Indian Journal of Engineering & Materials Sciences
Vol. 29, June 2022, pp. 299-306

# Simplified micromechanics approach to analysis the performance of UD composites

Surendra Singh Godara[a*], Prashanta Kumar Mahato[a], & Kuldeep Kr Saxena[b]

[a]Mechanical Engineering Department, Indian Institute of Technology, Indian School of Mines, Dhanbad, Jharkhand 826 004, India

[b]Mechanical Engineering Department, GLA University, Mathura, Uttar Pradesh 281 406, India

*Received: 25 January, 2022; Accepted: 16 February, 2022*

A simplified micromechanical approach is used for the modelling and analysis of unidirectional (UD) composite performance. In this paper, the influence of volume fraction and constituent properties on the effective longitudinal, transverse, and shear properties of unidirectional composites are investigated. These effective properties are determined using the micromechanical approach, which is based on mathematical modelling using the rule of mixtures. Four different types of unidirectional composites such as T300/BSL914C, IM7/8511-7, T300/PR319, and S2-Glass/epoxy were used for analysis purposes. The method was validated with existing experimental results. The response is dependent on an array of parameters, such as the orientation of fibers, the volume fractions of fibers, array of fibers and the material properties of their constituents. Further, this micromechanical method might be used with other reinforcing fibers for the prediction of properties of UD, hybrid and other composites architectures.

**Keywords:** Composite, Unidirectional composite, Micromechanics, Mathematical modelling, Elastic properties

## 1 Introduction

Composite materials are commonly employed in numerous engineering applications owing to superior mechanical properties. The calculation of the Effective Elastic Properties (EEP) of Unidirectional (UD) composites has been the principal target of many researchers and the scientific community. Extensive research has been performed to calculate the EEP of composites. The determination of mechanical properties can be done experimentally, it can be expensive. The designer should also understand the strength properties at the design stage of the material so that production costs can be reduced in order to achieve the needs of the user. Hence, it is an economical and effective method for first calculating strength properties theoretically, and micromechanics is the best method for the determination of composite properties.

These UD composites have secured a prospective applicability in the fields of automobiles, sporting goods, and aeronautical applications.

There has been consistently expanding demand for UD composites due to their excellent mechanical properties[1]. A new method based on Fourier transform has been presented for the scrutiny of the compressive strength properties of UD composites[2]. Further, thermal properties of UD composites were investigated using micromechanics based approach[3], As processing of these composites is challenging task hence the properties of composites can be determined firstly by using micromechanical method that allows for actual behaviour can be known before processing them experimentally. Transverse elastic properties for UD composites were determined by considering the hexagonal and random arrangement of fibers[4]. Various analytical models were presented to understand the elastoplastic behavior of composites[5]. The production of composites is still challenging task and to overcome this issue several properties of a composite material with stiff imperfect interface conditions were determined using analytic and numerical methods[6].

Micromechanical studies on the rotation of stress tensor in granular materials were carried out to understand the material behaviour[7]. Voigt and Reuss proposed a fundamental method for prediction of various materials using rule of mixtures[8]. Bridging model was incorporated in the prediction with the micromechanics method and was used to examine the strength of UD composites acted upon by complex loadings[9]. The response of plain woven polymer matrix composites was determined using micromechanical based approach[10]. The theoretical model was presented to assess the composite's

---

[*] Corresponding author (E-mail: godarasurendra@gmail.com)

volumetric interaction among the contents of the fiber, matrix, and porosity, and the effective properties of such composites were estimated. For this, Halpin –Tsai shown that composite properties are highly dependent on the shape and packing geometry of the fibers and on the spacing between them. Consequently, the Halpin-Tsai equations have adjustable parameters to accommodate this fact and allow use of experimental or finite element results [11]. Further, spring back phenomenon for UD composites were to study aircraft composite laminate structures[12].

The review study for the analysis of structural properties of polymer composites were carried out[13]. Failure analysis of the composite and short fiber reinforced composites were done by using various micromechanical methods[14, 15]. A simplified micromechanics approach was presented to estimate the EEP of a hybrid piezoelectric composite[16]. The determination of mechanical and thermal properties of UD polymer composites were presented using a micromechanical approach[17].The analysis was carried out to understand the compressive modulus and strength behavior as well as the kink band phenomenon using a micromechanical technique[18]. A new model was proposed for elastic-plastic modeling for porous composites[19]. Micromechanics is conventionally regarded as a subsidiary of solid mechanics that derives the EEP of composite materials from the composition and the properties of its constituents[20]. By using the Micromechanics approach (MOM), the EEP of UD composites are calculated using the rule of mixture and iso-field conditions [21, 22]. Various micromechanical models were reviewed for the analysis of elastic properties in composite laminates[23, 24].

