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First Order Shear Deformation Theory access for the stress research of CNT/Polymer Laminated Composite Plates

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ABSTRACT--- In the design of structural elements like shells, beams, and plates the analysis of stresses is one of the primary and most important considerations. The intention of the current research is to perform a study on stress behavior of laminated polymer composite plates reinforced with carbon nanotube(CNT). A theoretical first order shear deformation theory approach is executed on simply supported laminated composite plates subjected to uniformly distributed loads to study the effect of shear deformation on in-plane and transverse stresses. The numerical results are presented for symmetrical, eight layered polymer composite reinforced with Carbon Nanotube to explore the effect of various parameters like stacking sequence, the side-to-thickness ratio on stresses. The effect of carbon nanotube volume fraction and carbon nanotube radius is also investigated on stress distribution of composite plates. This study on stress analysis is conducted on plates principally to observe the structural suitability of nanocomposites.

Keywords: Nanocomposite, stress analysis, carbon nanotube, laminated plates

I. INTRODUCTION

Ever since the recorded exposure by Iijima in 1991[1], carbon nanotubes(CNTs) have been the subject matter of extensive concentration as a result of their exceptional physical and mechanical properties. For instance, their modulus of elasticity is over 1000 GPa and tensile strength is about 0.150 TPa, which makes it many times more stiff and stronger than conventional steel while being three to five times lighter[2,3]. The outstanding properties exhibited by CNTs at nanoscale have inspired much interest in the researchers in their use to reinforce in advanced polymer composites[4-6].
CNTs in specific have shown a strong potential for improvin g polymers material characteristics [7].

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Besides the enhancement of other properties like electrical conductivity[8,9],nique attention is paid to strengthening me chanical characteristics. The exceptionally high stiffness and strength [10, 11] make CNTs the most promising substance as reinforcement for polymeric materials. The thermal, mechanical and electrical properties of CNTs bring in innovative standpoint for multi functional materials, for example, conductive polymers with superior mechanical performance. However, the key challenge in the fabrication of CNTs reinforced composite is ineffective transport of the interesting thermal, mechanical, and electrical properties to the polymer due to improper dispersion of the individual CNTs in the polymeric matrix and inadequate adherence between filler and matrix. Numerous studies have been conducted to address these issues in the fabrication to improve the properties of polymers by adding CNTs as filler [12-14]. Modeling of CNTs reinforced composites has also received attention in recent past years. A wide-ranging theoretical and experimental analysis is conducted on CNT reinforced polymer composites (CNTRC) to obtain modeling aspects and the mechanical characterization. [15-18]. Even supposing, these explorations are reasonably useful in the get hold of the elastic properties of CNTRC, their employability in the substantial structural applications is the eventual purpose of development of these world-class ultra light materials. By itself there is a huge necessity to inspect the macro level study of this highly sophisticated material in actual structural elements for example beam and plate structures. In the analysis of plates, different theories have been devised depending on different suppositions for displacement fields. These analysis theories could be separated into three most vital hypotheses, namely the individual layer theories, the equivalent single-layer theory (ESL), and the 3-dimensional elasticity solutions approach. By involving various assumptionsnto, these categories are fu rther split into sub-theories. For example, the second approach embrace the classical laminate plate theory (CLPT), the first-order and higher-order shear deformation theories (FSDT and HSDT).The deflection, stress and vibration behavior of CNT/Polymer composite beams by using CLPT is presented by Wuite and Adali [19] for different CNT diameters and percentage of volume of CNTs. Theoretical explanation on deflection and stress behavior of CNTRC thin composite plates under static as well as dynamic loading by using CLPT approach are made by Madhu and Rao [20].

For the CNT/Polymer composite plates the extensive research on buckling behavior under various boundary conditions is carried out in FSDT approach by Pramod and Rao[21]. In the present analysis an analytical study on stress behavior of CNTRC plates is carried out by using FSDT with a prospect towards review the expediency of these innovative materials in the design of structural nanocomposites. For the design of CNTRC in structural functions, ultimate property–microstructure functions are compulsory in the type of micromechanics models. In the current analysis, micromechanics elastic properties of CNTRC are worked out by making use of Mori-Tanaka micromechanics procedure as given in [22, 23].

