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The Elastic Properties of Unidirectional Bamboo Fibre Reinforced Epoxy Composites

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***Abstract**: Natural fibres such as kenaf, jute, bamboo, flax and wood have been the subject of intensive researches in the area of fibre reinforced composite due to their environmental advantages of being renewable, biodegradable and sustainable. Bamboo fibre can be a good choice of natural fibre reinforcement for structural applications due to its excellent strength to weight ratio that is comparable to that of mild steel. In this study, mechanical properties of both continuous and short bamboo fibre reinforced composites are predicted using micromechanical approaches. The finite element method was used where three-dimensional micromechanical representative volume element with square and hexagonal packing geometry was implemented. The results were then compared with the findings from analytical approach that includes the rule of mixture and the Halpin-Tsai model. It was found that for all properties, the FEM and analytical methods give comparable trends of property on volume fraction plots. Furthermore, the longitudinal modulus given by all models are in excellent agreement as it increases linearly with the increase in bamboo fibre volume fraction.*

***Index Terms**: Natural fibres, Bamboo fibre, Representative volume element, Rule of mixture, Halpin-Tsai model.*

I. INTRODUCTION

The demand for composite material has increased over the years due to its many suitable applications and advantages [1, 2]. As our world is going green, natural fibres such as kenaf [3], jute [4], banana [5] and bamboo [6] have been important choices of reinforcement in fibre reinforced composites due to their environmental advantages of being renewable, biodegradable and sustainable. Specifically, bamboo can be converted from its raw form into several forms, including continuous and short fibres such as shown in Fig. 1 [7]. Bamboo fibre is one of the stand-out natural fibres because its strength to weight ratio is as good as that of mild steel [8, 9]. The properties of several natural fibres are given in Table I along with properties of glass fibre, for comparison purpose [10, 11]. These properties enable bamboo based composites to be applied in structural engineering applications equivalent to the applications of kenaf [12, 13] and jute [14].

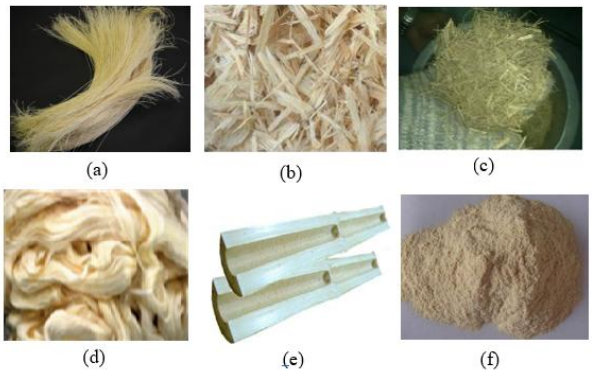

Fig.1: Forms of bamboo being used as composite reinforcement (a) long fibres (b) flake (c) short fibres (d) sliver (e) strips and (f) powder [7]

Table I: Material properties of several natural fibres and glass fibre [10, 11]

No	Fibre	Density (g/cm^3)	Young's Modulus (MPa)	Ultimate strength (MPa)	Elong. at break (%)
1	E-Glass	2.5	79	1200-1500	2.5
2	Bamboo	1.4	30-50	500-700	4.0-7.0
3	Flax	1.45	50-70	500-900	2.0-4.0
4	Jute	1.3-1.5	20-50	300-700	2.0-3.0
5	Sisal	1.5	10-30	300-500	3.0-7.0
6	Hemp	1.48	30-60	350-800	1.5-4.0
7	Coir	1.2	4-6	150-180	30.0
8	Kenaf	1.4-1.5	53	930	1.6

For the purpose of structural engineering applications, the determination of mechanical properties of bamboo fibre reinforced composite (BFRC) is crucial. Even though the determination of BFRC properties through experiments give accurate results, the prediction through theoretical works have been preferred since the method is easier, costs less and repeatable. In past decades, studies on predicting global properties of fibre reinforced composites has been an active area of researches [15-18]. Under theoretical approach, the analytical method that applies micro-mechanic model are quite established while finite element analysis (FEA) of representative volume element (RVE) of fibre reinforced composite has also been popularly used. Sun and Vaidya [19] applied appropriate constraints that were based on symmetry and periodicity conditions in their FEA of RVE of unidirectional fibre composites under various loadings.

