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Analysis of Nano and Hybrid Composites with Voids Using Micromechanics

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ABSTRACT: *Unavoidable presence of void influence on composite material is required to understand in order to design these materials for particular strength. Prediction of Composite material properties through experimentation techniques with the involvement of voids is very expensive in terms of cost and time. Careful measurement of void effect on the composite material is possible through powerful Micromechanics approach using finite element method. In this article, the affect of void on the properties of nano and hybrid composites are evaluated. From the study it is found that transverse modulus of hybrid composite is greatly affected by voids than longitudinal modulus.*

KEYWORDS - *Voids, Young's modulus, Poisson's ratio, Micromechanics*

Nomenclature:

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E_p	Young's modulus of the buckminster fullerene
E_m	Young's modulus of the polymer matrix
ν_p	Poisson's ratio of the buckminster fullerene
ν_m	Poisson's ratio of the polymer matrix
E_c/E_m	Normalized Young's modulus of the fullerene Reinforced Composites
ν_c/ν_m	Normalized Poisson's ratio of the fullerene Reinforced Composites
V_f	Volume fraction of the fullerene reinforcement
V_{fiber}	Volume fraction of the fiber reinforcement
E_1	Longitudinal Young's modulus of hybrid composite
E_2	Transverse Young's modulus of hybrid composite
ν_{12}	Poisson's ratio of composite under longitudinal loading
ν_{21}	Poisson's ratio of composite under transverse loading

I. INTRODUCTION

Most of the composite materials aim for high strength and high stiffness along with low weight. The serious defects which decrease the performance of composite materials are voids, cracks, misalignment of reinforcement and debonding between the hosting medium and the reinforcement. [1-3]. Specially, the voids obstruct the performance of composite material under designed and desired conditions. The presence of void in the composite is inevitable. Most of the studies on the composite material concentrate on the identification of good reinforcement for hosting medium and highlighting the improvement in the properties due to the recognized reinforcement. In the same scope, the realization on nano size reinforcement brought a revolution in the enhancement of composite material properties. Besides, the authors of the present work are concentrated on the decrement caused on the properties of nano and hybrid composites which is very important while designing a particular product under designed load. Many analytical models are prepared by several authors to quantify the effect of void on the behavior of composite material. Park et al., [4] developed analytical equations using Micromechanics approach to quantify the effect of void on Young's modulus of composite material with clay nano particles by applying homogenization approaches. Static strength, fatigue life of the composite laminates with voids is explored by Sergio Frascino and Zabulon dos [5] under flexural loading adopting experimentation techniques. The authors demonstrated that, critical void content shows very high intensity on fatigue life of composite structure.

Coefficient of thermal expansion is the important property while considering the material under thermal loading. Hiroshi Hatta et al., [6] performed their research on the effect of micro voids on coefficient of thermal expansion of composite material using analytical techniques.

Many controlling parameters need to consider while evaluating the void effect on composite material. Void volume fraction, the position of the void in the polymer matrix, shape of the void are few factors need to consider while disclosing the lamina behavior with void. Along with the above mentioned parameters, laminate configuration is one of the deciding factors while analyzing the building block of laminas i.e laminate behavior with a void. Hongyan Zhu et al., [7] explored the void effect on tensile strength of laminate with two different configurations with fiber orientation of 0^0, 45^0 and 90^0. To simplify the Micromechanics studies, the distribution of voids on the hosting medium is assumed to be uniform. Deviating from the above assumption, Kun Xu and Xiaomei Qian [8] studied the influence of random distribution of voids on the elastic properties of resulting composite using finite element based software. 4

The influence of the aspect ratio of void on different elastic parameters is identified with the help of finite element method by Hansong Huang and Ramesh Talreja [9]. K. Danas, N. Aravas [10] presented a model which is able to predict the void shape effect on material failure. Zhang et al., [11] performed experimental studies on T-300/ epoxy resin composite to verify the void influence on compressive, bending and interlaminar strength by treating them in different cure conditions. Abdellatif Selmi [12] reported the void effect of carbon fiber reinforced epoxy composites using a finite element method. In their work, the researcher adopted two-step homogenization techniques to predict elastic responses. The void content influence in the range of 1 to 6% on the flexural fatigue properties of unidirectional carbon fiber reinforced composites is investigated by Mohamed Suhot et al. [13].

The fracture response of a rubber behavior material to the inclusions is analyzed by Ait Hocine N. et al. [14] using numerical approach. From their work, authors found that the size and content of small voids depend on the shape factor of the specimen to be analyzed.

The present work addresses the influence of voids on the properties of nano and hybrid composites using finite element method. The aggregate properties of void effected nano composites are obtained by two-level homogenization, and three-level homogenization for hybrid composites. In the first stage of homogenization, properties of matrix with voids are determined. In the second level, by considering nano fullerene as reinforcement and first level homogenized material as a matrix, the properties of nano composite with voids are obtained. In the third level, properties are determined for a hybrid composite consisting of continuous fiber as reinforcement and second level homogenized material as a matrix.

II. FINITE ELEMENT MODELING OF COMPOSITE MATERIAL

The following Fig.1., Shows the uniform distribution of fibers in a polymer matrix with voids and buckminster fullerenes distributed in a random fashion. To simplify the analysis, a homogenization approach of Micromechanics is applied.