The micromechanical modelling can form the foundation for establishing a quantitative estimation to diagnose the transverse cracks in the steels[25]. A new micromechanical model based on self-consistent formulation was applied to describe the elastic-visco plastic behaviour of steels in a large range of strain rates[26]. The residual stresses in alumina-chromium composites was estimated using a micromechanical approach[27]. Recently effective properties of hybrid smart nanocomposites was evaluated by using micromechanical technique [28].

The main reason of using micromechanical approach is that the results obtained by this method are very near to experimentally obtained results for determination of composite properties. In author's opinion mathematical modeling based micromechanical approach is economical and robust process which can be carried out for the investigation of composite properties before the fabrication of composite materials and their experimental investigation. The flexibility of this method is outstanding, making it suitable for any composite material whether UD, hybrid or nano composites.

Incredible endeavours have been achieved so far to develop reliable methods for analysing the failure strength of composites. In continuation, multiple micromechanical approaches were examined to calculate the EEP of UD composites. In the present paper, the micromechanical method is used for the analysis of UD composites. The purpose of this paper is to predict effective elastic behaviour for UD composites built on micromechanical technique. The four different types of UD composites are considered for study purpose. Specifically, the influences of the orientation of fibers and the effect of their volume fractions, and properties of component segments of the fiber and matrix on the effective elastic properties are investigated.

## 2 Materials and Methods

The commonly used micromechanical techniques are mechanics of material approach, Mori Tanaka Method and self-consistent method. The comparison between these three different micromechanical methods with merits and demerits are mentioned in the Table 1.

A sketch figure of the UD composite with planar array of equi-spaced circular fibers is explained in Fig. 1(a) and its cross-sectional model part is shown in Fig. 1(b). When these types of unidirectional fibers are inserted in a matrix, they form a UD composite, as shown in Fig. 1. The 1, 2, and 3 axes, as shown in Fig. 1(a) represent a longitudinal direction for axis 1 and a transverse direction for axis 2 and 3, respectively.

In this paper, four different types of unidirectional composites such as T300/BSL914C, IM7/8511-7, T300/PR319, and S2-Glass/epoxy were used for analysis purposes. These unidirectional polymer–matrix composite plies are the building blocks of the multidirectional laminates used in the majority of structural applications[33]. They have been used for decades in structural applications in rockets, boats, auto motives, unmanned aerial vehicles, recreational sticks, bicycles, airplanes and civil structures etc. The

Table 1 — Comparison between different micromechanical techniques

| | Micromechanics based mechanics of material (MOM) approach | Mori Tanaka method (MTM) | Self-consistent (SC) method [31, 32] |
|---|---|---|---|
| Merits | a) Micromechanical based MOM modeling can be regarded as the most reliable modeling technique for structure–property correlation in composites. | a) This method is commonly used for modeling different kinds of composite materials. | a) For spherical reinforcements with large volume fractions i.e. >0.5, the effective Young's modulus of composites can be found by self-consistent method. |
| | b) MOM start with modeling of representative volume element. | b) The effect of interface can be estimated using this technique. | b) The SC estimate has always an implicit form and gives satisfactory predictions of the behavior of composites. |
| | c) This technique helps to evaluate the impact of microstructure features on the mechanical properties and hence can be used for optimization of constituent parameters. | c) Eshelby tensor which depends on the shape of the inclusion and the Poisson's ratio of the matrix plays important role in this method. | |
| | d) The MOM modeling is done based on Rule-of-mixtures which was derived based on Voigt and Reuss estimations, hence MOM results are very close to experimentally obtained results. | d) The main purpose of using MTM method is to estimate effective Young's modulus and Poison's ratio of composite. | |
| Demerits | a) The effect of interface in composites is difficult to estimate by this MOM approach. | a) This method does not provide the explicit relations for the effective stiffness tensor of composite using Eshelby tensor [29]. However, the calculation of Eshelby tensor is relatively difficult task. | a) This method overestimates the interaction between inclusions, thereby getting an overvaluation of the effective modulus of the composite when particles are stiffer than the matrix. |
| | b) The size of the RVE is usually an important drawback for this kind of simulations. If a large size of the RVE were needed to represent the composite, it would make impossible to perform the numerical computation. | b) The MTM model doesn't take into account the inclusions distribution and underestimates the interaction between inclusions [30]. | b) The elastic moduli of a material containing voids vanish at a void volume fraction of 50% and these moduli become infinite at a particulate volume fraction of 40% of a material containing rigid particulates. |

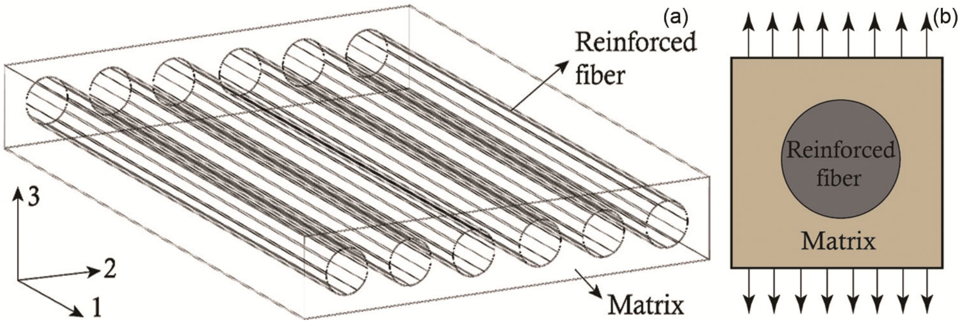

Fig. 1 — (a) Sketch of a UD composite, and (b) a representative outlook of UD composite.

micromechanical method based on mathematical modeling was used to predict the effective properties of these composites.

