# Modeling the Effective Composite properties of Fiber Reinforced polymers with Nano Inclusions

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# Problem Definition

**1.** *Develop a constitutive model to predict the composite properties of Hybrid composite system*.

**2.** Find Effective properties of CFRP laminates after nano-inclusion

**3.** Find the changes in Interlaminar shear stress of CFRP laminates after nano-inclusion

## Micromechanics model - Method of cells

- Method of Cells (MOC) has been originally developed by Jacob Aboudi .

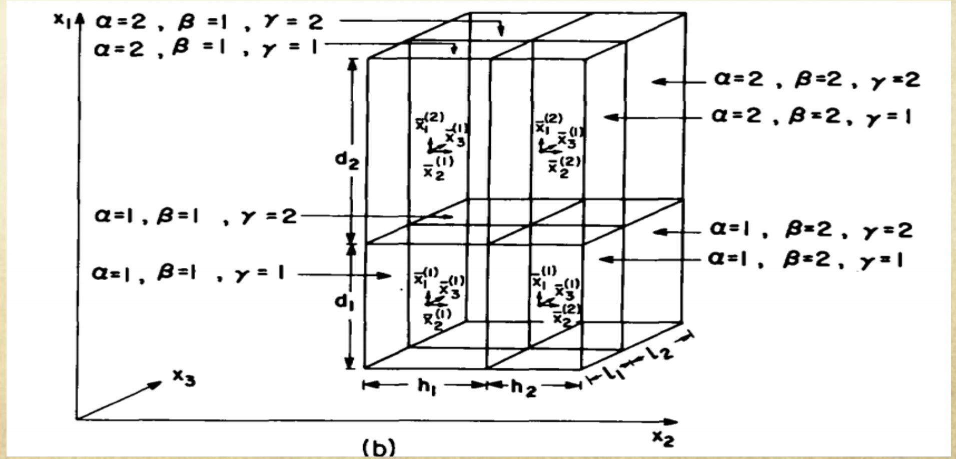
- The MOC has been successfully used to model:

Infinite long fiber-matrix composites

Bilaminates

Particulates

Aligned finite short fiber-matrix composites



## Extending MOC to model Nanocomposites

- To model nanocomposites, 2 essential parameters are further considered in MOC.

They are:

1. Random orientation of fiber in the matrix
   - Random orientation has been incorporated using a statistical averaging approach by considering finite number of fibers

2. Agglomeration of fibers in the matrix
   - A uniform agglomeration model is considered by assuming a constant cluster size throughout the matrix
   - Composite is assumed to be consisting of two reinforcements; isolated and agglomerated fiber
   - Equivalent composite property is evaluated using a multistep homogenization model.