II. MICROMECHANICS MODEL

The micromechanics model involves an elastically isotropic, and homogeneous polymer dispersed with aligned and straight CNTs. Each CNT is presumed to be substantially lengthy and continuous solid fibers with transversely isotropic elastic constants. The values of Hill's elastic constants for the CNT are taken from Popov. V..N, Doren and Balkanski [23]. Further the resulting nanocomposite is also considered to be transversely isotropic and its constitutive stress strain relations $\sigma = C\,\epsilon$ can be expressed as follows:

$$\begin{Bmatrix}\sigma_{11}\\\sigma_{22}\\\sigma_{33}\\\sigma_{23}\\\sigma_{13}\\\sigma_{12}\end{Bmatrix}=\begin{bmatrix}n & l & l & 0 & 0 & 0\\ l & k+m & k-m & 0 & 0 & 0\\ l & k-m & k+m & 0 & 0 & 0\\ 0 & 0 & 0 & 2m & 0 & 0\\ 0 & 0 & 0 & 0 & 2p & 0\\ 0 & 0 & 0 & 0 & 0 & 2p\end{bmatrix}\begin{Bmatrix}\varepsilon_{11}\\\varepsilon_{22}\\\varepsilon_{33}\\\varepsilon_{23}\\\varepsilon_{13}\\\varepsilon_{12}\end{Bmatrix} \qquad (1)$$

In which k represents the plane-strain bulk modulus of elasticity in a direction normal to the fiber orientation, n represents the axial tension coefficient in the direction of fiber, l be the associated transverse elastic modulus, m and p represents the shear coeffcient in the planes perpendicular and parallel to the filler material orientation, in that order are Hill's elastic constants. By the application of the Mori-Tanaka method for a CNT/Polymer composite material comprising a reinforcing phase volume fraction C_r, matrix phase with volume fraction C_m , Young's modulus E_m and Poisson's ratio υ_m, the Hill's elastic modulus are found to be

$$k=\frac{E_m\{E_m c_m+2k_r(1+\nu_m)[1+c_r(1-2\nu_m)]\}}{[E_m(1+c_r-2\nu_m)+2c_m k_r(1-\nu_m-2\nu_m^2)]2(1+\nu_m)}$$

$$l=\frac{E_m\{c_m\nu_m[E_m+2k_r(1+\nu_m)]+2c_r l_r(1-\nu_m^2)\}}{(1+\nu_m)[2c_m k_r(1-\nu_m-2\nu_m^2)+E_m(1+c_r-2\nu_m)]}$$

$$n=\frac{E_m^2 c_m(1+c_r-c_m\nu_m)+2c_m c_r(k_r n_r-l_r^2)(1+\nu_m)^2(1-2\nu_m)}{(1+\nu_m)\{2c_m k_r(1-\nu_m-2\nu_m^2)+E_m(1+c_r-2\nu_m)\}}+\frac{E_m[2{c_m}^2 k_r(1-\nu_m)+c_r n_r(1-2\nu_m+c_r)+4c_m c_r l_r\nu_m]}{2c_m k_r(1-\nu_m-2{\nu_m}^2)+E_m(1+c_r-2\nu_m)}$$

$$p=\frac{E_m[E_m c_m+2(1+c_r)p_r(1+\nu_m)]}{2(1+\nu_m)[E_m(1+c_r)+2c_m p_r(1+\nu_m)]}$$

$$m=\frac{E_m[E_m c_m+2m_r(1+\nu_m)(3+c_r-4\nu_m)]}{2(1+\nu_m)\{E_m[c_m+4c_r(1-\nu_m)]+2c_r m_r(3-\nu_m-4{\nu_m}^2)\}} \qquad (2)$$

Where kr, lr, mr, nr and pr representing the corresponding Hill's elastic modulus for the reinforcing fiber material. The empirical formulae for the different elastic modulus of the CNTRC with regards to the stiffness constants are determined for a unidirectional single layer composite as follows:

$$E_L=n-\frac{l^2}{k},\qquad E_T=\frac{4m(kn-l^2)}{kn-l^2+mn}\qquad G_{LT}=2p \quad \text{and} \quad \nu_{LT}=\frac{l}{2k} \qquad (3)$$