These micromechanical technique will help for the experimental validation of various types of composites such as SLM-Ti composites. It is presumed that the fiber and matrix are rigidly connected and there is no shear lag between them. The governing equation relating stress and strain for the fiber (with super/subscript f), and matrix (with super/subscript m) can expressed in x, y, and z direction as

$$\{\sigma_f\} = [C_f]\{\varepsilon_f\}, \{\sigma_m\} = [C_m]\{\varepsilon_m\} \quad \dots (1)$$

Where

$$\{\sigma_f\} = \left[\sigma_x^f;\ \sigma_y^f;\ \sigma_z^f;\ \sigma_{yz}^f;\ \sigma_{xz}^f;\ \sigma_{xy}^f\right], \{\varepsilon_f\} = \left[\varepsilon_x^f;\ \varepsilon_y^f;\ \varepsilon_z^f;\ \varepsilon_{yz}^f;\ \varepsilon_{xz}^f;\ \varepsilon_{xy}^f\right]$$

$$\{\sigma_m\} = \left[\sigma_x^m;\ \sigma_y^m;\ \sigma_z^m;\ \sigma_{yz}^m;\ \sigma_{xz}^m;\ \sigma_{xy}^m\right], \{\varepsilon_m\} = \left[\varepsilon_x^m;\ \varepsilon_y^m;\ \varepsilon_z^m;\ \varepsilon_{yz}^m;\ \varepsilon_{xz}^m;\ \varepsilon_{xy}^m\right]$$

$$[C_f] = \begin{bmatrix} C_{11}^f & C_{12}^f & C_{13}^f & 0 & 0 & 0 \\ C_{21}^f & C_{22}^f & C_{23}^f & 0 & 0 & 0 \\ C_{31}^f & C_{32}^f & C_{33}^f & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44}^f & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{55}^f & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66}^f \end{bmatrix}, [C_m] = \begin{bmatrix} C_{11}^m & C_{12}^m & C_{13}^m & 0 & 0 & 0 \\ C_{21}^m & C_{22}^m & C_{23}^m & 0 & 0 & 0 \\ C_{31}^m & C_{32}^m & C_{33}^m & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44}^m & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{55}^m & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66}^m \end{bmatrix}$$

Here, $\sigma_x^f, \sigma_y^f$, and $\sigma_z^f$ denote the normal stresses; normal strains are represented by $\varepsilon_x^f, \varepsilon_y^f$, and $\varepsilon_z^f$; shear stresses and shear strains are denoted by $\sigma_{yz}^f$, $\sigma_{xz}^f$ and $\sigma_{xy}^f$ and $\varepsilon_{yz}^f$, $\varepsilon_{xz}^f$ and $\varepsilon_{xy}^f$, respectively and similar representation for matrix. The $[C_f]$ and $[C_m]$ represent the elastic constant tensor components for fiber and matrix, respectively, and $[V_1]$ & $[V_2]$ denotes the volume fraction matrices for fibers and matrix respectively.

Next, using the above equations incorporating mixture rule along with iso field conditions, the behavior for a composite under stress and strain can be expressed as

$$\{\sigma\} = [C_1]\{\varepsilon^f\} + [C_2]\{\varepsilon^m\} \quad \text{... (2)}$$

$$\{\varepsilon\} = [V_1]\{\varepsilon^f\} + [V_2]\{\varepsilon^m\} \quad \text{... (3)}$$

$$[C_3]\{\varepsilon^f\} - [C_4]\{\varepsilon^m\} = 0 \quad \text{... (4)}$$

Further, the equations (2), (3) and (4) are compared with generalized Hooke's law to obtain

$$[V_3] = [V_1] + [V_2][C_4]^{-1}[C_3], \quad \text{... (5)}$$

$$[V_4] = [V_2] + [V_1][C_3]^{-1}[C_4], \quad \text{... (6)}$$

$$[C] = [C_1][V_3]^{-1} + [C_2][V_4]^{-1} \quad \text{... (7)}$$

Where,

[C] signifies the EEP of composite and [V] matrix represents the volume fraction matrix based on MOM approach.