The effect of void on nano and hybrid composites is achieved applying three stages of homogenization. In this work, reinforcement of T-300 fiber in nano particle mixed matrix is named as hybrid composite. The influence of void on the properties of nano composites are evaluated by applying two stages of homogenization. In the first stage of homogenization, the effect of void on pure polymer matrix is determined; Later the homogenized void effected polymer matrix is used as a hosting medium instead of pure polymer matrix to quantify the void effect on nano composite.

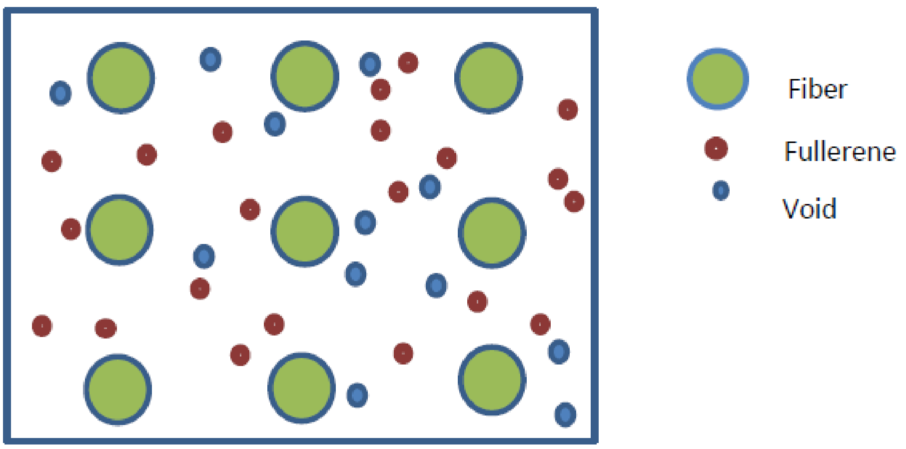

Fig.1. Schematic representation of uniformly distributed fiber with voids and nano reinforcement in composite.

Finally, the influence of void on hybrid composite is determined by reinforcing T-300 fiber in homogenized void and nano fullerene mixed matrix. The longitudinal and transverse properties are determined to disclose the influence of void on hybrid composites.

III. FIRST STAGE OF HOMOGENIZATION

Spherical shaped voids are considered for the present work; isolated cubic shaped unit cell is selected to perform the finite element analysis. Owing to the symmetry of unit cell with respect to geometry, loading and boundary conditions, only one eighth portion of the unit cell is opted to quantify the effect of void on polymer matrix. The Fig.2. a and b. show the procedure adopted in the perspective of symmetry. The dimensions of one eighth portion of the unit cell are obtained according to the volume fraction of void. Fig.3. a and b show the geometrical model and finite element model at 2% volume fraction of void.

The finite element mesh is generated with Solid 95 of finite element software ANSYS [17]. This element is defined by 20 nodes and each node possess three degrees of freedom. i.e translation on global X, Y and Z directions respectively.

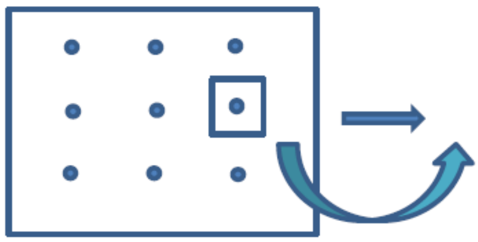

Fig.2.a Uniform distribution of voids in matrix

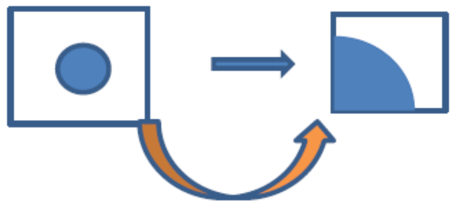

Fig.2. b. Isolated unit cell and one eighth portion of unit cell

Three positive faces of the finite element model are constrained to have the same normal displacement to avoid distortions due to heterogeneity in the model and the remaining three negative faces normal to coordinate axes are restricted to move in the normal direction. Uniform pressure (σ_x) is applied on the area corresponding to the positive X- plane of the cube. Applying simple Hook's law, the properties of the matrix with void is determined. The material properties required for the analysis specified in Table. 1