III. MATERIALS AND METHADOLOGY

The plate under this study is assumed to be made-up of a composite material which consists of Polystyrene polymer as the resin material having the modulus of elasticity and Poisson's constant of E_m = 1900 MPa and υ_m= 0.3 respectively and a single walled CNT (SWCNT) as the reinforcement. In this analysis, The carbon nanotube radius is taken to be 10Å for all the instances or else stated for which the diplomat values of the Hill's elastic constants of single walled carbon nanotubes (SWCNT) are used as k_r= 30 GPa, n_r= 450 GPa m_r= p_r= 1 GPa and l_r= 10 GPa [23]. The union at the nanotube–polymer boundary is taken to be ideal. An analytical FSDT approach is applied to explore the reaction of CNT/Polymer composite plates under stress at different ratios of side-to-thickness, for various CNT(fiber) volume fractions and also for various stacking orders. For the specially-orthotropic laminated composite plates taking both static and thermal loads, the constitutive relations for the bending deflections under FSDT are given by Reddy [24] as follows:

$$\begin{bmatrix}\hat{s}_{11} & \hat{s}_{12} & 0 & 0 & 0\\ \hat{s}_{12} & \hat{s}_{22} & 0 & 0 & 0\\ 0 & 0 & \hat{s}_{33} & \hat{s}_{34} & \hat{s}_{35}\\ 0 & 0 & \hat{s}_{34} & \hat{s}_{44} & \hat{s}_{45}\\ 0 & 0 & \hat{s}_{35} & \hat{s}_{45} & \hat{s}_{55}\end{bmatrix}\begin{Bmatrix}U_{mn}\\V_{mn}\\W_{mn}\\X_{mn}\\Y_{mn}\end{Bmatrix}=\begin{Bmatrix}0\\0\\Q_{mn}\\0\\0\end{Bmatrix}-\begin{Bmatrix}\alpha N_{mn}^1\\\beta N_{mn}^2\\0\\\alpha M_{mn}^1\\\beta M_{mn}^2\end{Bmatrix} \qquad (4)$$

Decoupling the in-plane displacements from the bending displacements, we have

$$\begin{bmatrix}\hat{s}_{33} & \hat{s}_{34} & \hat{s}_{35}\\ \hat{s}_{34} & \hat{s}_{44} & \hat{s}_{45}\\ \hat{s}_{35} & \hat{s}_{45} & \hat{s}_{55}\end{bmatrix}\begin{Bmatrix}W_{mn}\\X_{mn}\\Y_{mn}\end{Bmatrix}=\begin{Bmatrix}Q_{mn}\\0\\0\end{Bmatrix}-\begin{Bmatrix}0\\\alpha M_{mn}^1\\\beta M_{mn}^2\end{Bmatrix} \qquad (5)$$

By solving the equation (5), by using static condensation procedure, we arrive at

$$W_{mn}=\frac{1}{b_{mn}}\left[Q_{mn}+\frac{\hat{s}_{34}}{b_0}(\alpha M_{mn}^1\hat{s}_{55}-\beta M_{mn}^2\hat{s}_{45})-\right.$$
s35b0αMmn1s45− βMmn2s44

$$X_{mn}=\frac{1}{b_0}[b_1W_{mn}-(\alpha M_{mn}^1\hat{s}_{55}-\beta M_{mn}^2\hat{s}_{44})]$$

$$Y_{mn}=\frac{1}{b_0}[b_2W_{mn}+(\alpha M_{mn}^1\hat{s}_{45}-\beta M_{mn}^2\hat{s}_{44})]$$

Where $b_{mn}=\hat{s}_{33}+\hat{s}_{34}\frac{b_1}{b_0}+\hat{s}_{35}\frac{b_2}{b_0}$,