$$[C_1] = \begin{bmatrix} C_{11}^f & C_{12}^f & C_{13}^f & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}, [C_2] = \begin{bmatrix} \nu_m C_{11}^m & \nu_m C_{12}^m & \nu_m C_{13}^m & 0 & 0 & 0 \\ C_{21}^m & C_{22}^m & C_{23}^m & 0 & 0 & 0 \\ C_{31}^m & C_{32}^m & C_{33}^m & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44}^m & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{55}^m & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66}^m \end{bmatrix},$$

$$[C_3] = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ C_{21}^f & C_{22}^f & C_{23}^f & 0 & 0 & 0 \\ C_{31}^f & C_{32}^f & C_{33}^f & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44}^f & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{55}^f & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66}^f \end{bmatrix}, [C_4] = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ C_{21}^m & C_{22}^m & C_{23}^m & 0 & 0 & 0 \\ C_{31}^m & C_{32}^m & C_{33}^m & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44}^m & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{55}^m & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66}^m \end{bmatrix},$$

$$[V_1] = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & \nu_f & 0 & 0 & 0 & 0 \\ 0 & 0 & \nu_f & 0 & 0 & 0 \\ 0 & 0 & 0 & \nu_f & 0 & 0 \\ 0 & 0 & 0 & 0 & \nu_f & 0 \\ 0 & 0 & 0 & 0 & 0 & \nu_f \end{bmatrix}, [V_2] = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \nu_m & 0 & 0 & 0 & 0 \\ 0 & 0 & \nu_m & 0 & 0 & 0 \\ 0 & 0 & 0 & \nu_m & 0 & 0 \\ 0 & 0 & 0 & 0 & \nu_m & 0 \\ 0 & 0 & 0 & 0 & 0 & \nu_m \end{bmatrix}$$

## 3 Results and Discussion

In this section, Longitudinal, Transverse, and in-plane shear moduli values are calculated by using a micromechanical approach, as presented in section 2. Four different types of UD composites: T300/BSL914C, S2-Glass/epoxy, T300/PR319, and IM7/8511-7 are taken for this purpose. The results obtained by solving equation (7) are plotted with fiber volume fractions. The EEP values of these UD composites are plotted with fiber volume fraction ($v_f$). Furthermore, results obtained using the micromechanical approach, have been validated for these four UD composites[24]. The original constituent elastic properties together with experimentally measured data for these composites are taken from Ref. [34, 35].

Table 2 shows the validation of results obtained for T300/BSL914C UD composite at 0.6 fiber volume fraction ($v_f$). When available experimental results and micromechanical based results are compared, then it is observed that the value of longitudinal elastic properties ($E_{11}$) is almost the same, i.e., the error is 1.14%. However, when Transverse, Shear, and Poisson's ratio are compared, then some error is observed in the results obtained between micromechanical approach and experimentally found results. This is because of alignment of fibers in longitudinal direction, hence negligible error in longitudinal direction and some error in the transverse and in-plane direction.

Table 2 — Comparison of experimentally found and calculated elastic modulus of T300/BSL914C UD Composite (Fiber volume fraction= 0.6)

| Property | Fiber (GPa) | Matrix (GPa) | Experimentally found (GPa) [24] | Micromechanics (GPa) | Error |
|---|---|---|---|---|---|
| $E_{11}$ | 230 | 4.0 | 138 | 139.6 | 1.14% |
| $E_{22}$ | 15 | 4.0 | 11 | 7.8046 | 40.94% |
| $G_{12}$ | 15 | 1.481 | 5.5 | 3.2249 | 70.54% |
| $G_{23}$ | 7 | 1.481 | 3.92 | 2.8106 | 39.47% |
| $\mu$ | 0.2 | 0.35 | 0.28 | 0.26 | 7.69% |

Table 3 shows the validation of results obtained for S2-Glass/epoxy reinforced unidirectional composite at fiber volume fraction ($v_f$) of 0.6. When available experimental results and micromechanical based results are compared, then it is observed that the value of longitudinal elastic modulus ($E_{11}$) is almost the same, i.e. ,the error is 2.76%. However, when Transverse, shear, and Poisson's ratio are compared, then there is more error in the results obtained between experimental and micromechanical results. In the transverse direction, there is abrupt change in material properties considering fiber and matrix zone, then the bonding zone. So, it is very difficult to make a proper model. On the other way if we move through the longitudinal way we get the same material. Further, composites are tailor made materials and hence alignment of fibers can be done as per required properties in the desired direction. Hence, in these UD composites alignment of fibers are in the longitudinal direction to get increased properties in the longitudinal directions, due to this reason negligible error in longitudinal direction and significant error in the transverse and in-plane direction. However, if alignment of fibers are made in the transverse directions then there will be less error in transverse directions. The similar type of trend was observed by the previous researchers [24] when properties were determined using Mori Tanaka approach.

The percentage error is less for the longitudinal properties and more in the transverse direction; this is due to the fact that UD composites show reduced mechanical properties in the transverse directions.

