The International Journal Of Engineering And Science (IJES)
|| Volume || 3 || Issue || 3 || Pages || 01-08|| 2014 ||
ISSN (e): 2319 – 1813 ISSN (p): 2319 – 1805

Modeling and Simulation of Three Dimensionally Braided Composite and Mechanical Properties Analysis Using Finite Element Method (FEM)

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ABSTRACT

This research work was done by modeling and simulating a four step three dimensionally braided composite micromechanical model using Finite Element Analysis software ANYSYS. Three-dimensionally (3D) braided composites are strong contenders for the structural applications in situation like aerospace, aircraft, building and automobiles industries due to their good mechanical properties, structural layout and strength coupled with their thickness stiffness properties. The mechanical properties of the 3D-braided micromechanical composite model was analyzed, based on the result some relevant conclusion were made. With the assumption that the fiber bundle is transversely isotropic and the matrix is isotropic, the macroscopic elastic constants of 3D-braided composites were simulated, and the elastic constants versus the braiding angles and fiber volume fraction were analyzed. The presence of reinforcement along the thickness direction in three-dimensionally braided composites, increases the through thickness stiffness and strength properties.

Based on this research, it was also discovered that FEM technique has the ability to model and study the response of complex shapes subjected to complex load applied at any boundary of the design model.

Keywords *- Mechanical properties, Three-dimension, Elastic constant, Poisson's ratio, Braided composites*

Date of Submission: 19 February 2014 Date of Acceptance: 5 March-2014

I. INTRODUCTION

A model intended for a simulation study is a mathematical model developed with the help of simulation software. Mathematical model classifications include deterministic (input and output variables are fixed values) or stochastic (at least one of the input or output variables is probabilistic); static (time is not taken into account) or dynamic (time-varying interactions among variables are taken into account). Simulation is used before an existing system is altered or a new system built, to reduce the chances of failure to meet specifications, to eliminate unforeseen bottlenecks, to prevent under or over-utilization of resources, and to optimize system performance. The operation of the model can be studied, and hence, properties concerning the behavior of the actual system or its subsystem can be inferred. The use of modeling and simulation (M&S) within engineering is well recognized. Simulation technology belongs to the tool set of engineers of all application domains and has been included in the body of knowledge of engineering management. M&S has already helped to reduce costs, increase the quality of products and systems, and document and archive lessons learned. In this research work, the four step three dimensionally braided composite model was simulated and mechanical properties analysis were done based on some assumption that were made in the modelling.The steps involved in developing a simulation model, designing a simulation experiment, and performing simulation analysis are almost the same as that of designing and performing real experiment.

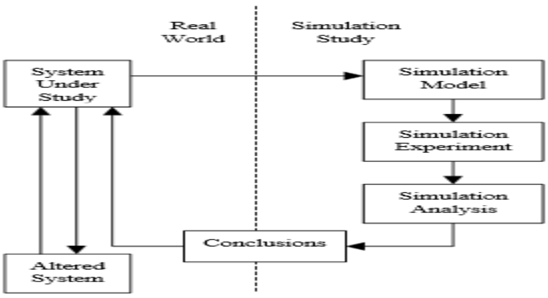

Fig. 01 Simulation study schematic

II. BRAIDING

The dimensions of the braided structures are used as criteria for categorizing braiding. A braided structure having two braided yarn systems with or without a third laid-in yarn is considered as two-dimensional braided structure involving three or more systems of braided yarns to form an integrally braided structure is three dimensional braided processes.

THREE DIMENSIONAL BRAIDING PROCESS

The recently developed three-dimensional braiding techniques have greatly improved the design of performs for advanced composites. Different three different dimensional processes have be built, such as horn-gear braiding process, two step braiding process, four step braiding process, multi-step process.