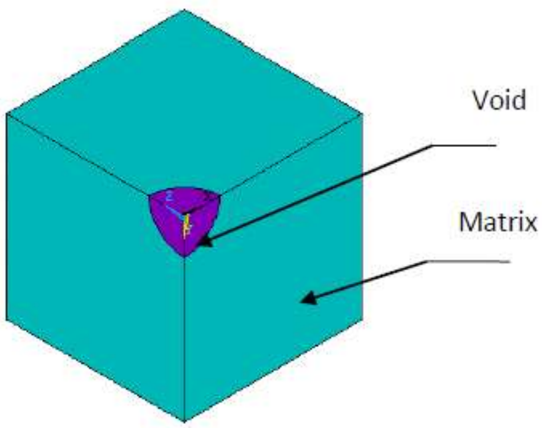

Fig. 3.a Geometrical model with void at 2% Vv

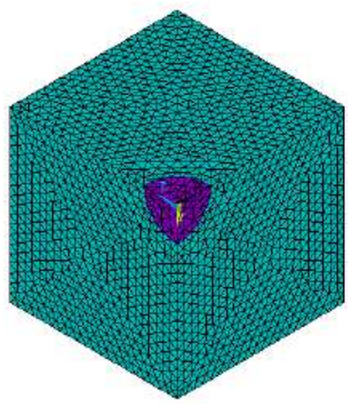

Fig. 3.b Finite Element Model

Tabel.1 Material properties for the analysis

Material	Young's Modulus (GPa)	Poisson's ratio
Void	1e-20	0.4
Polymer Matrix	5.171	0.35
Buckminster Fullerene	1000	0.3
T-300 fiber (orthotropic fiber)	E_1 = 230, E_2 (= E_3) = 15, G_{12} = (G_{13}) =27, G_{23}=7	ν_{12} (= ν_{13}) = 0.2, ν_{23} = 0.07,

The finite element procedure is validated with published literature. Hansong et al., [9] determined the longitudinal and transverse Young's modulus of fiber reinforced properties at various volume fractions of the void. The work is performed under the same conditions and same input parameters. The correlation between the reference [9] and the obtained results are shown in the Fig.4.

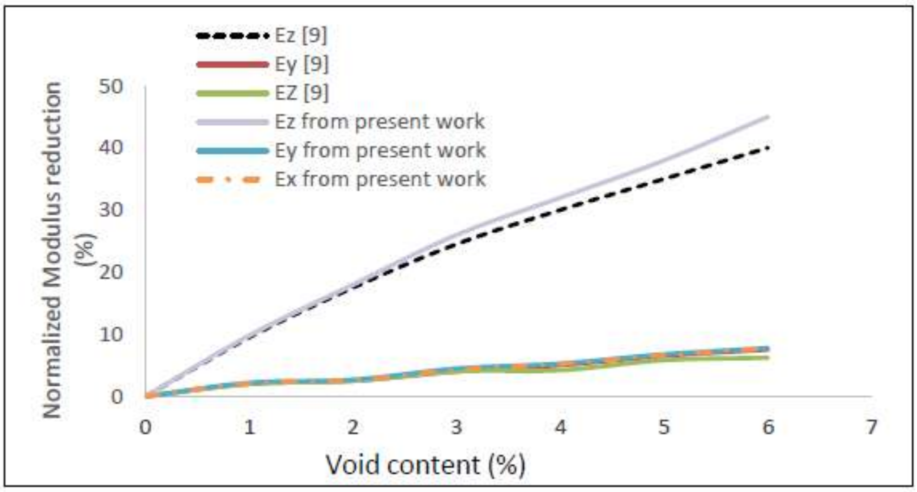

Fig. 4. Normalized modulus reductions vs. void content [Ref 9]

IV. RESULTS AND DISCUSSIONS FOR FIRST LEVEL HOMOGENIZATION

Displacement contours in x- and y- directions of FE model with and without the presence of void are shown in figs. 5-6. In the presence of void, non-uniform contour patterns are observed with more deformation when compared to defect free model.