Table 4 and Table 5 shows the validation of results obtained for T300/PR319 and IM7/8511-7 reinforced unidirectional composites respectively at fiber volume fraction (vf) of 0.6.

Table (2-5) illustrate that the results obtained from the micromechanical approach are accurate for the determination of longitudinal elastic moduli and more error in transverse directions as expected. As illustrated in Table (2-5), the error in transverse directions ($E_{22}$, $G_{12,}$ and $G_{23}$) much more pronounced as these composites are tailor made materials hence desired directional properties can be maximized only in one direction either longitudinal or transverse. This provides evidence that this method can be used further for the investigation of UD composite properties in longitudinal as well as transverse directions. However, the results obtained in longitudinal directions are very much close to the experimentally obtained results.

The longitudinal modulus determines behavior of composite upon initiation of force parallel to fiber direction. Fig. 2 depicts the effect of $v_f$ on longitudinal properties($C_{11}$). Fig. 2 illustrates values of $C_{11}$ increases for all the four UD composites with increment in $v_f$ ,and the values of $C_{11}$ are very high compared to other elastic moduli at all values of fiber volume fraction. This occurred because the composite stiffness heightens with a rise in the fiber volume fraction.

The variation of $v_f$ on the transverse properties of composites ($C_{23}$, $C_{22,}$and $C_{12}$) using micromechanical analysis for four different types of composites are graphically shown in Figs (3 – 5). It is evident that transverse properties escalates with an increment in $v_f$. The values of transverse properties obtained illustrated much less values, as displayed in Figs (3 – 5) compared to the longitudinal modulus due to the fiber direction. Also, it is clear that unidirectional composites showed much more values in the fiber direction.

Figures 6 and 7 shows the variation of $v_f$ on the effectives hear modulus ($G_{12}$ & $G_{23}$) of the composite. It can be observed from Figs 6 and 7 that the values of $G_{12}$ and $G_{23}$ heightened with rise in $v_f$, it can be revealed that in-plane modulus values are much less than transverse modulus values.

Table 3 — Comparison of experimentally found and calculated elastic modulus of S2-Glass/epoxy UD Composite (Fiber volume fraction = 0.6)

| Property | Fiber (GPa) | Matrix (GPa) | Experimentally found (GPa) [24] | Micromechanics (GPa) | Error |
|---|---|---|---|---|---|
| $E_{11}$ | 87 | 3.2 | 52.0 | 53.48 | 2.76% |

Table 4 — Comparison of experimentally found and calculated elastic modulus of T300/PR319 UD Composite (Fiber volume fraction = 0.6)

| Property | Fiber | Matrix | Experimentally found [24] | Micromechanics | Error |
|---|---|---|---|---|---|
| $E_{11}$ | 231 | 0.95 | 129.0 | 139.6 | 7.62% |

Table 5 — Comparison of experimentally found and calculated elastic modulus of IM7/8511-7 UD Composite (Fiber volume fraction = 0.6)

| Property | Fiber | Matrix | Experimentally found [24] | Micromechanics | Error |
|---|---|---|---|---|---|
| $E_{11}$ | 276 | 4.08 | 165.0 | 170.0 | 2.94% |

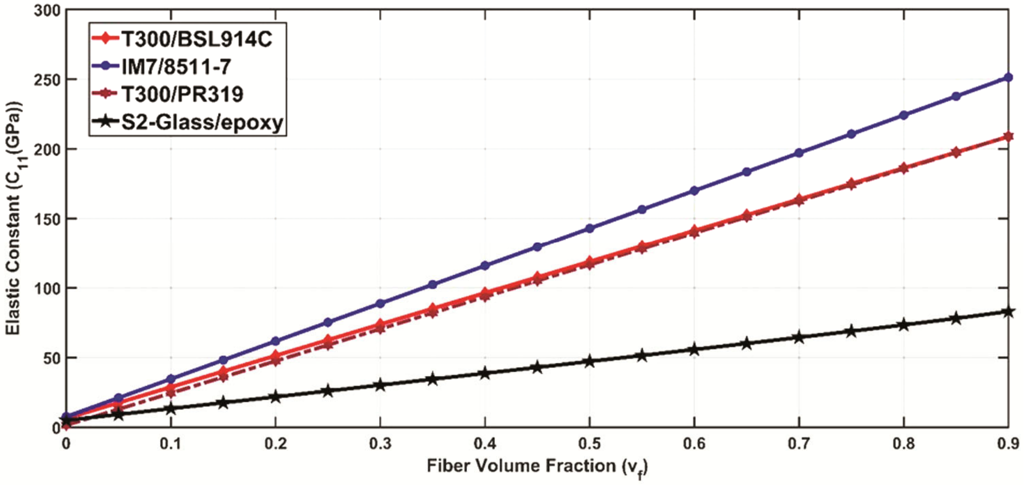

Fig. 2 — EEP $C_{11}$ for various composites.