$b_1=\hat{s}_{44}\hat{s}_{55}-\hat{s}_{45}\hat{s}_{45}$

$$b_1 = \hat{s}_{45}\hat{s}_{35} - \hat{s}_{34}\hat{s}_{55} \quad , \quad b_2 = \hat{s}_{34}\hat{s}_{45} - \hat{s}_{44}\hat{s}_{35} \tag{6}$$

When the thermal forces are zero, the bending deflections are given by

$$w_0(x,y) = \sum_{n=1}^{\infty}\sum_{m=1}^{\infty} W_{mn} \sin\alpha x \; \sin\beta y$$

$$\phi_x(x,y) = \sum_{n=1}^{\infty}\sum_{m=1}^{\infty} X_{mn} \cos\alpha x \; \sin\beta y$$

$$\phi_y(x,y) = \sum_{n=1}^{\infty}\sum_{m=1}^{\infty} Y_{mn} \sin\alpha x \; \cos\beta y$$

With $\alpha = \frac{m\pi}{a}$, $\beta = \frac{n\pi}{b}$ and

$$W_{mn} = \frac{Q_{mn}}{b_{mn}} \quad , \quad X_{mn} = \frac{b_1}{b_0 b_{mn}} Q_{mn} \quad , \quad Y_{mn} = \frac{b_2}{b_0 b_{mn}} Q_{mn} \tag{7}$$

The in-plane stresses are given by

$$\begin{Bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{xy} \end{Bmatrix}^{(k)} = -z \sum_{n=1}^{\infty}\sum_{m=1}^{\infty} \begin{Bmatrix} \left(\bar{Q}_{11}^{(k)} \alpha X_{mn} + \bar{Q}_{12}^{(k)} \beta Y_{mn}\right) \sin\alpha x \; \sin\beta y \\ \left(\bar{Q}_{12}^{(k)} \alpha X_{mn} + \bar{Q}_{22}^{(k)} \beta Y_{mn}\right) \sin\alpha x \; \sin\beta y \\ \left(-\bar{Q}_{66}^{(k)} (\beta X_{mn} + \alpha Y_{mn}) \cos\alpha x \; \cos\beta y\right) \end{Bmatrix} \tag{8}$$

and the transverse shear stresses are given by

$$\begin{Bmatrix} \sigma_{yz} \\ \sigma_{xz} \end{Bmatrix}^{(k)} = \sum_{n=1}^{\infty}\sum_{m=1}^{\infty} \begin{Bmatrix} \bar{Q}_{44}^{(k)} (Y_{mn} + \beta W_{mn}) \sin\sigma x \; \cos\beta y \\ \bar{Q}_{55}^{(k)} (X_{mn} + \alpha W_{mn}) \cos\alpha x \; \sin\beta y \end{Bmatrix} \tag{9}$$

The following nondimensionalisations are used to present results in graphical and tabular forms.

$$\bar{\sigma}_{xx} = \sigma_{xx}\left(\frac{h^2}{b^2 q_0}\right) , \quad \bar{\sigma}_{yy} = \sigma_{yy}\left(\frac{h^2}{b^2 q_0}\right) , \quad \bar{\sigma}_{xy} = \sigma_{xy}\left(\frac{h^2}{b^2 q_0}\right) , \quad \bar{\sigma}_{xz} = \sigma_{xz}\left(\frac{h}{b q_0}\right) ,$$

$$\bar{\sigma}_{yz} = \sigma_{yz}\left(\frac{h}{b q_0}\right) \tag{10}$$

IV. RESULTS AND DISCUSSIONS

A good-ordered MATLAB program is coded in order to study the response of composite plates under stresses using plate theory FSDT. The elastic constants of CNTRC are computed using Mori-Tanaka micromechanics approach and the same are in turn used to work out the in-plane and transverse stresses of the plate. To confirm the elastic constants, a simply supported laminated CNT/Polymer composite beam problem is solved whose outcomes are available in the literature. The deflections of the beam carrying a central point load are figured out for various stacking sequences of symmetric laminated composite using the coded program and shown in Figure 1. The present findings and published outcomes [19] are found to be in excellent harmony.