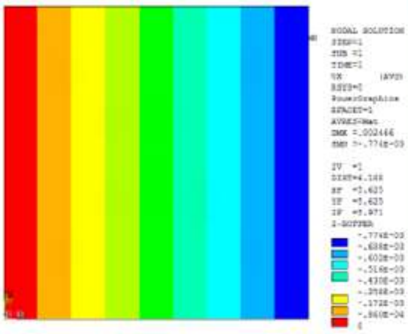

FIG. 5.A UX CONTOUR WITHOUT VOID

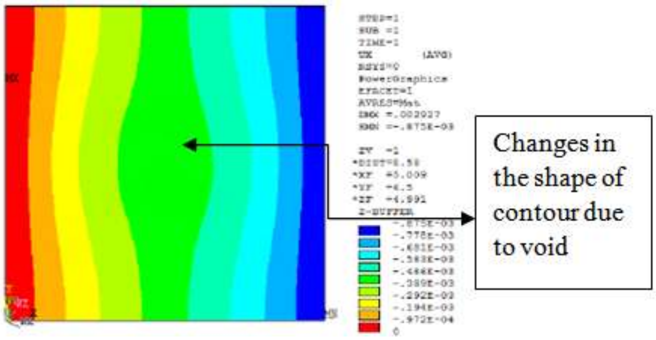

FIG. 5.B UX- CONTOUR WITH VOID

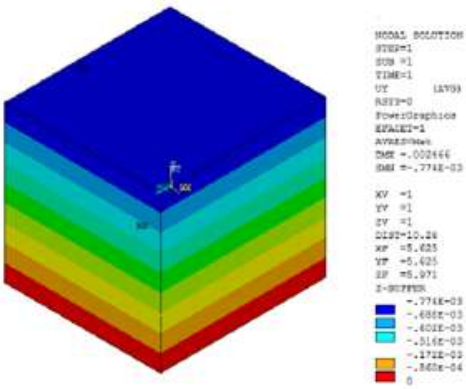

Fig. 6.a UY- contour without void

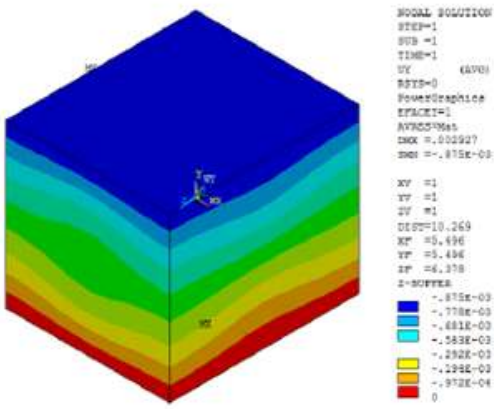

Fig. 6.b Y- contour with void

Figs. 7 and 8 show the normalized Young's modulus (E_{vc}/E_m) and normalized Poisson's ratio (ν_{vc}/ν_m) respectively of polymer matrix with void. Inner diagram shows the percentage deviation of the respective property with reference to void free matrix. The void volume fraction is varied between 2 to 10% with the interval of 2%.The increase in the volume fraction of void decreases the stiffness of matrix, resulting in

reduction in normalized Young's modulus. A maximum of 17% reduction is observed at 10% of void volume fraction (Fig. 7).
The normalized Poisson's ratio also decreases with the increase in void content in the matrix (Fig.8). This is due to more increment of longitudinal strain than lateral strain. Maximum of 6% drop in Poisson's ratio is observed at 10% of void volume fraction.

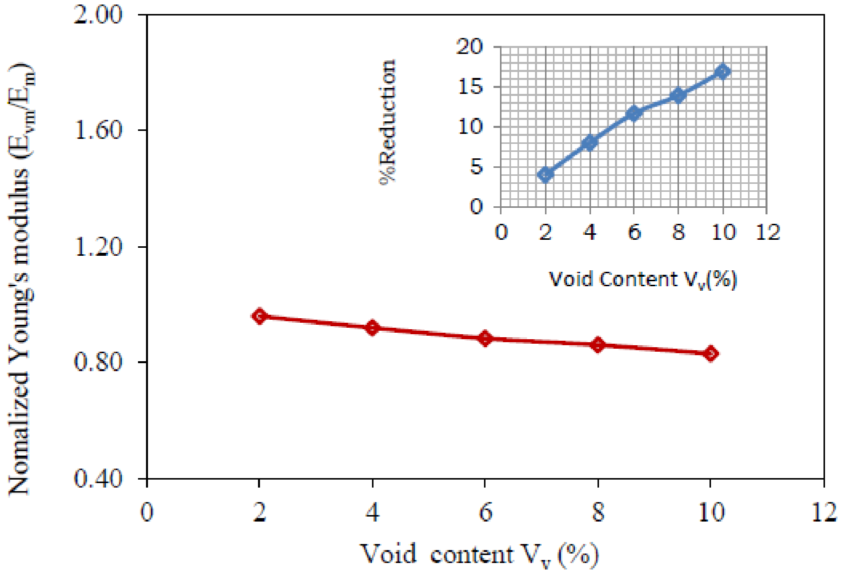

Fig.7 Normalized Young's modulus of matrix with void

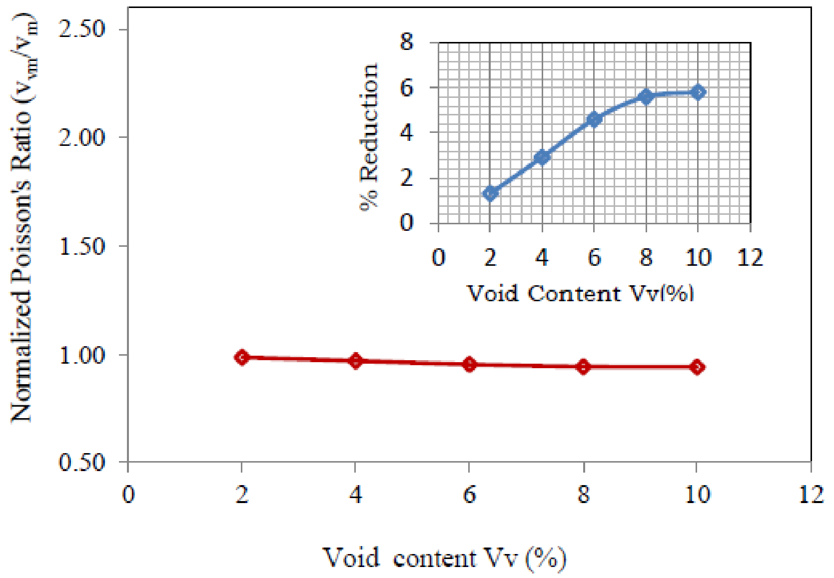

Fig. 8 Normalized Poisson's ratio of matrix with void

V. ANALYSIS OF VOID EFFECT ON PROPERTIES OF NANO COMPOSITES

The nano composites with voids are analyzed by opting buckminster fullerene of carbon allotrope as nano reinforcement and void effected polymer matrix as a hosting medium. Continuum model of buckminster fullerene is appeared to be in hollow spherical shape. Assuming uniform distribution of fullerene in void effected matrix and applying the possible symmetric conditions of geometry, loading and boundary conditions, one eighth portion of unit cell is analyzed to obtain the resultant properties. (Fig. 9 and 10). The study is carried by maintaining the fullerene volume fraction to 2%, 4% and 10%, in voided matrix concentration of 2 to 10% with the interval of 2%. The decrement of the properties due to void is studied at various level of fullerene contribution (2%, 4% and 10%). The geometry loading and boundary conditions for the evaluation of nano composite is same as mentioned in section.III. The material properties required for the analysis is taken from Table.1.