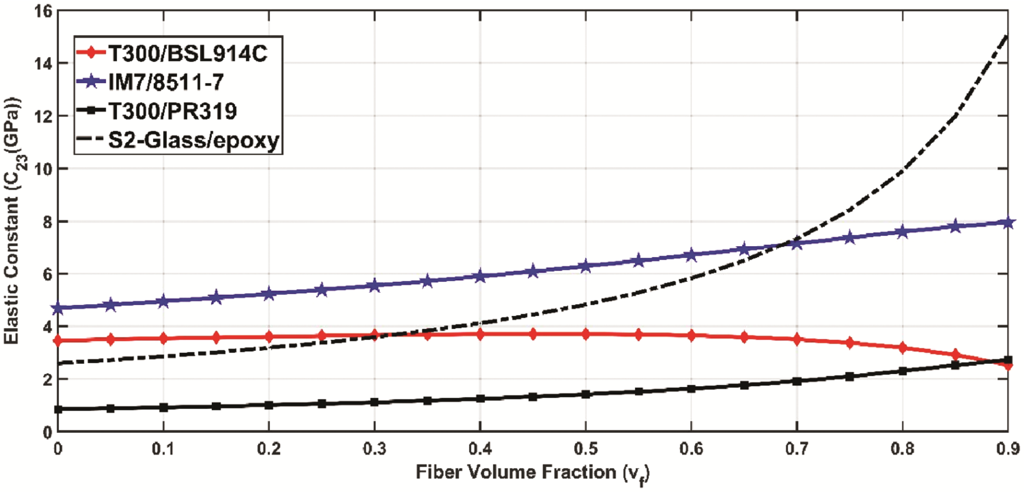

Fig. 3 — EEP $C_{23}$ for various composite.

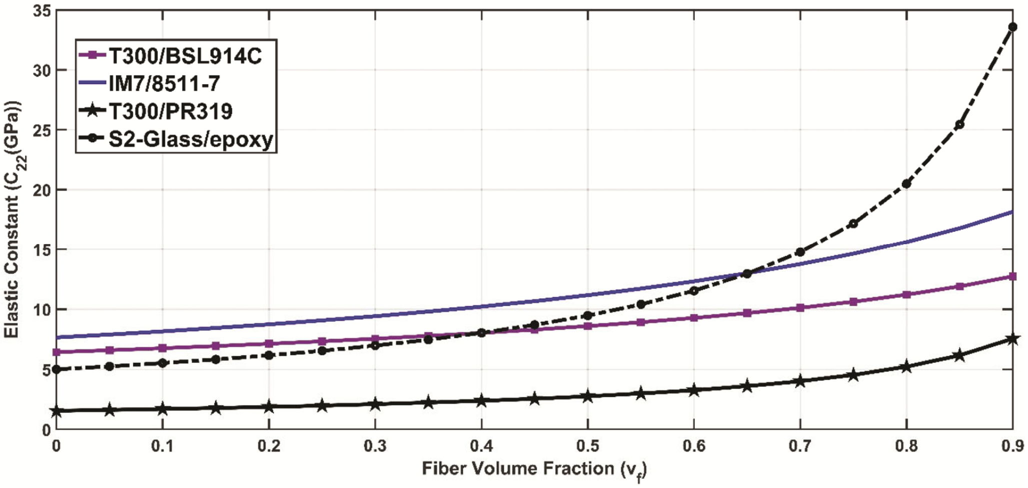

Fig.4 — EEP $C_{22}$ for different composites.

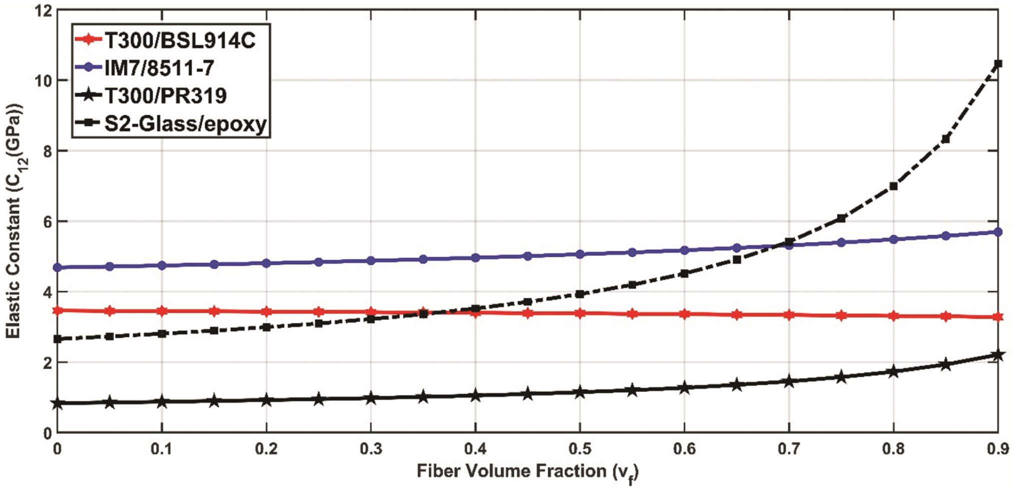

Fig.5 — EEP $C_{12}$ for different composites.