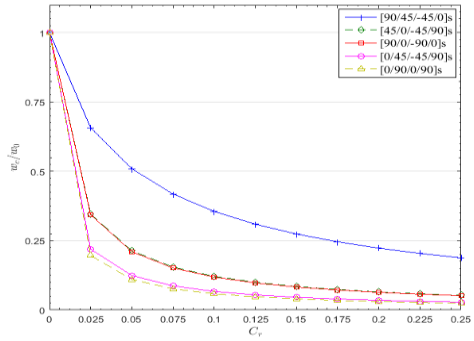

Figure 1 Nondimensionalized maximum deflection vs fiber volume percentage for a simply supported composite beam under concentrated point load acting at the center for different stacking sequences.

Having validated the developed source code, it is further extended to estimate the stresses in a simply supported plate subjected uniformly distributed load using constitutive relations derived by using FSDT. A parametric exploration has been carried out to distinguish the effect of thickness of the CNTRC plates on in-plane and transverse stresses.

The nondimensionalised normal stress $\bar{\sigma}_{xx}$ for a simply supported plate carrying uniformly distributed load is calculated and its variation from top to neutral axis along the thickness for the stacking sequences [90/45/-45/0]s, [0/90/0/90]s and [45/-45/45/-45]s is presented in fig 2. The CNT volume fraction is taken as 0.3 and the side-to thickness ratio is 10.

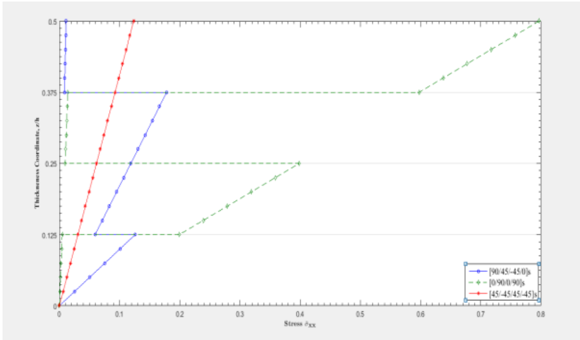

Figure 2Curves of nondimensionalized stress $\bar{\sigma}_{xx}$ plotted verse thickness coordinate for a choice of stacking sequences for a simply supported plate.

The results from the fig 2 show the effect of stacking sequence on the maximum normal stress which can be abridged significantly by lamina order optimization. With respect to the normal stress, the stacking sequence [45/-45/45/-45]s inducing the lower normal stress among other and behaves like isotropic material. The stacking sequence [90/45/-45/0]s induced less maximum stress than that of cross ply lay-up. The studies have been conducted to evaluate the effect of plate side-thickness ratio and volume fraction of fiber (CNT) on maximum stress and are shown in fig. 3 and fig. 4.

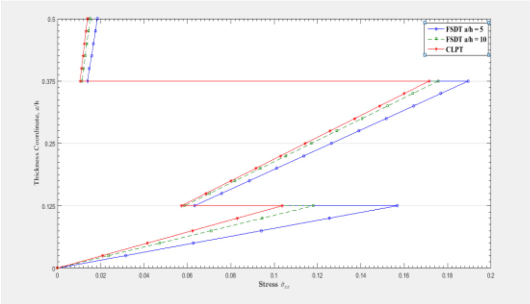

Figure 3Curves of nondimensionalized stress $\bar{\sigma}_{xx}$ plotted against thickness coordinate for a choice of side by thickness ratios under FSDT and CLPT for stacking sequences [90/45/-45/0]s.

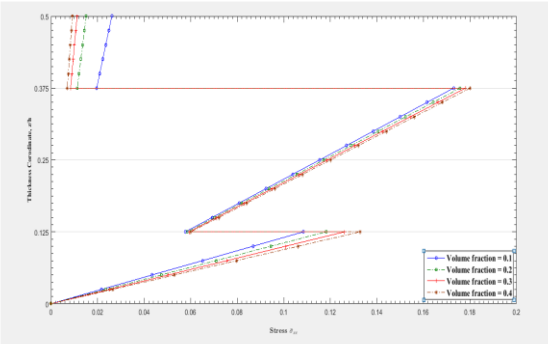

Figure 4Curves of nondimensionalized stress $\bar{\sigma}_{xx}$ plotted verses thickness coordinate for a choice of fiber volume fraction for stacking sequences [90/45/-45/0]s.