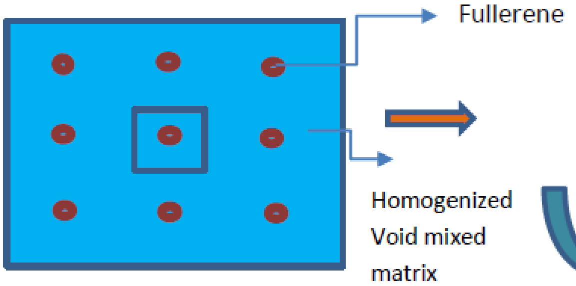

Fig.9.a Uniform distribution of fullerenes

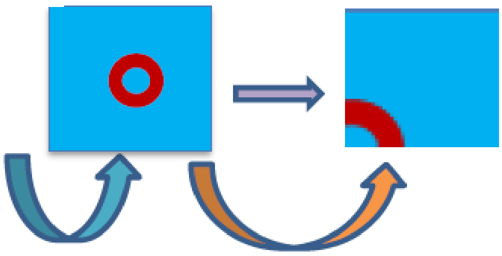

Fig.9.b isolated Unit cell and one eighth in homogenized void effected matrix portion of unit cell

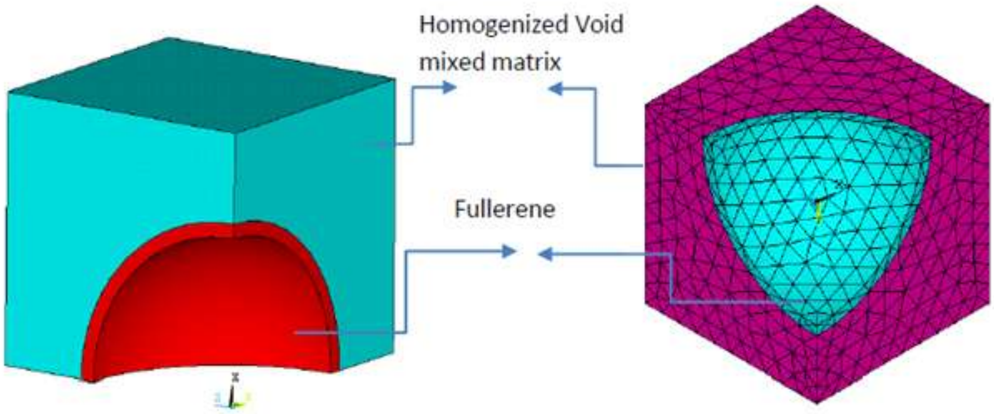

Fig. 10. a Finite element model at 10% Vp

Fig. 10.b Converged Finite element model at 10% Vp

Fig. 11, shows the variation of normalized Young's modulus with respect to the volume fraction of the fullerene. In all the three cases, the Young's modulus of the resulting composite is increased with respect to fullerene volume fraction. Reinforcement of fullerene dominates the existence of voids in the matrix. High stiffness of nano material (fullerene) improves the stiffness of the material and its Young's modulus. It is also observed that the Young's modulus decreases with increase in void volume fraction. Inner diagrams show the percentage of deviation of the normalized Young's modulus with reference to void free nano composite. Maximum deviations are observed at low volume fraction of fullerene where the property of composite is influenced by matrix. A maximum of 6.5%, 8% and 20% deviations at respective void percentages of 2, 4 and 10 are noticed at 2% of fullerene volume fraction.

Fig. 12, shows the variation of normalized Poisson's ratio of nano composite with respect to fullerene volume fraction at three different void volume fractions. It is observed that both the fullerene and void volume fractions cause for reduction in this property. High stiffness reinforcement may alter the changes in longitudinal and lateral strains, and this behavior is different from that of matrix with voids. A maximum of 8% reduction in ν_c/ν_m is observed at 10% of void and 10% fullerene volume fractions.