FOUR-STEP BRAIDING PROCESS

The four step braiding process involves four distinct Cartesian motions of groups of yarns termed rows and columns. For a given step, alternate rows (or columns) are shifted a prescribed distance relative to each other. The next step involves the alternate shifting of the columns (or rows) a prescribed distance. The third and fourth steps involve simply the reverse shifting sequence of the first and second steps, respectively. A complete set of four steps is called a machine cycle as shown in Fig.01. It should be noted that after one machine cycle the rows and columns have returned to their original positions. The braid pattern shown is of the 1×1 variety, so termed because the relation between the shifting distance of the rows and columns is one to one. Other braid patterns (i.e., 1×3, 1×5, vect.) are possible but they requires different machine bed configurations and a specialized machine. Row and column braiding yarn carries of the type depicted in Fig.01 may be used to fabricate performs of rectangular cross sections such as T-beam, I-beam, and box beam.

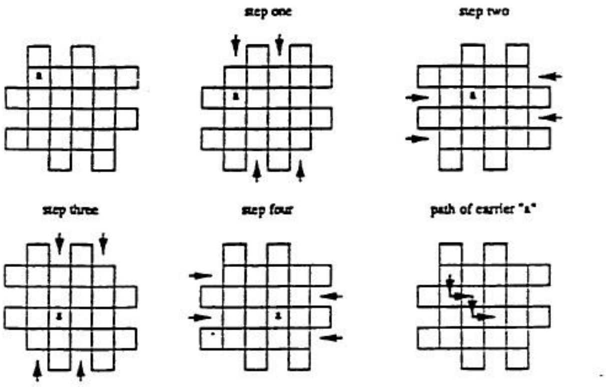

Fig. 02 The four-step braiding process

III. MODELING AND STIFFNESS ANALYSIS

The analysis of stiffness and modeling were discussed below.

BASIC ASSUMPTION

The fiber bundle passes along six surface unit cell body in diagonal direction, and the geometric fiber bundles is simply regarded as line. Four step braided composites for three-dimensional cell body geometry assumption will be analyzed in this work. This model does not completely reflect the fiber bundle structure and the interleaving mode, which in the actual three-dimensional braided composite material structure can completely be reflected. The cell body, fiber bundles and the gap are all in the same level of scale in terms of characteristic. So in terms of geometric concepts or the mechanics meaning general fiber bundles is simplified as a line is not suitable.

The combination of previous work as well as my own understanding in the establishment of braided composite material model as brought about the following assumptions:

[1] Fiber bundle has a circular cross section, and cross section shapes along the fiber axis direction remains the same. So in this paper, the cylinder shaped fiber bundle is transversely isotropic.
[2] All have the same geometric properties of fiber bundle.
[3] Substrate is a cube model, and isotropic.
[4] The fibers and the matrix is bonded, no relative displacement.
[5] As a result of the braiding process retraction movement of the tension, the preforms internal fibre beam bending was caused.

MODEL SELECTION

This research takes a cylinder instead of fiber bundles; a cuboids representing matrix material. Due to boundary and corner cell bodies in the total volume of the percentage, this paper focuses on the analysis of body of single cell and the establishment of finite element model, in order to simulate three-dimensional braided composite performance. Single cell is divided into two forms which are denoted by type A and type B (as shown in fig.03, fig.04). There are three kinds of single cell in the material arrangement which is displayed in fig.05. Here is the internal unit cell geometry parameter of the cell as shown in fig.06.

Therefore,

$$\gamma = \arctan (h_x/hz) \quad \ldots\ldots \quad (1.1)$$

$$V = 2\pi r^2 / h_x^2 \cos \gamma \quad \ldots\ldots \quad (1.2)$$

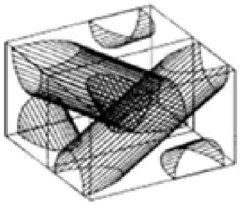

Fig03 Type A

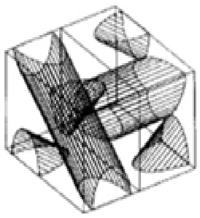

Fig04 Type B

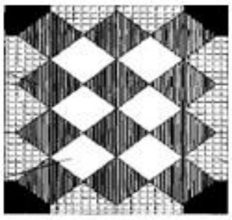

Fig05 Cell arrangement

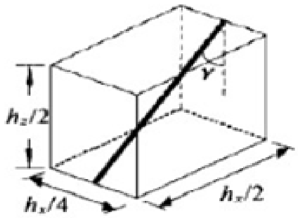

Fig06 Unite Cell Geometry

IV. MODELING AND STIFFNESS ANALYSIS

Putative braided yarn after curing was put into the composite material rod, whose cross section is circular, and cross sectional area is the same as the composite material with a fixed value. As a result of this, it resulted in a transversely isotropic with a unidirectional composite material bar with a high rigidity of elastic constants.

