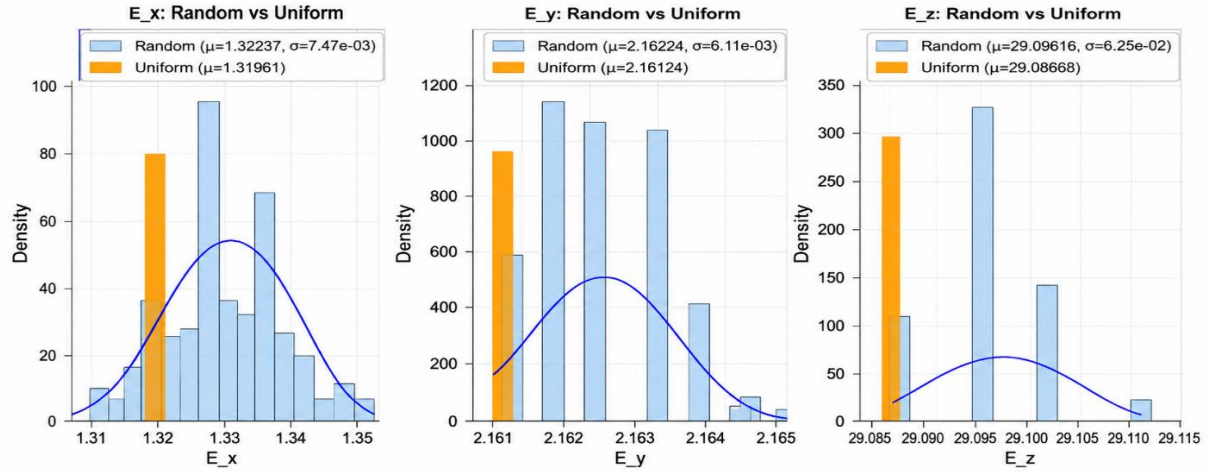


Figure 6: Statistical distributions of the effective elastic moduli for random and uniform fiber distributions.

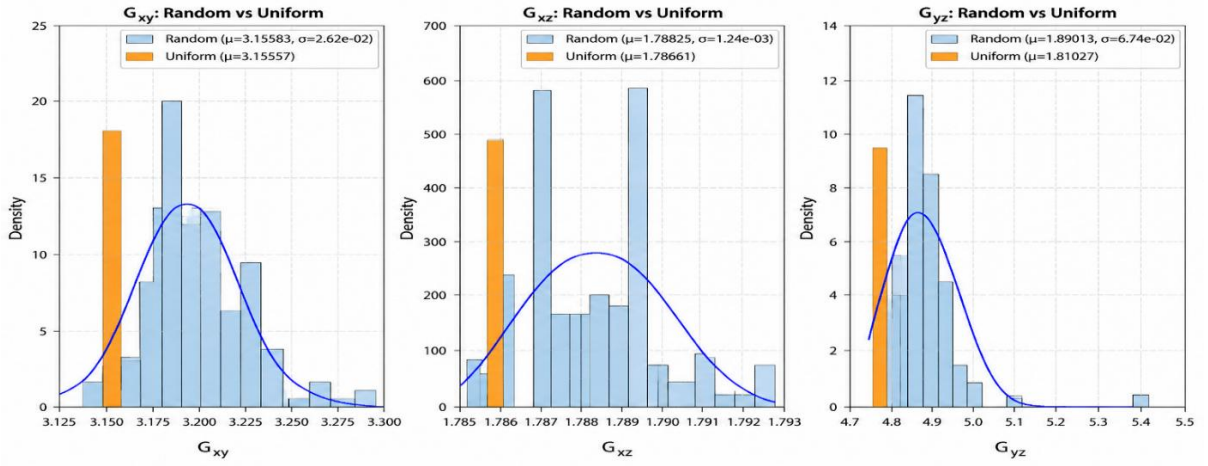


Figure 7: Statistical distributions of the effective shear moduli for random and uniform fiber distributions.