The diameter of carbon nanotube is another important factor that affects the stiffness of CNTRC. The overall stiffnesses gained for smaller diameters of nanotubes. This characteristic of the reinforcements at side-to-thickness ratio 10 and CNT volume fraction 0.2 is studied from Fig 5.

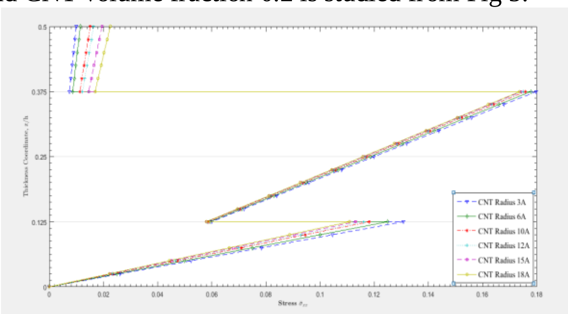

Figure 5Curves of nondimensionalized stress $\bar{\sigma}_{xx}$ plotted against thickness coordinate for a choice of CNT radii for stacking sequences [90/45/-45/0]s.

The effect of lay-up, side-by-thickness ratio and CNT volume fraction on nondimensionalised stress $\bar{\sigma}_{yy}$ is also evaluated and the results are as shown in fig 6 to fig 8.

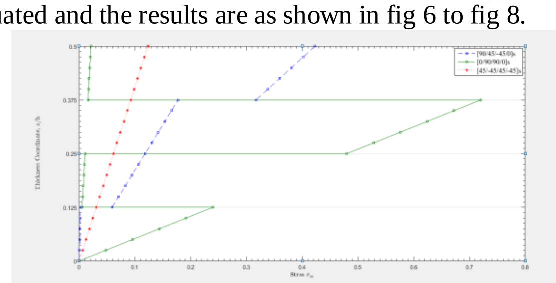

Figure 6Curves of nondimensionalized stress $\bar{\sigma}_{yy}$ plotted against thickness coordinate for a choice of stacking sequences for a simply supported plate.

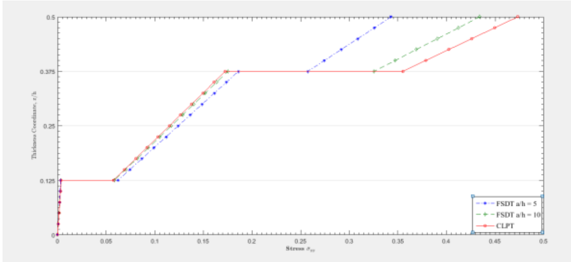

Figure 7 curves of nondimensionalized stress $\bar{\sigma}_{yy}$ plotted against thickness coordinate under FSDT and CLPT for various side-by-thickness ratios for stacking sequences [90/45/-45/0]s.

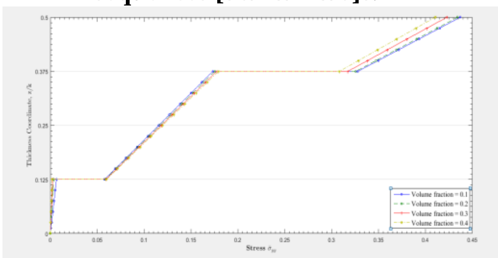

Figure 8 curves of nondimensionalized stress $\bar{\sigma}_{yy}$ plotted against thickness coordinate for a choice of CNT volume fraction for stacking sequences [90/45/-45/0]s.

The results indicating that the effect lay-up and side-to-thickness ratio on stress $\bar{\sigma}_{yy}$ is opposed to that of stress $\bar{\sigma}_{xx}$. However, the effect of CNT volume fraction on stresses is to stiffen the composite which is indicated by the same effect in both x and y direction. The observations under FSDT on in-plane shear stress $\bar{\sigma}_{xy}$ are given in fig 9 also compared with CLPT in fig 10.