$$E_1 = E_{f1}V_{f1} + E_mV_{m1} \quad \ldots\ldots \quad (1.3)$$

$$E_2 = E_3 = E_m / [1 - V_{f1}(1 - E_m / E_{f2})] \quad \ldots\ldots (1.4)$$

$$G_{12} = G_{13} = G_m / [1 - V_{f1}(1 - G_m / G_{f12})] \quad \ldots\ldots (1.5)$$

$$G_{23} = G_m / [1 - V_{f1} (1 - G_m / G_{f23})] \quad \ldots\ldots (1.6)$$

$$V_{12} = V_{13} = V_{f12} V_{f1} + V_m V_{m1} \quad \ldots\ldots (1.7)$$

$$V_{21} = V_{12} E_2 / E_1 \quad \ldots\ldots (1.8)$$

$$V_{23} = E_2 / 2G_{23} - 1 \quad \ldots\ldots (1.9)$$

In the formula above,
E- Elastic modulus,
G - Shear modulus,
V - Poisson's ratio
M – Matrix angle
F – Fiber
V_m – Matrix volume fraction
V_f – Fiber volume fraction

This paper assume $V_m = 0$, $V_f = 1$ which means that the model used in this paper identified the fiber bundle as only fiber without been mixed with the matrix. For clarity and proper calculation of needed data for the needed materials, below is the table for all parameters used in this model as shown in Table -01.

Table – 01: Material Parameters

Materials	E_1/GPa	E_2/ GPa	G_{12}/GPa	G_{23}/GPa	ν_{12}	ν_{23}
Carbon Fiber	220	13.8	9.0	4.8	0.20	0.25
Epoxy Resin	4.5				0.34	0.34

V. MODEL

This project work using Finite Element Method created 8 different types of three dimensional braided composite materials, and there geometric parameters are shown below in Table - 02:

Table – 02: Geometry Parameters of the Model

Number	1	2	3	4	5	6	7	8
Braiding Angle (°)	50	40	30	25	25	25	25	25
Fiber Vol Ratio	0.45	0.45	0.45	0.45	0.50	0.35	0.40	0.45

From the geometry parameter, γ=50°, V_f= 0.45, the following figure represent the matrix model -fig.07 , fiber model -fig.08, and the single cell model -fig.09.