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The findings were able to be validated based on past experiments. In a study by Li [20] to find properties of fibre reinforced composite,

the approach adopted allowed the unit cells to accommodate irregular cross-sections and imperfections such as micro-cracks and local debonding in the system. At the same time, the loads can come from the stress and strain simultaneously. Applying circular and rectangular cross-sections of fibres in square and hexagonal RVE, Devireddy and Biswas [21] conducted FEA on variety of the RVEs to give elastic and thermal properties of unidirectional fibre-reinforced composites while assuming the unidirectional composites showed transversely isotropic properties. Babu et al. [22] moved further in developing RVE for short fibre composites where mathematical theory of homogenization with periodic boundary conditions were used.

The above reviews are for fibre reinforced composite in general, while the theoretical works on predicting the global properties of natural fibre reinforced composite have been scarce. Experimentally, tensile test was conducted by Ogihara et al. [23] on bamboo fibre composite and it was found that tensile strength increases with increasing weight fibre fraction for wt% of less than 30%. Furthermore, Ochi [24] managed to increase volume fraction of bamboo fibres in a starch-based emulsion-type biodegradable resin up to 70% where after conducting tensile test, the composites gave high tensile strength of 265 MPa and tensile modulus of 12.4 GPa. Sapuan et al. [25, 26] conducted several experimental procedures to determine mechanical properties of several chemically treated and non-treated natural fibre composites including sugar palm and kenaf. Facca et al. [27] predicted elastic properties of composites with several natural fibres using several micromechanical models and compared the results by conducting experiments. It was found that the Tsai-Hill model gave the most accurate results when compared to the experimental results. Virk et al. [28] developed a new micromechanical model to predict modulus and strength of natural fibre reinforced composites considering the fibre area correction factor and improving each parameter in the rule of mixture. The results showed improvement in property values when compared to experiment values. Da Silva et al. [29] conducted analytical and experimental studies in determining Young's moduli of structural bio-composites based on sisal and banana fibres. The experimental procedures applied a design of experiment approach.

In this study, mechanical properties of continuous bamboo fibres reinforced in epoxy matrix are predicted using micromechanical approaches. Two methods, namely the finite element method (FEM) and analytical methods, were employed. In the FEM, elastic properties were predicted using three-dimensional micromechanical RVEs with square and hexagonal packing geometry while in the later method, the rule of mixture (ROM) and the Halpin-Tsai model were used. The predicted properties from both methods were then compared.

II. Methodology

In this section, the material properties of the composite constituents and the methodology of the analysis are given. Bamboo fibres are considered to be of 2 types: unidirectional long fibres and short aligned fibres such as pictured in Fig.2.

The elastic properties of the BFRC to be determined are the longitudinal modulus, Poisson's ratio, transverse modulus and the shear modulus.

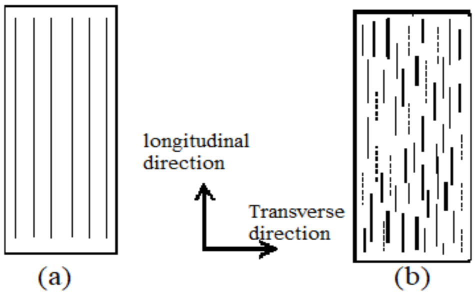

Fig.2: The unidirectional (a)long and (b)short bamboo fibres

A. *Materials*

Both bamboo fibre and epoxy matrix are considered isotropic while the continuous BFRC is assumed to be transversely isotropic. The properties of bamboo fibres and epoxy matrix [30] used in this study are shown in Table II.

Table II: Material properties of the two constituents [30]

Property	Bamboo	Epoxy
Young's modulus, E (GPa)	35.45	3.42
Poisson's ratio, v	0.3	0.39

The volume fraction of bamboo fibre may vary from 0 to 70%. The BFRC under study here can be viewed in Fig.3. The x-y-z coordinate is the global coordinate system that coincides with material coordinate system, 1-2-3.