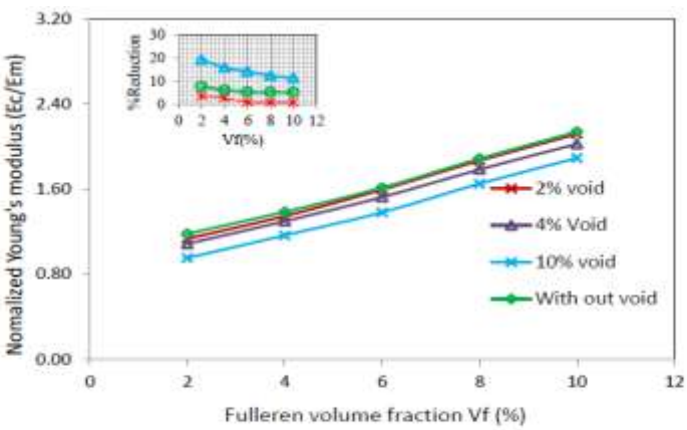

Fig. 11 Normalized Young's modulus of nano composite with void

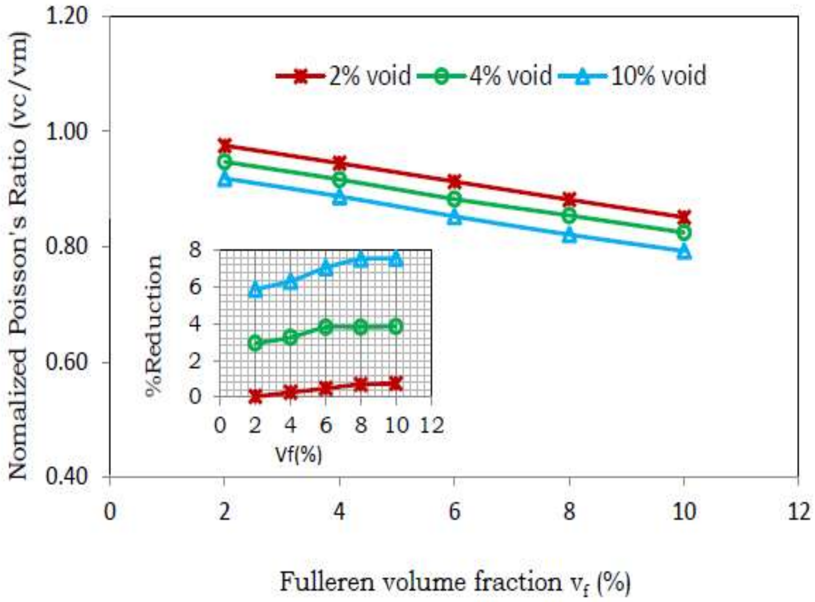

Fig.12 Normalized Poisson's ratio of nano composite with void

VI. ANALYSIS OF VOID EFFECT ON PROPERTIES OF HYBRID COMPOSITES

To understand the influence of voids on T-300 fiber reinforced hybrid composites, the homogenized fullerene mixed matrix at 2% volume fraction and voids at three different volume fractions (2%, 4% and 10%) are used as hosting material for T-300 fibers. (Fig.13-15). The analysis is performed by varying the T-300 fiber volume fraction from 10% to 75%. Applying symmetric boundary condition and varying the load direction on the finite element model the longitudinal and transverse properties of T-300 hybrid composites are determined. The depicted diagrams provide the information of reduction in the properties over void free hybrid composite.

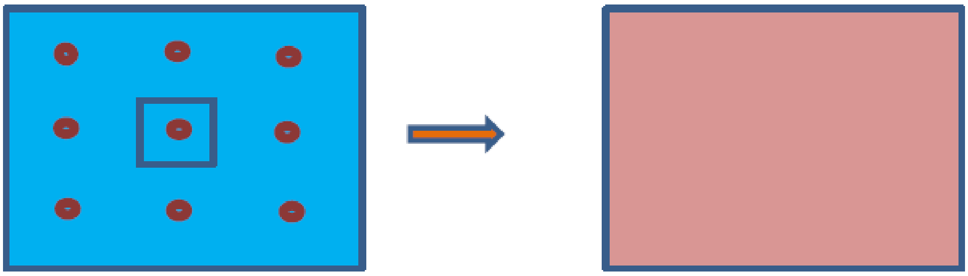

Fig.13.a Uniform distribution of fullerenes

Fig.13.b Second stage of Homogenization in void effected matrix

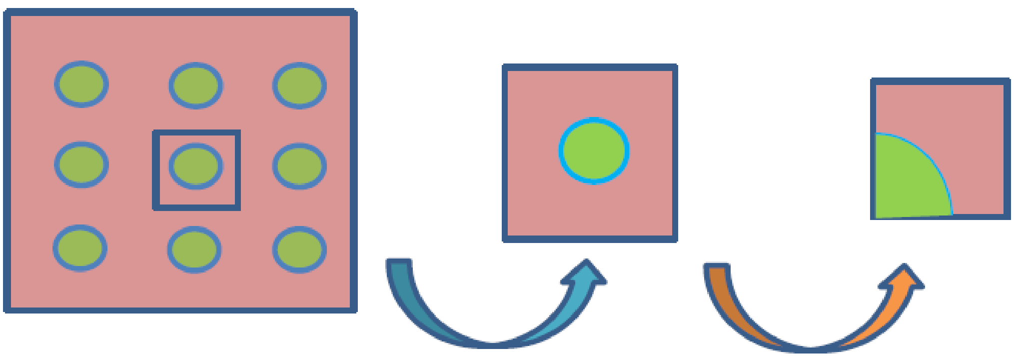

Fig.14.a Uniform distribution of T-300 fiber

Fig.14.b isolated Unit cell and one eighth in homogenized fullerene and void mixed matrix portion of unit cell

Uniform Tensile load of 1 MPa is applied on the area at z = 10 units for prediction of Longitudinal Young's Modulus E1 and associated Poisson's ratio (Fig.15. a.) Uniform Tensile load of 1 MPa is applied on the area at x =100 units for prediction of Transverse Young's Modulus E2 and associated Poisson's ratio (Fig.15. b.)