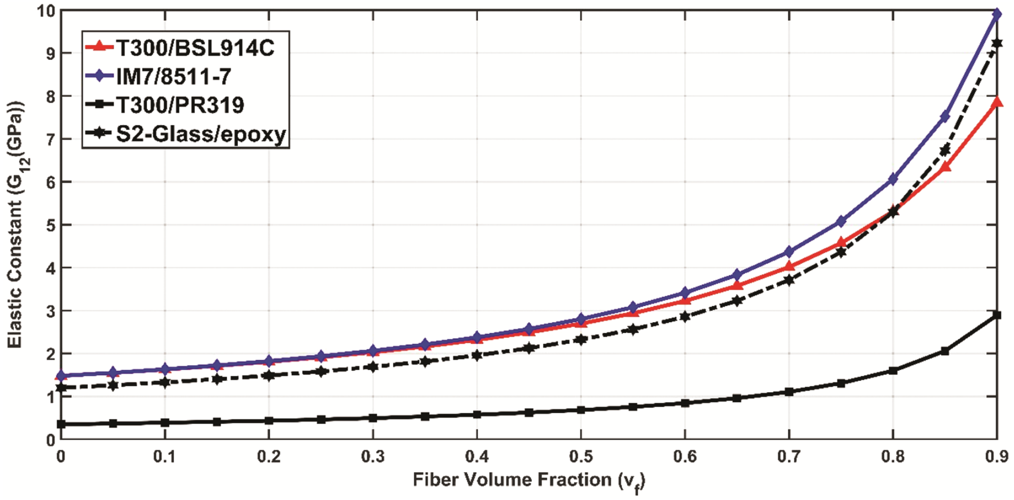

Fig.6 — EEP $G_{12}$ for various composites.

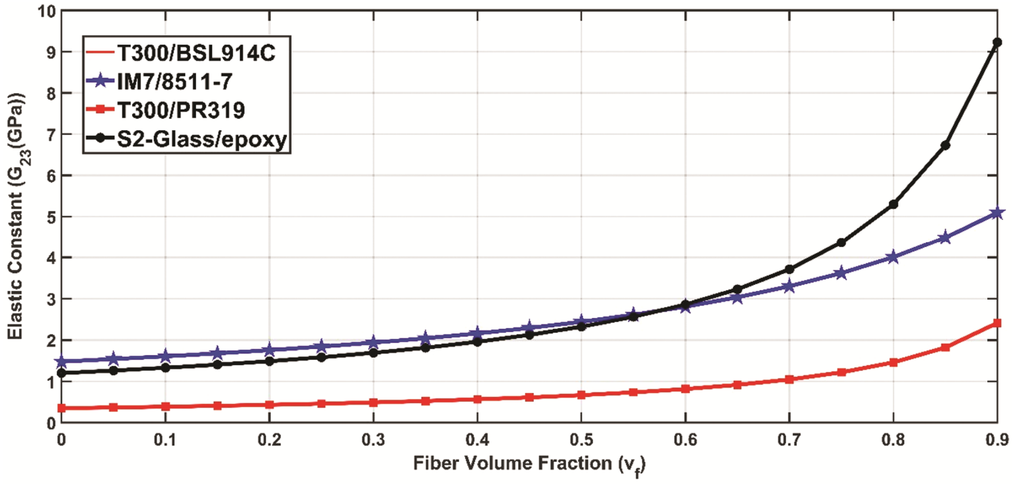

Fig.7 — EEP $G_{23}$ for different composites.

## 4 Conclusion

A simplified micromechanical approach to analyze unidirectional composites with arbitrary volume fraction and the choice of reinforcement for alteration in the properties have been used. Further, the emphasis was given to predict effective properties of UD composites using this micromechanical approach. This might aid the user surveying for effective moduli of a composite with any combination of fiber and matrix with any type of inclusion and give an estimate of failure initiation. In this study, the results were evaluated for the elastic properties of four different types of UD composites using the conventional analytical micromechanical approach. The main observations of this study are-

- The values of longitudinal modulus are enhanced than the transverse modulus values for all the fiber volume fractions.
- The transverse moduli are higher than the in-plane shear modulus values. Because, composites are tailor-made materials, and hence properties in the fiber directions are much higher than in the other two directions.
- As UD composite fibers are aligned in the longitudinal direction in our case; hence, properties are much higher in the longitudinal direction compared to other directions.
- It is envisaged that the micromechanical approach endeavor an efficient and effective path for evaluating EEP and hence UD composite behavior and eventually an exquisite structural design of the composites.