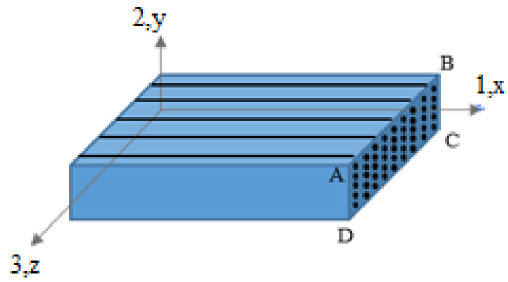

Fig.3: The x-y-z coordinate in the global coordinate system for bamboo reinforced composite

The periodic arrangements of bamboo fibres, viewed from side ABCD, can be assumed to be in square or hexagonal fashions such as shown in Fig. 4 (a) and (b**),** respectively.

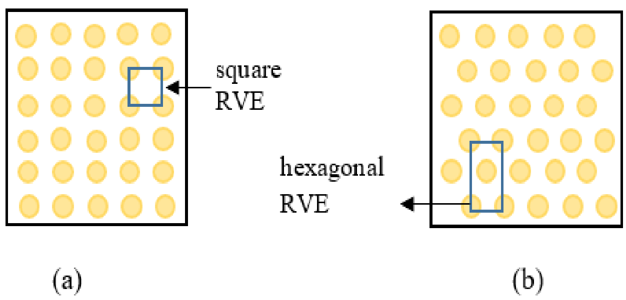

Fig.4: The (a) square and (b) hexagonal arrangements

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B. The Finite Element Method

In this method, RVEs representing periodic fibre packing sequence are developed. Here, long and short aligned fibres and matrix are arranged in either square array packing or hexagonal array packing such as shown in Fig.4. The RVEs are given boundary conditions based on symmetry and periodicity conditions such that they simulated the actual deformation within the composite [19]. The displacements determined through linear analysis conducted on the RVEs will allow the calculation for the material properties of the composite using the standard constitutive equations.

C. The RVE Modelling

The fibres are assumed to be uniformly distributed and are perfectly aligned within the matrix while the interfaces between the fibre and matrix are assumed to be perfectly bonded. The radius of fibres taken corresponds to the fibre volume fraction which ranges from 0.1 to 0.7 for continuous fibre and 0.1 to 0.4 for short aligned fibre. The two types of RVE in 2D correspond to the two packing arrangement are as shown in Figure 4. Figure 5 shows 3 RVEs developed in ANSYS correspond to square packing arrangement for long fibre composite, hexagonal packing arrangement for long fibre composite and square packing arrangement for short aligned fibre composite. Having the geometric modelling, the RVEs are meshed and further given the boundary conditions and loadings. The ANSYS workbench automatically generates the meshing for these RVE models, applying rectangular and triangular solid element meshing. Element sensitivity analysis has been conducted to determine the optimum element size.

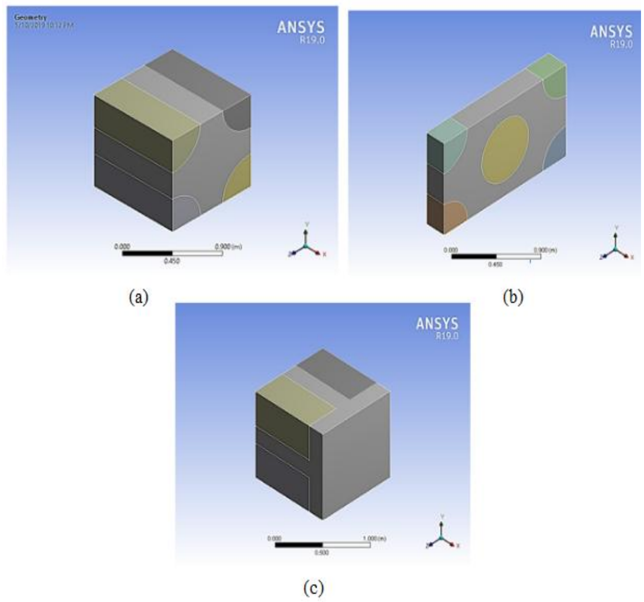

Fig.5: The (a) square RVE for long fibre (b) hexagonal RVE for long fibre and (c) hexagonal RVE for aligned short fibre modelling in ANSYS