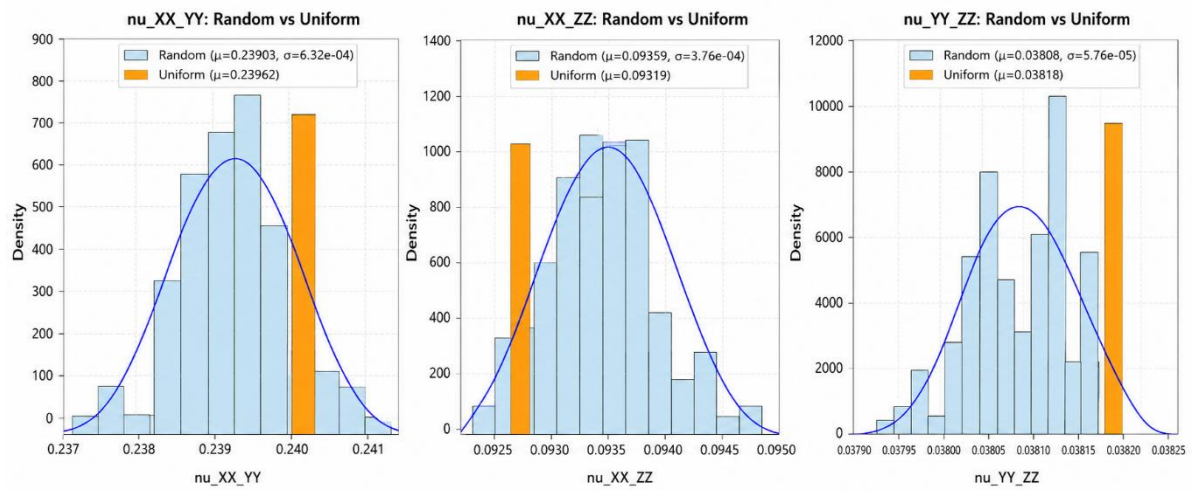


Figure 8: Statistical distributions of the effective Poisson's ratios for random and uniform fiber distributions.

Analysis of the histograms shows that the distributions of most effective mechanical properties are close to normal. Furthermore, the values obtained for the regular model are located near the centers of the corresponding distributions. This indicates that random displacements of fiber centers do not significantly affect the average mechanical properties of the composite. However, they introduce a measurable statistical variation in the predicted effective properties, reflecting the influence of microstructural heterogeneity on the material response.

For a quantitative assessment of the obtained distributions, the main statistical characteristics of the effective elastic properties are presented in Table 3. The table includes the mean value μ , the standard deviation σ , and the coefficient of variation CV, which is defined as

$$CV = \frac{\sigma}{\mu} \cdot 100\%, \quad (15)$$

The coefficient of variation provides a measure of the relative dispersion of the results independently of the absolute magnitude of the considered parameter. Higher values of CV indicate greater sensitivity of the corresponding mechanical property to the random spatial distribution of fibers within the composite matrix.

Table 3
Statistical characteristics of effective elastic properties for stochastic composite microstructures

Property	Regular Mode	Mean Value (μ)	Standard Deviation (σ)	CV, %
E _x , (GPa)	4.320	4.327	0.0075	0.17
E _y , (GPa)	2.461	2.462	0.0008	0.03
E _z , (GPa)	29.087	29.096	0.0063	0.02
G _{xy} , (GPa)	3.156	3.186	0.0262	0.82
G _{xz} , (GPa)	1.787	1.788	0.0012	0.07
G _{yz} , (GPa)	4.840	4.890	0.0674	1.38
ν_{xy}	0.2396	0.2390	0.00063	0.26
ν_{xz}	0.0932	0.0936	0.00038	0.40
ν_{yz}	0.0382	0.0381	0.00006	0.15

To quantitatively assess the influence of stochastic fiber arrangement on the effective mechanical properties of the composite, the homogenization results obtained for the regular and stochastic models were compared. Table 4 presents the effective elastic moduli and shear moduli calculated for both types of microstructures, together with the relative deviation between them:

$$\Delta P = \frac{|P_{ran} - P_{reg}|}{P_{reg}} \cdot 100\%, \quad (16)$$

where P_{reg} and P_{ran} denote the effective property obtained for the regular and stochastic microstructures, respectively.