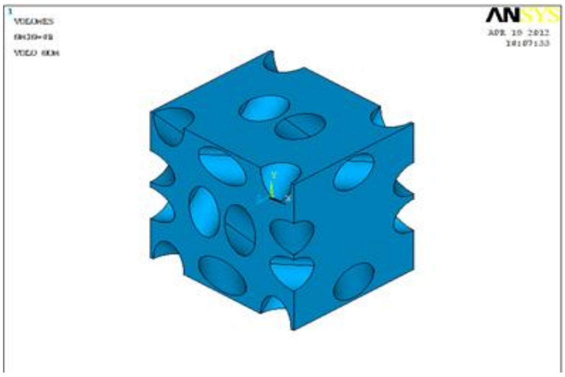

Fig.07 Matrix model when γ=50°, V_f = 0.45

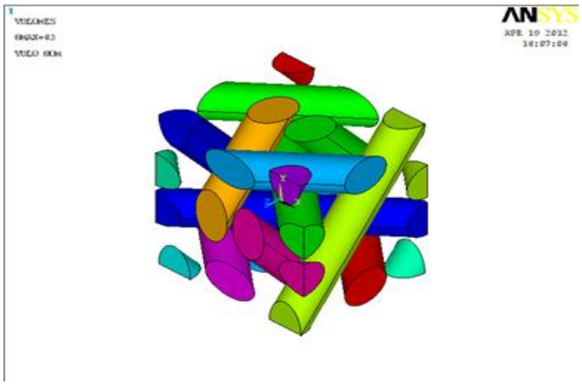

Fig.08 Fiber model when γ=50°, V_f= 0.45

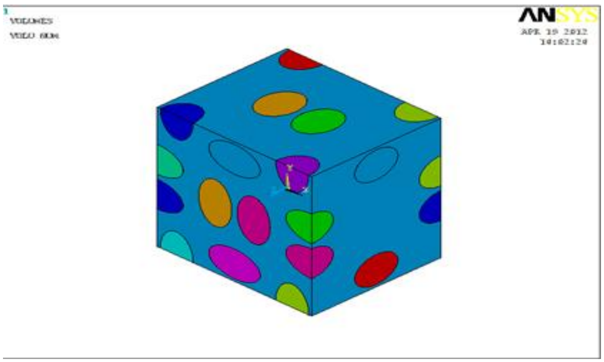

Fig.09 Single cell model when γ=50°, V_f= 0.45

VI. MODELING AND STIFFNESS ANALYSIS

In accordance with our assumption, using eight nodes, and each node has 3 degrees of freedom of the SOLID-45unit, the bundle of fibers and matrix are grid. These units in general constitutive equation of discrete produces discrete results:

$$[C]^e \{D\}^e = \{R\} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1.10)$$

In the formula, $[C]^e$ represent the element stiffness matrix, $\{D\}^e$ for node displacement, $\{R\}^e$ the unit node load. In equation (1.10) by Integration, the result is:

$$[C]\ \{D\} =\{R\} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1.11)$$

Putative In the formula above, [C] is the structural stiffness matrix, {D} for nodal displacements, and {R} is the structure node load. Below is the fiber and single cell combined finite element mesh when γ=50° and V_f =0.45 (Fig.10). Due to the fiber local material coordinates and global coordinates inconsistency, to create a uniform view of the fiber material the coordinate transformation method was used. The effective elastic properties of the local coordinate system of the material were converted to the overall. The effective elastic properties in the coordinate system were then substituted into the unit (Solid-45) attribute to be calculated, so that the entire specimen could be known and calculated. The stiffness matrix of the fiber bundle can be expressed as:

$$[C\ Y]= [T]\ [CY/]\ [T]\ T \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1.12)$$

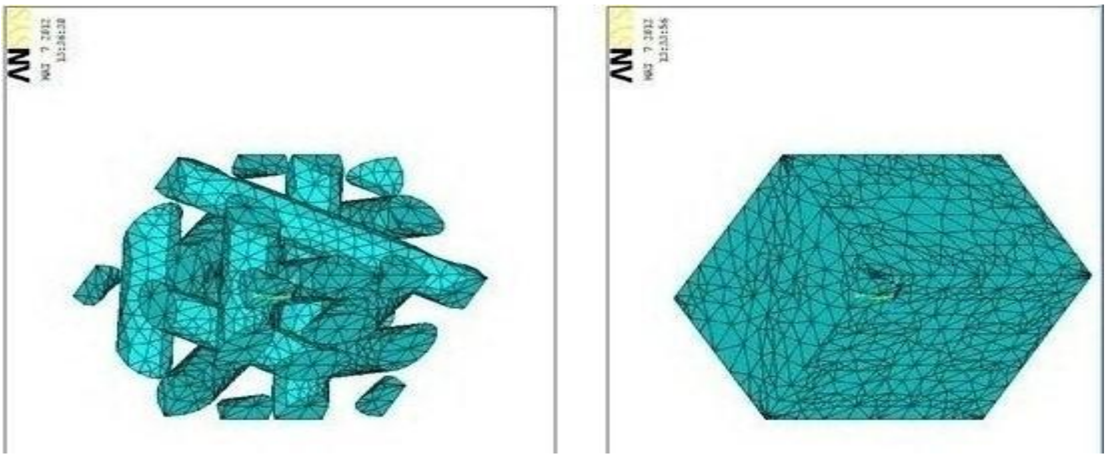

Fig.10 Fiber and single cell finite element mesh when γ= 50 and V_f = 0.45

Where, [C Y] is the stiffness of the fiber bundles in the global coordinate system matrix, [CY/] is the stiffness matrix of the fiber bundles in the local coordinate system, which can be expressed as:

$$\left[C'_Y\right]=\left[S'_Y\right]^{-1}=\begin{bmatrix} \frac{1}{E_1} & -\frac{\nu_{12}}{E_1} & -\frac{\nu_{12}}{E_1} & 0 & 0 & 0 \\ -\frac{\nu_{12}}{E_1} & \frac{1}{E_2} & -\frac{\nu_{23}}{E_2} & 0 & 0 & 0 \\ -\frac{\nu_{12}}{E_1} & -\frac{\nu_{23}}{E_2} & \frac{1}{E_2} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{G_{23}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G_{12}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G_{12}} \end{bmatrix}^{-1}$$

The coordinate transformation matrix [T]:

$$[T]=\begin{bmatrix} l_1^2 & m_1^2 & n_1^2 & 2m_1n_1 & 2n_1l_1 & 2l_1m_1 \\ l_2^2 & m_2^2 & n_2^2 & 2m_2n_2 & 2n_2l_2 & 2l_2m_2 \\ l_3^2 & m_3^2 & n_3^2 & 2m_3n_3 & 2n_3l_3 & 2l_3m_3 \\ l_2l_3 & m_2m_3 & n_2n_3 & m_2n_3+m_3n_2 & n_2l_3+n_3l_2 & l_2m_3+l_3m_2 \\ l_3l_1 & m_3m_1 & n_3n_1 & m_3n_1+m_1n_3 & n_3l_1+n_1l_3 & l_3m_1+l_1m_3 \\ l_1l_2 & m_1m_2 & n_1n_2 & m_1n_2+m_2n_1 & n_1l_2+n_2l_1 & l_1m_2+l_2m_1 \end{bmatrix}$$

So,

l_1= cosγcosθ , l_2= cosγsinθ , l_3= sinγ ;
m_1= sinγ , m_2= cosθ , m_3= 0 ;
n_1 = sinγcosθ , n_2= sinγsinθ , n_3= cosγ ;

Where γ is the unit cell of braided angle, θ is the angle of the fiber bundles in the XY plane projection of the Y-axis. According to the equation 1.12, we can get the stiffness matrix [C Y], inverse flexibility matrix [SY], and then obtain the fiber bundles in the global coordinate. The engineering relationship between elastic constants and the flexibility matrix is shown below:

$E_{fz}=1/S_{11}$, $E_{fy}=1/S_{22}$, $E_{fx}=1/S_{33}$ …………….. (1.13)

$V_{fyz}=-S_{21}/S_{11}$, $V_{fxz}=-S_{31}/S_{11}$, $V_{fxy}=S_{32}/S_{22}$ ….(1.14)

$G_{fxy}=1/S_{44}$, $G_{fyz}=1/S_{55}$, $G_{fxz}=1/S_{66}$ ……………(1.15)

VII. ELASTIC CONSTANT CALCULATIONS

For different analysis on the objects, various loads were imposed on the model; the displacement field of the model can be calculated. The average strain field can be obtained by the load of the average stress of the model, and the macroscopic elastic constants of the model as a whole can be obtained by the stress and strain. Zero displacement constraints imposed at the bottom of the model and the upper part exert a uniform pressure; while the rest of the plane left with free boundary conditions, the Z-direction is the displacement distribution (see fig.11).