D. The stress-strain relationship

The transversely isotropic BFRC is assumed. Thus the stress-strain formulation is [31]

$$\begin{Bmatrix}\sigma_1\\ \sigma_2\\ \sigma_3\\ \sigma_4\\ \sigma_5\\ \sigma_5\end{Bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0\\ C_{12} & C_{22} & C_{23} & 0 & 0 & 0\\ C_{13} & C_{23} & C_{33} & 0 & 0 & 0\\ 0 & 0 & 0 & \frac{1}{2}(C_{22}-C_{23}) & 0 & 0\\ 0 & 0 & 0 & D_{12} & C_{55} & 0\\ 0 & 0 & 0 & D_{13} & 0 & C_{66}\end{bmatrix} \quad (1)$$

With this assumption and by conducting FEA to determine the value of C_{ij}, the properties of the composites can be calculated based on the following equations [31].

$$E_1 = C_{11} - \frac{2C_{12}^2}{C_{22}-C_{23}} \quad (2)$$

$$E_2 = -\frac{[C_{11}(C_{22}+C_{23})-2C_{12}^2](C_{22}+C_{23})}{(C_{11}C_{22}-C_{12}^2)} \quad (3)$$

$$v_{12} = \frac{C_{12}}{C_{22}+C_{23}} \quad (4)$$

$$G_{23} = \frac{1}{2}(C_{22}-C_{23}) \quad (5)$$

E. The Analytical Method

The analytical methods applied here are the ROM and the Halpin-Tsai model and for short aligned fibre, the Manera model is also considered. The ROM is the Voight model or iso-strain model that assumes both matrix and fibre experience the same strain in the 1-direction. This results in the following well-known equations for Young's modulus in longitudinal direction.

$$E_1 = E_f V_f + E_m V_m \quad (6)$$

where subscript E_f and E_m refer to fibre and matrix, respectively.

Similarly, Poisson's ratio is

$$v_{12} = v_f V_f + v_m V_m \quad (7)$$

For properties in transverse direction,

$$E_2 = \frac{E_f E_m}{E_f V_m + E_m V_f} \quad (8)$$

$$v_{13} = \frac{v_{12}}{E_1} E_2 \quad (9)$$

For shear properties,

$$G_{12} = \frac{G_f G_m}{G_f V_m + G_m V_f} \quad (10)$$

The Halpin-Tsai model is semi-empirical model that is based on analytical formulation. It can be considered as the ROM equations supplemented by correction factors obtained through experiments. The effective properties of composite, P_c is stated in terms of matrix properties, P_m such as

$$P_c = P_m\left(\frac{1+\xi_\eta V_f}{1-\eta V_f}\right) \quad (11)$$

where ξ is a shape fitting parameter that considers the types of load and the geometry of the inclusions and η is a function that considers the case when $V_f = 0$ and $V_f = 1$.

III. RESULTS AND DISCUSSION

In the FEA, the element sensitivity analysis is firstly conducted to determine the suitable element sizes for both square and hexagonal RVEs. As indicated in Fig. 6, the study shows that both RVEs provide convergence to the E_1 value and the square RVE converged earlier at element sizing factor of 0.1, which corresponds to 618 elements compared to the hexagonal RVE that converged at element sizing factor of 0.05, which corresponds to 3942 elements.