As shown in Table 4, the mean values of the effective properties obtained for the stochastic models remain close to those of the regular microstructure. The largest deviation is observed for the shear

modulus G_y however, even in this case the difference does not exceed 1.1%. For the elastic moduli E_x , E_y , and E_z , the deviations are below 0.2%, indicating that the average stiffness of the material is largely preserved despite the random displacement of fiber centers.

Table 4

Comparison of effective elastic and shear moduli for regular and stochastic composite models.

Property	$P_{regular}$ (GPa)	P_{random} (GPa)	ΔP (%)
E_x	4.319	4.327	0.19
E_y	2.461	2.462	0.04
E_z	29.09	29.10	0.03
G_{xy}	3.155	3.186	0.98
G_{yz}	4.840	4.890	1.03
G_{xz}	1.787	1.788	0.06

These results suggest that moderate microstructural heterogeneity has only a limited effect on the mean effective mechanical properties of the composite. Nevertheless, as demonstrated by the statistical analysis presented in Table 4, stochastic fiber distributions introduce a measurable variability in the predicted properties, which should be considered when assessing the reliability and uncertainty of composite material performance

Table 5 presents a comparison of the effective Poisson's ratios obtained for the regular and stochastic composite microstructures. Similar to the elastic and shear moduli, the calculated values exhibit only minor differences between the two models. The close agreement between $\nu_{regular}$ and ν_{random} indicates that the random spatial distribution of fibers does not significantly affect the macroscopic deformation behavior of the composite material.

These results confirm that moderate microstructural heterogeneity has a negligible influence on the effective Poisson's ratios, while the overall elastic response of the composite remains governed primarily by the constituent material properties and the fiber volume fraction.

Table 5

Comparison of effective Poisson's ratios for regular and stochastic composite models

Property	$\nu_{regular}$	ν_{random}
ν_{xy}	0.2396	0.2390
ν_{xz}	0.0932	0.0936
ν_{yz}	0.0382	0.0381

Conclusions

This study investigated the influence of non-uniform fiber distribution on the effective elastic properties of a unidirectional fiber-reinforced composite through a comparison of regular and stochastic voxel-based representative volume element (RVE) models. The stochastic fiber distribution was generated by randomly displacing fiber centers relative to a regular square lattice according to a Gaussian probability distribution, with a maximum displacement of 15% of the characteristic cell size.

The obtained results demonstrated that the introduction of spatial heterogeneity has a negligible effect on the mean values of the effective elastic properties of the composite. For the elastic moduli, the maximum deviation between the regular and stochastic models was less than 0.2% for E_x , 0.04% for E_y , and 0.03% for E_z . A similar trend was observed for the shear moduli, where the deviations did not exceed 1.03%.

The highest sensitivity to fiber distribution irregularity was observed for the shear moduli G_{xy} and G_{yz} , for which the relative increases in the effective properties reached 0.98% and 1.03%, respectively. These findings indicate that local variations in inter-fiber spacing have a greater influence on the mechanisms of shear stress transfer within the matrix than on the longitudinal stiffness of the composite along the reinforcement direction.

The analysis of Poisson's ratios revealed an even lower sensitivity to spatial heterogeneity. The differences between the regular and stochastic models remained below 0.5%, indicating the stability of the transverse deformation behavior of the composite at the investigated level of fiber distribution randomness.

At the same time, it was established that stochastic fiber arrangements introduce a statistical variability of the effective mechanical properties that is absent in the regular model. The obtained distributions of elastic moduli, shear moduli, and Poisson's ratios exhibit an approximately normal distribution pattern. This confirms that even when the average effective properties remain nearly unchanged, local microstructural heterogeneity can serve as a source of variability in the mechanical response of the material.

Therefore, for the investigated composite with a fiber volume fraction of 40% and a maximum fiber displacement of 15%, the regular model provides sufficiently accurate predictions of the mean effective mechanical properties. However, stochastic models become necessary when it is important to evaluate the variability of mechanical properties, local stress concentrations, and the statistical reliability of composite materials.

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Declaration on Generative AI

During the preparation of this work, the authors used ChatGPT and Gemini in order to: Text Translation, Sentence Polishing, and Rephrasing. After using these tools/services, the authors reviewed and edited the content as needed and take full responsibility for the publication's content.

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