This presents a challenge for researchers in enhancing the transverse and in-plane modulus values for UD composites to prevent their failure. The results obtained through this micromechanical method can be validated through finite element based numerical modeling as a future work. The current model is two-dimensional. The extension to 3D is obviously an important step for the extension of existing work. Three-dimensional models would allow a complete study of the deformation and failure of the laminate under any possible state of loads.

## References

1 Hassanzadeh-Aghdam M K, Ansari R, & Darvizeh A, *Int J Eng Sci*, 130(2018) 215.

2 Wang B, Fang G, Tan X, Liang J, Ge J, & Liu S, *Compos Struct*, 247(2020) 112448.

3 Hassanzadeh-Aghdam M K, Ansari R, & Darvizeh A, *Compos - A: Appl Sci Manuf*, 96(2017) 110.

4 Beicha D, Kanit T, Brunet Y, Imad A, Moumen A E, & Khelfaoui Y, *Mech Mater*, 102(2016)47.

5 WangY, & Huang Z, *Procedia Eng*, 173(2017) 1283.

6 Castro L P, Kapanadze D, & Pesetskaya E, *Math Methods Appl Sci*, 38(2015) 4638.

7 HosseininiaES, *Powder Technol*, 283(2015) 462.

8 Niklas K J, Ann Bot, 70(4) (1992) 347.

9 MingH Z, & Ye-XinZ, Advanced Topics in Science and Technology in China (Springer, Berlin, Heidelberg), 1st Edn, ISBN: 9783 6422 29572, 2011, p.99.

10 ChenYH, &Aliabadi MH, *Int J Eng Sci*, 145(2019) 103163.

11 Affdl JCH , & Kardos J L, *Polym. Eng Sci,* 16(1976)344.

12 Zakaria M, Yulfian A, Rashidi S A , & Mat Sah M A, *J Phys Conf Ser*, 1005(1) (2018) 012003.

13 Rao Y S, Mohan N S, Shetty N, & Shivamurthy B, *Mater Manuf Process*, 34(14) (2019) 1549.

14 HuangZ-M, Failure Analysis edited by Zheng-Ming Huang and Sayed Hemeda, (Intech Open) ISBN: 978-1-83968-254-4, 2018, p.1.

15 Huang H-B, & Huang Z-M, *Compos. - A: Appl Sci Manuf,* 134 (2020) 105889.

16 Ray M C, *Smart Mater Struct,* 19(2010) 035008.

17 Rao SB D, & Biswas S, *J Compos,* 629175 (2014)1.

18 Longwei Z, Zhao L, Liu F, & Zhang J, *Results Phys,* 10 (2018) 841.

19 Hamid G, Wanqing S, Yurtdas I, & Shao J, *Mech Res Commun*, 72(2016) 81.

20 Van der GE, *European, Eur J Mech A Solids*, 75(2019)277.

21 Godara S S, & Mahato P K, *Mater Today: Proc*, 21(2) (2020) 1375.

22 Ray M C, & Batra R C, *J Appl Mech*,76(3) (2009) 0345031.

23 Lucas L V, Savi M A, Pacheco P MCL, & Kalamkarov A L, *Compos B Eng*, 174(2019) 106961.

24 Ling L, & Zhengming H, *Acta Mech Solid a Sin*, 27(2014) 234.

25 Chimani C, Shan G X, Mörwald K, Kolednik O, Böhm H-J, Duschlbauer D, & Drabek T, *Metall Res Technol*, 103 (3) (2006), 131.

26 Berbenni S, Favier V, Berveiller Mand Lemoine X, *Metall Res Technol*, 101 (5) (2004) 381.

27 Geandier G, Weisbecker P, Denis S, Hazotte A, Mocellin A, Lebrun J-L, & Elkaim E, *Metall Res Technol,* 100(12) (2003)1163.

28 Godara S S, & Mahato P K, *Mech Ad Mater Struct,* 29:14 (2022) 2065

29 Jagadeesh G V, & Setti SG, *J Mater Sci,* 23 (2020).

30 Mori T, & Tanaka K, *Acta Metall*, 21(5) (1973) 571.

31 Qu J, & Cherkaoui M, Fundamentals of Micromechanics of Solids (John Wiley & Sons Inc.), 1stEdn, ISBN: 9780 4714 64518, 2006, p.386.

32 Bennoura M, & Aboutajeddine A, *J Reinf Plast Compos*, 35(14) (2016) 1115.

33 Naya F, Lopes C S, González C, & L Lorca, J, *Numerical Modelling of Failure in Advanced Composite Materials,* edited by Pedro Camanho and Stephen Hallettn (*Woodhead Publishing),* ISBN: 978-0081003329, 2015, p. 411.

34 Soden P D, Hinton M J, & Kaddour A S, *Compos Sci Technol*, 58(7) (1998) 1011.

35 Kaddour A S, & Hinton M, *J Compos Mater,* 46(2012) 2295.