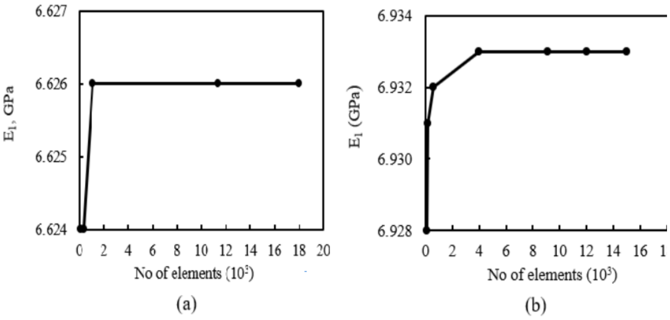

Fig.6: The element sensitivity analysis for (a) square RVE and (b) hexagonal RVE

Fig.7 shows that the longitudinal Young's modulus, E_1 increases linearly with the increase of volume fraction of fibre, a trend shared by past researchers [32] and here, the results produced by FEM model and analytical models are in excellent agreement. The linear increase of E_1 with the increase of volume fraction of fibre shows that the longitudinal stiffness improves linearly as the V_f is increased. In composite system, less stiff polymer matrix is replaced by stiffer fibre material. Thus, it is obvious that as fibre percentage increases, the composite becomes stiffer and offers higher longitudinal modulus. Sudheer et al. [33] also reported that the effective longitudinal modulus values that obtaining from FEM analysis, rule of mixture, Halpin-Tsai, Nielsen and Chamis methods are in good agreement for the glass fibre epoxy composites. They indicated that the Halpin-Tsai and Nielsen equation for longitudinal Young's modulus share the same formulation as that of rule of mixture. The elastic properties of coir fibre reinforced epoxy composites with different fibre parameters using a micromechanical approach was also studied by Biswas [34]. They mentioned that rule of mixture and FEA models are in perfect agreement, while Halpin-Tsai and Lewis-Neilsen models are slightly lower between the finite element and analytical methods. It can be suggested that the longitudinal modulus of bio-composites is significantly affected by a number of parameters including volume fraction of the fibre, geometry and RVE.

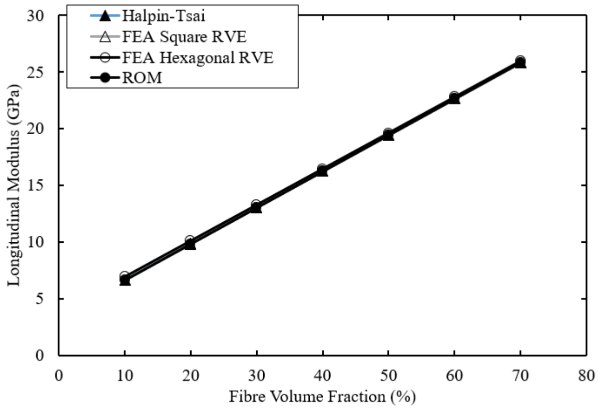

Fig.7: Longitudinal modulus (GPa) of the unidirectional bamboo-epoxy composite varying with fibre volume fraction.

The transverse modulus is the stiffness of the composite when the load is applied in the direction perpendicular to the fibre direction. It can be seen in Fig.8 that the transverse modulus increase as bamboo fibre volume fraction is increased but not in a linear fashion as does the longitudinal modulus. While the changing trend is shared by all models and similar to past studies [21], the FEA square RVE model gives the highest values of E_2, followed by the Halpin-Tsai model and the FEA hexagonal RVE model, while the ROM model give the lowest values. It can also be seen that the plot for the FEA hexagonal RVE model closely agrees with the plot for the Halpin-Tsai model. The results corresponding to the FEA square RVE are slightly higher than those of the Halpin-Tsai, ROM and hexagonal RVE models. Similar finding was reported by Krishna et al. [35] where the finite element results for small unit cell were in close agreement with the results corresponded to analytical methods.

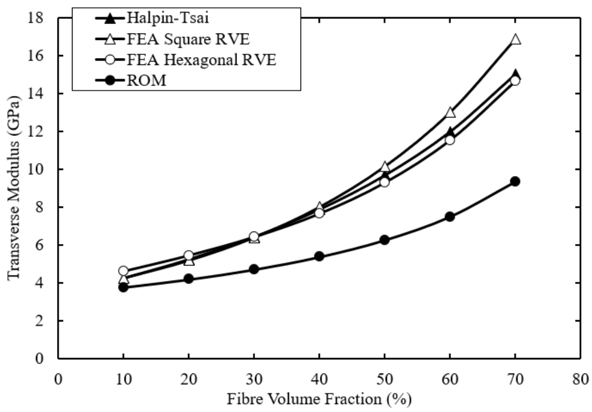

Fig.8: Transverse modulus (GPa) of the unidirectional bamboo-epoxy composite varying with fibre volume fraction.