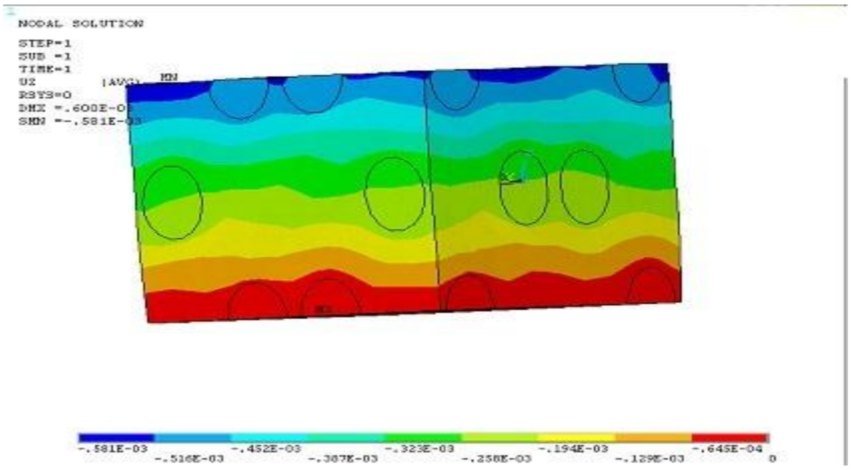

Fig. 11 Displacement distribution in Z-direction

At Z = 2 the model at the top in force displacement distribution can be obtained by the weighted average of the surface displacement from Z = 2 to z = 0.5485 × 10^{-3}mm, the model can be calculated in accordance with the following formulas in the direction of the elastic modulus:

$$E_z = (F/A)/(\Delta z/h_z) = 16.13\text{GPa}$$

According to X= 2.2, the mean displacement Δx can be calculated as ΔV_{xz}:

$$V_{xz} = (\Delta x/h_x)/(\Delta z/h_z) = 0.27$$

Average displacement Δy according to Y = 2.2 surface, it can be calculated as V_{yz}:

$$V_{yz} = (\Delta y/h_y)/(\Delta z/h_z) = 0.35$$

Using different geometric parameters on the braided composite model to obtain the elastic constant which are different based on the geometric parameters used. This method was repeated for 8 times with varying parameters in order to obtain the data below. Table - 03 shows the detail.

Table – 03 Geometry parameters under varying elastic constants of braided composites

	1	2	3	4	5	6	7	8
E_z/GPa	16.14	24.98	37.78	62.74	47.70	50.85	34.41	31.64
E_x/GPa	17.51	14.73	12.51	10.14	11.57	12.75	10.37	7.31
E_y/GPa	17.74	14.57	12.62	10.77	11.42	12.55	10.63	7.56
V_{xy}	0.31	.28	0.24	0.29	0.27	0.24	0.29	0.32
V_{yz}	0.33	0.53	0.67	0.51	0.62	0.67	0.54	0.50

VIII. RESULT ANALYSIS

According to the result obtained, the graph of change in elastic constants with changing in fiber volume ratio, and changing in braiding angle can be plotted. In this paper, the graph of elastic constants with the braiding angle graph is represented in fig.12 and fig.13 at $V_f = 0.45$ and $\gamma = 25$ °, while the graph of elastic constants with fiber volume ratio is represented in fig.14 and fig.15.The elastic modulus E_Z against the braiding angle can be seen from fig.11 from the graph, it is discovered that the elastic constants of braided composites decreases as the braiding/weaving angle increases significantly. While E_X and E_Y increases slightly as weaving angle increases. As shown in fig.12 as the weaving angle increases V_{ZY} and V_{ZX} increases sharply for the first increase in the weaving angle and started decreasing for the consequence increases in the weaving angle. While V_{XY} decreases for the first increase in the weaving angle, and keep increasing for the consequence increase in the weaving angle. The trend V_{ZY} and V_{ZX} are basically the same, which is as large as the weaving angle, by the influence of the spatial position of the fiber bundles in the z direction the deformation increases, but the x, y direction of the deformation decreases gradually. Braiding angle reaches a certain angle, which corresponds to the maximum deformation ratio in the z-direction. The corresponding x, y directions represent the minimum deformation, which make V_{XY} first decreases and then increases.