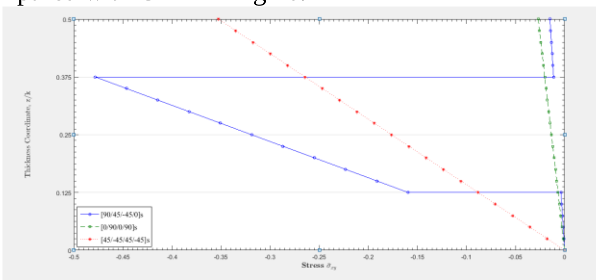

Figure 9Curves of nondimensionalized stress $\bar{\sigma}_{xy}$ plotted against thickness coordinate for various stacking sequences for a simply supported composite plate.

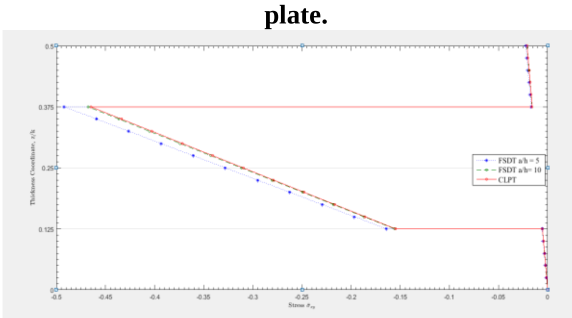

Figure 10 Curves of nondimensionalized stress $\bar{\sigma}_{xy}$ plotted against thickness coordinate for [90/45/-45/0]s stacking sequence for a simplysupported composite plate under FSDT and CLPT.

From the above results it is evident that the stacking [0/90/0/90]s have linear stress distribution with lesser maximum stresses than that of stacking sequence [45/-45/45/-45]s. The shear deformation has no effect on the transverse shear stress therefore the shear stress $\bar{\sigma}_{xz}$ and $\bar{\sigma}_{yz}$ is constant throughout the thickness of the ply however the stress in each ply is different.

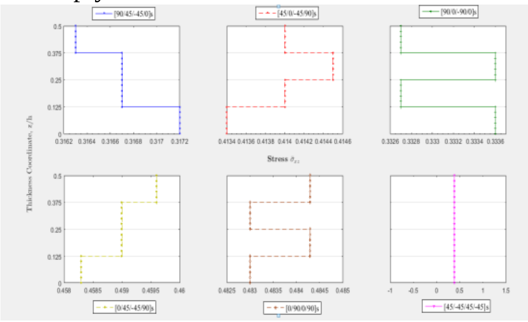

Figure 11Curves of nondimensionalised stress $\bar{\sigma}_{xz}$ plotted against thickness coordinate for different stacking sequences for a simplysupported composite plate.

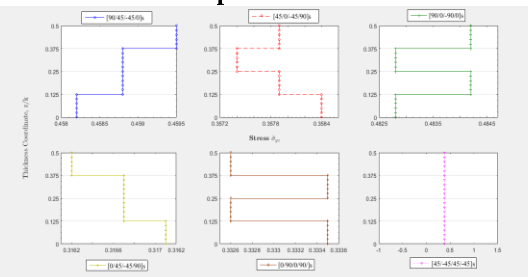

Figure 12 Curves of nondimensionalized stress $\bar{\sigma}_{yz}$ plotted against thickness coordinate for differentstacking sequences for a simply supported composite plate.

V. CONCLUSIONS

The stress behaviour of nanocomposite simply supported plates under FSDT was analyzed by using Mori-Tanaka micromechanics methodology to find out the elastic strengths in relation of CNT volume fraction. The effects of the stacking order and side by thickness ratio were premeditated on the stress distribution of laminated plates.

The approach CLPT is independent of thickness of the plate so it cannot be used with thick plates (a/h<20) where as FSDT holds good for thick plates as well as thin plates (a/h>20). The stress distribution in the stacking sequence [45/-45/45/-45]s is found to be linear for both in-plane transverse stresses. The increase in CNT volume fraction is to increase the stiffness there by reduces stresses. The stacking sequence of the composite greatly effects the stress distribution so the optimization of sequence must be done in the design of structural elements. It is also observed that the higher stiffness can be obtained with smaller CNT radius.

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