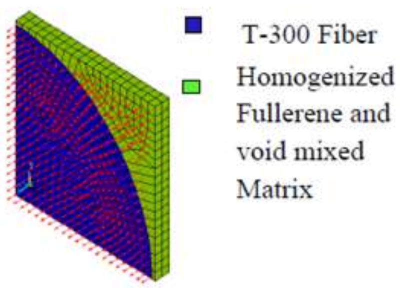

Fig.15. a. Fe Model under Longitudinal Loading at 75% V_{fiber}

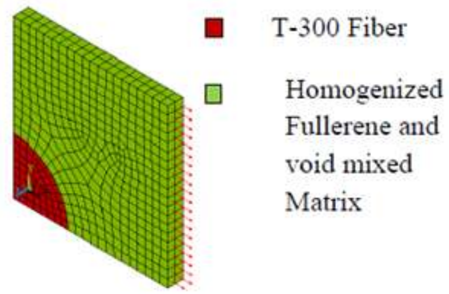

Fig.15. b. Fe Model under Transverse Loading at 10% V_{fiber}

Fig.16 shows the variation of longitudinal Young's modulus with respect to the volume fraction of the T-300 fiber. In all the three cases, the E_1 of the resulting composite is increased with respect to T-300 volume fraction. High stiffness of reinforcement (T-300) improves the stiffness of the material and its Young's modulus. It is also observed that the Young's modulus decreases with increase in void volume fraction.

Inner plots show the percentage deviation of the E_1 with reference to void free hybrid composite. Maximum decrement in the property is observed at low volume fraction of T-300 fiber where the property of composite is influenced by matrix. With increasing T-300 fiber the influence of void on E_1 decreases due to the increment of resulting composite stiffness at every volume fraction of void considered. A maximum 0.8, 1.7 and 3.2% of decrement at respective void volume fraction of 2, 4 and 10 are noticed at lower volume fraction of fiber.

Fig.17 shows the variation of Poisson's ratio ν_{12} of hybrid composite with respect to fiber volume fraction at three different void volume fractions. It is observed that both the T-300 fiber and void volume fraction cause reduction in this property. High stiffness fiber reinforcement may alter the longitudinal and lateral strain and these behaviors are different from that of matrix with voids. A maximum of 5.8% reduction in ν_{12} is observed at 10% of void and lower volume fraction of T-300 fiber.

Fig.18 shows the variation of Transverse modulus (E_2) of hybrid composite with respect to T-300 fiber volume fraction at three different void volume fractions. In all the three cases (void volume fraction of 2%, 4% and 10%), the transverse modulus of the resulting composite is increased with respect to fiber volume fraction. Due to the high stiffness of fiber reinforcement, the stiffness of the resulting material improves which in turn increases the Young's modulus.

The percentage of variation of the E_2 with respect to void free hybrid composite is shown in the inner diagram. Maximum decrement in E_2 is observed at low volume fraction of T-300 fiber where the matrix plays the dominant role in transverse direction. 4%, 8% and 17% deviation at respective void percentages of 2, 4 and 10 are noticed at 2% fullerene volume fraction. Compared to E_1, the decrement in the E_2 is more due to the domination of weak phase (matrix) in transverse direction while the high stiffness reinforcing phase (Fiber) is continuous in longitudinal direction.

Fig. 19 shows the variation of Poisson's ratio ν_{21} of T-300 hybrid composite with respect to T-300 fiber volume fraction at three different void volume fractions. Reduction in this property is observed due to the increase of T-300 fiber and void volume fractions. ν_{21} at different volume fraction of void with 2% fullerene volume fraction. The reinforcement of high stiffness T-300 in the matrix material may alter the longitudinal and lateral strain which yield the decrement of ν_{21} with voids. A maximum of 16% reduction in ν21 is observed at 10% of void and 10% T-300 fiber volume fraction.