In Fig.9 the in-plane Poisson's ratio, v_{12} can be seen to decrease almost linearly with the increase of V_f. The results given by all models are fairly similar, except for the results of to the Halpin-Tsai model, which is above the values of other models. This shows that as the volume fraction is increased, the increase in longitudinal stiffness will at the same time increase the resistance of the composite to give lateral displacement and as such the longitudinal Poisson's ratio is decreased. Buddi et al.[36]

[36] showed that the same plot was obtained for another longitudinal Poisson's ratio, v_{13} while the plot for transverse Poisson's ratio showed a sharp decrease in the Poisson's ratio as the V_f was increased. Subrahmanyam et al. [37] found that the Poisson's ratio value decreases with increase in fibre volume fraction as expected. However, as far as comparison of the methods, finite element results are in closer agreement with the rule of mixture and periodic microstructure than the Halpin-Tsai methods. An estimation between analytical and numerical results is also reported by Pal and Haseebuddin [37] are in close agreement, however the data revealed that the rules of mixtures are slightly higher than the finite-element results.

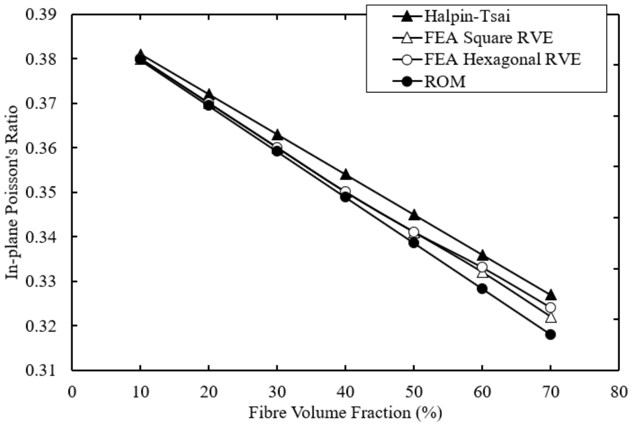

Fig.9: In-plane Poisson's ratio of the unidirectional bamboo-epoxy composite varying with fibre volume fraction.

Fig.10 shows the effect of volume fraction of fibres on the shear modulus of bamboo reinforced composite. The shear modulus is increased as the volume fraction is increased due to increase in the material resistance. It has been shown that the rule of mixture and Halpin-Tsai are overestimated from FEM method. In the range between 30 to 70% of fibre volume fraction, the in-plane shear modulus value is almost doubled.

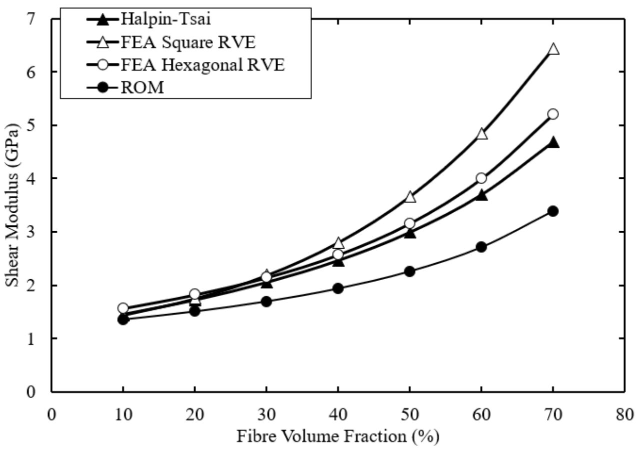

Fig.10: In-plane shear modulus (GPa) of the unidirectional bamboo-epoxy composite varying with fibre volume fraction.