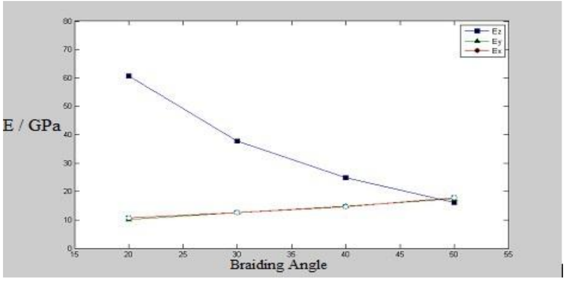

Fig.12 Elastic constant E against braiding angle γ at constant V_f =0.45

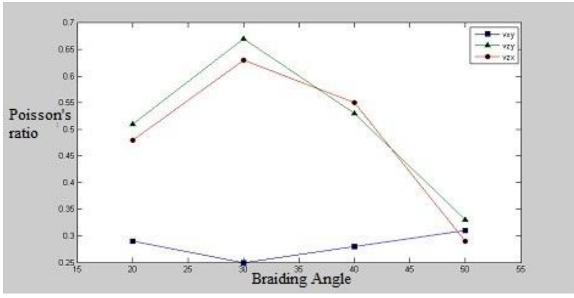

Fig.13 Poisson's ratio against braiding angle γ at constant V_f = 0.45

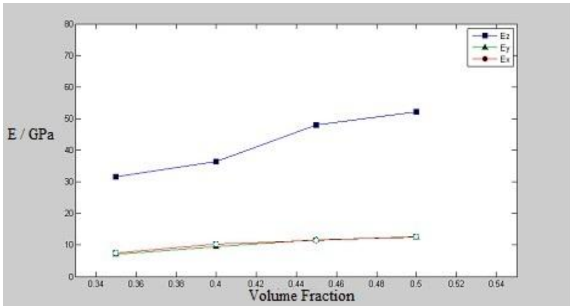

Fig.14 Elastic constant E against fiber volume fraction curve at γ = 25 °

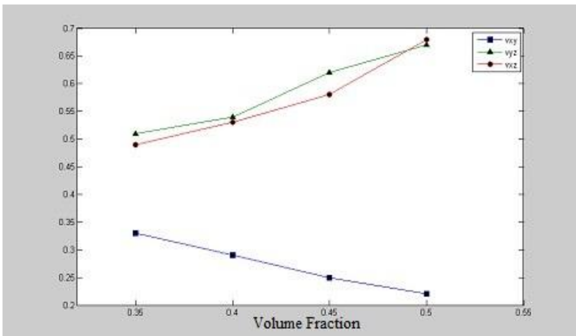

Fig.15 Poisson's ratio against Fiber volume fraction at γ = 25°

From fig.14 it can be seen that as fiber volume fraction increases, modulus of elasticity is gradually increasing as well, with the rate of increase E_Z, E_X and E_Y. Also from fig.15, V_{XZ} and V_{YZ} similar increasing trend, V_{XY} showed a downward trend. This is because with the increase of fiber volume fraction, the effective performance of the material as a whole has been enhanced. In X, Y, and Z-direction deformation were reduced, while the z direction enhances the effect of strength, V_{XZ} and V_{YZ} have a corresponding increase, and V_{XY} reduces. This study found that both woven angular size and the effective performance of the materials have similar trends with the changes in the fiber volume fraction, but decreases gradually with an increase in the weave angle trend.

IX. CONCLUSION

From the result generated from this research work, it could be concluded that the elastic modulus varies with the braiding angle of the 3D-braided composite. Also when the braiding angle increases the elastic modulus decreases significantly. E_Z decreases as braiding angle increases, while E_X and E_Y increases slightly as braiding angle increases. The Poisson's ratio of both V_{XZ} and V_{YZ} in XY and YZ direction increases with an increase in the fiber volume fraction, while V_{XY} in the XY direction decreases as the fiber volume fraction increases.

ACKNOWLEDGEMENTS

This work was funded by National Natural Science Foundation of China (No. 51005122) and National Defense Basic Technology Foundation (No. IBA12003).

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