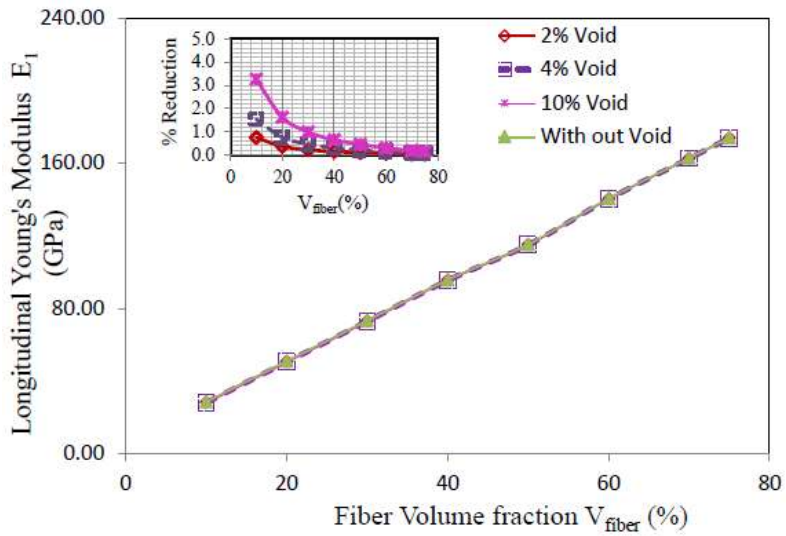

Fig.16. E1 of T-300 hybrid composite with void at 2% fullerene volume fraction

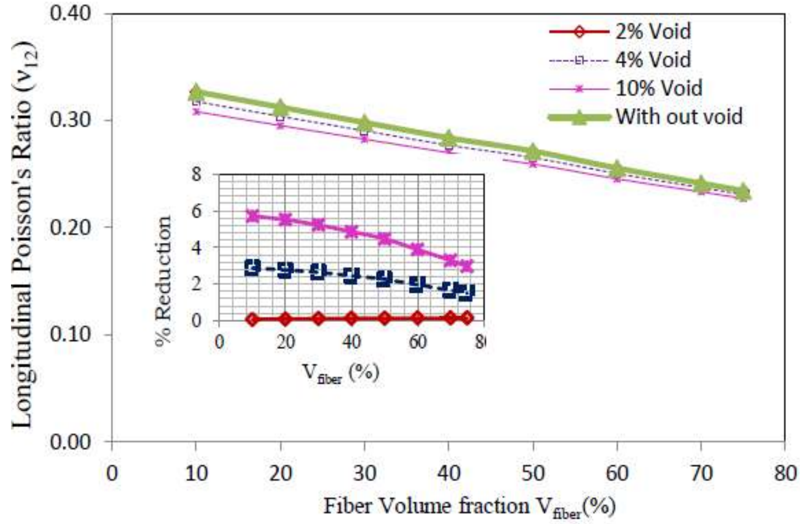

Fig.17. ν_{12} of T-300 hybrid composite with void at 2% fullerene volume fraction

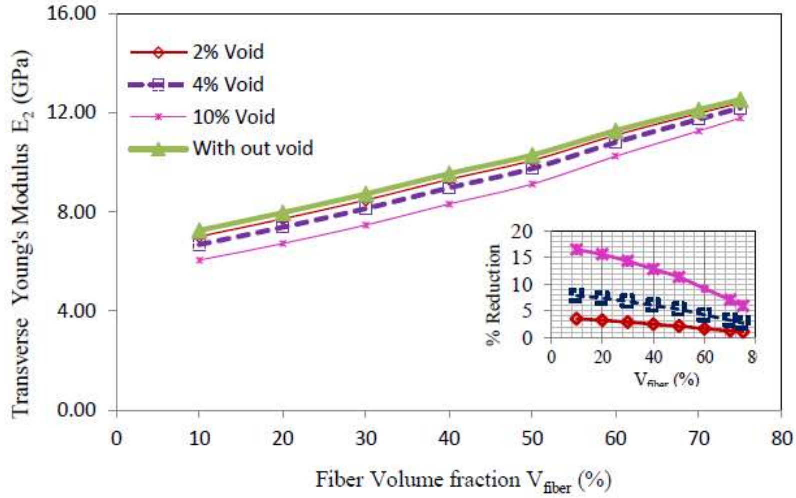

Fig.18 E_2 of T-300 hybrid composite with void at 2% fullerene volume fraction

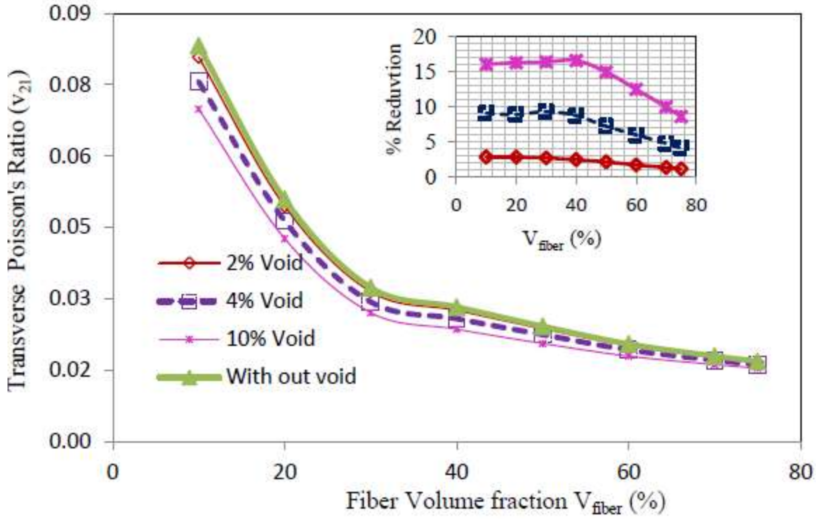

Fig.19. ν_{21} of T-300 reinforced composites with void at 2% fullerene volume fraction

VII. CONCLUSIONS

The following conclusions are obtained from the present work

- The Young's moduli of nano and hybrid composites are greatly influenced by the uncertainties such as voids.
- Unavoidable loss in the Young's modulus of polymer matrix due to void is decreased by the fullerene reinforcement. From the present study, a void in the neat polymer decreased the Young's modulus in a range of 3.99% to 16.97% by raising the void volume fraction from 2% to 10% with the interval of 2%.
- By the reinforcement of 10% volume fraction of fullerene in void presented polymer matrix at 2% and 10%, the resulting Young's modulus decrement is reduced to 1.24% from 3.99% (without fullerene) at 2% void and at higher volume fraction of void the reduction is reached 11.54% from 16.97%.
- The decrement caused due to void is more on transverse modulus (E_2) of hybrid composite than longitudinal modulus (E_1).
- In case of T-300 hybrid composite, the maximum loss in E_1 is 3.2% at lower volume fraction of fiber and higher volume fraction of void (10%). By the increase of fiber volume fraction the effect of void on E_1 is completely decreased, whereas the transverse modulus for same void content (10%) is reduced by 16%, 6% at lower and higher volume fraction of fiber respectively.

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