As can be observed in Fig.10, the fibre percentage increases the shear modulus, and also increases in a quadratic manner. This suggests that the bamboo fibres offer a better interlocking between matrices under shear loading condition, while obtaining higher fibre volume fractions. The FEA square array values are 122% higher compared to the rule of mixture findings at 60% fibre volume. The large difference in the Young's moduli values between bamboo fibre and epoxy-resin matrix (Table 2) could be resultant for such considerable variation in the values of in-plane shear modulus for FEM and analytical methods. Closely similar results are also reported by de Macedo [38].

Fig.11 shows the short bamboo fibre composite modelled using the Halpin-Tsai, ROM and RVE model. The Manera model was also included in this study.

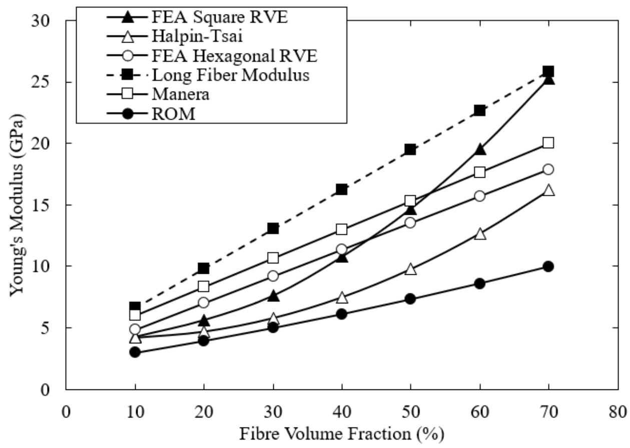

Fig.11: Young's Modulus (GPa) of the short bamboo fibre epoxy composite varying with fibre volume fraction.

As the volume fraction increases, the FEA square array and Manera's equations tend to give higher values of elastic modulus. Reddy and Narayana [39] reported that as the volume fraction increases, the Manera model offered a higher value of longitudinal modulus over the range of volume fraction for the short fibre composites. It is interesting to note that the long bamboo fibre composite gives higher longitudinal Young's modulus compared to short fibre composites. A comparison is made between the longitudinal modulus of long and short fibres. The effect of fibre loading, experimentally studied by Gupta et al. [40], was shown to have significant influence on mechanical behaviour of roving bamboo fibre epoxy composite. They mentioned that the tensile modulus increased by the increase of fibre loading up 20%wt, and with increasing fibre loading up to 30%wt, it decreases sharply. This decrease is attributed to the inability of the fibre to support load bearing transferred from the polymer matrix. The properties of bio-composites are greatly influenced by fibre length and orientation, and interaction of hydrophilic bamboo fibre with hydrophobic epoxy resin. These factors may also contribute in poor interfacial bonding between fibre and matrix material, thereby generating a partially weak structure. The idealizations presented by mathematical model are influenced by many factors including [i] the perfect bonding interface between fibre and matrix,

[ii] no fibre waviness [iii] all fibres are in perfect alignment and parallel to the periodicity and [iv] fibres are perfectly distributed inside the matrix resulting in a larger difference between analytical, FEA model and experimental work [38].

In addition, the interface properties between fibre and matrix as well as the deformities in the composites are not considered for the most natural fibre composite's FEA models [41]. The previous models depend on the presumptions that the cross-section of the natural fibre is either round-hollow (cylindrical) or curved (elliptical). Nevertheless, the actual cross section of every natural fibre differs that depending on various lengths and processing methods. These limitations become restriction to achieve the desired outcomes as predicted by FEA model.

IV. CONCLUSIONS

The elastic properties of bamboo fibre reinforced composites have been determined using FEM and analytical methods. The longitudinal modulus was found to increase linearly with the increase in volume fraction where the results produced by the RVE models and analytical models are in excellent agreement. In the case of transverse and shear modulus, the results produced by the Halpin-Tsai model are seen to be the closest to those produced by the FEA hexagonal RVE model. Furthermore, the aligned short fibre composite gives lower value of longitudinal modulus compared to the long fibre reinforced composite.

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