# Extending MOC to model Hybrid nanocomposites

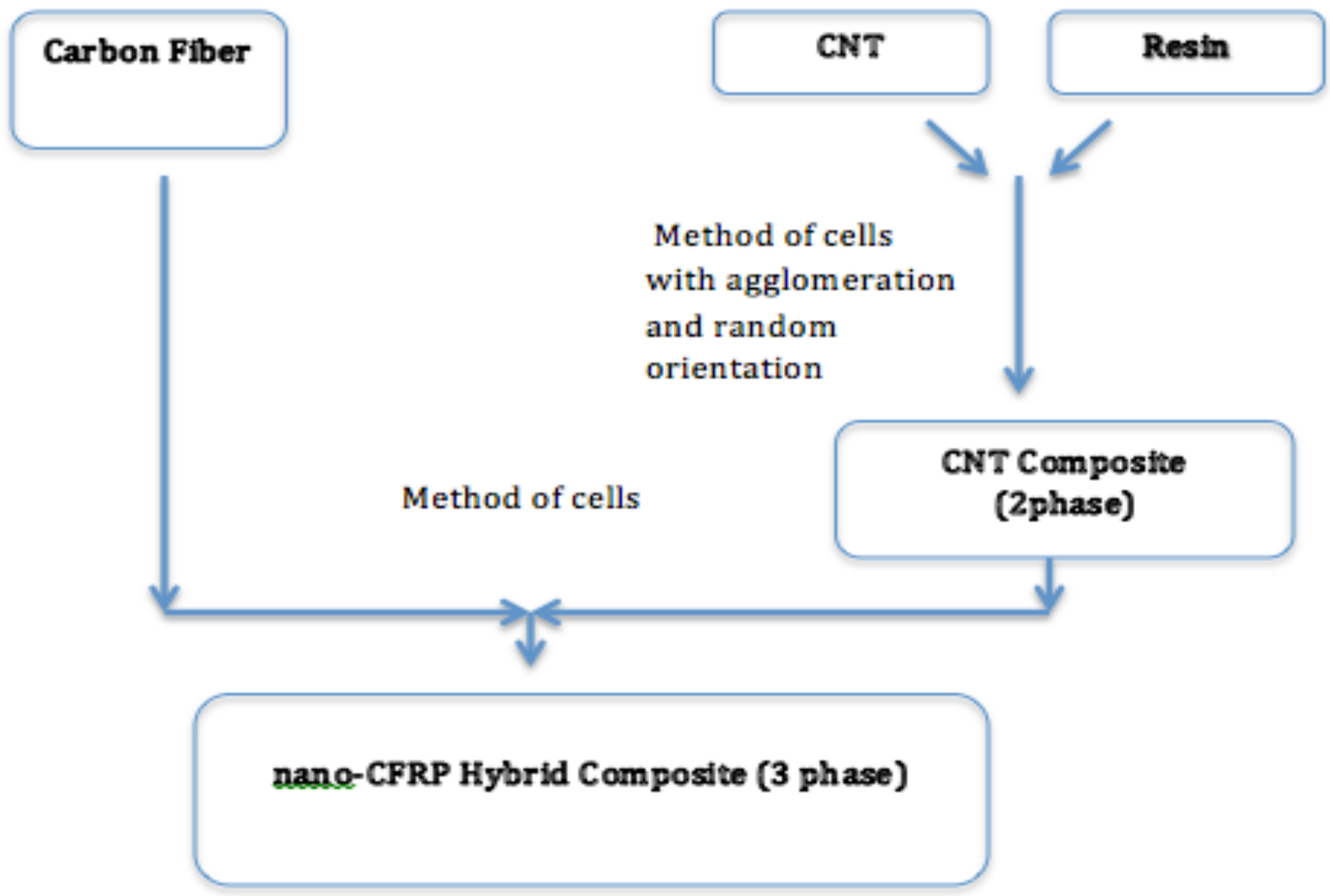



Fig.6 Multistep Homogenization Scheme

# Algorithm

<u>Step1</u>: Compute elastic moduli for composite with random nano fiber as inclusions using MOC-3D.

<u>Step2</u>: Compute elastic moduli for composite with agglomerated random nano fiber as inclusions using MOC-3D with agglomeration model.

<u>Step3</u>: Compute elastic moduli for composite with matrix properties from step1 and fiber properties from step-2 using MOC-3D .

#The resulting effective moduli are taken as Matrix properties in the last step.

<u>Step4</u>: Compute elastic moduli of composite with CFRP fiber system .

#The resulting effective moduli are taken as Fiber properties in last step.

<u>Step5</u>: Compute effective properties of nano-CFRP hybrid composite with Matrix properties form step3 and fiber properties form step-4

# Validation-1

Material properties of Epoxy/Carbon Fiber System:

- *Epoxy properties:*

$E_m$=3.0 GPa, $\upsilon_m$=0.3

- *Carbon Fiber properties:*

$E_a$=230 GPa, $E_t$=8 GPa, $\upsilon$ =0.256, G=27.3 GPa $V_f$ =.502

- **Results:**

**$E_{MOC\text{-}Hybrid}$ = 116.96 (longitudenal modulus)**

**$E_{MOC\text{-}Hybrid}$ = 7.28 (transverse modulus)**

**$E_{Exp\ (L)}$ = 117**

**$E_{Exp\ (T)}$ = 7.02 (deviation=3.71 %)**

# Validation-2

Material properties of Epoxy/CNT:

- ***Epoxy properties:***

$E_m$=2.59 GPa, $\upsilon_m$=0.3  ρ=1200kg/m3

***CNT properties:***

- ***Swcnt:***

$E_{cnt}$=1000 GPa, length of CNT (l)= 30μm, diameter of CNT (d)=  2 nm, $\upsilon_f$=0.33
ρ=2100kg/m3 wt%=.1

- ***Dwcnt***:

$E_{cnt}$=1000 GPa, length of CNT (l)= 30μm, diameter of CNT (d)=  2.8nm, $\upsilon_f$=0.33
ρ=2100kg/m3 wt%=.3

- ***Mwcnt***:

$E_{cnt}$=1000 GPa, length of CNT (l)= 50μm, diameter of CNT (d)=  15nm, $\upsilon_f$=0.33
ρ=2100kg/m3 wt%=.3

# Validation-2

**Results**:

- <u>Swcnt:</u>

$\mathbf{E_{MOC\text{-}Hybrid} = 2.763}$

$\mathbf{E_{exp} = 2.691}$ **(deviation= 2.67 %)**

- <u>Dwcnt:</u>

$\mathbf{E_{MOC\text{-}Hybrid} = 3.099}$

$\mathbf{E_{exp} = 2.885}$ **(deviation= 7.417%)**

- <u>Mwcnt:</u>

$\mathbf{E_{MOC\text{-}Hybrid} = 2.844}$

$\mathbf{E_{exp} = 2.765}$ **(deviation= 2.80%)**

# Validation-3

- Material properties of Epoxy/CNT/Carbon Fiber System:

Epoxy properties:

$E_m$=3.0 GPa, $\upsilon_m$=0.3

CNT properties:

$E_{cnt}$=1000 GPa, length of CNT (l)= 100 nm, diameter of CNT (d)= 10 nm, $\upsilon_f$=0.3

Carbon Fiber properties:

$E_a$=294 GPa, $E_t$=18.5 GPa, $\upsilon_a$=0.27, $\upsilon_t$=0.3, G=25 GPa

Results:

**$E_{MOC\text{-}Hybrid}$ = 8.29 (Transverse modulus)**

**$E_{Exp}$ = 10.02**

# Validation-4

Material properties of Epoxy/CNT/Carbon Fiber System:

- *Epoxy properties:*

$E_m$=2.72.0 GPa, $\upsilon_m$=0.33

*CNT properties:*

- *Swcnt:*

$E_{cnt}$=640 GPa, length of CNT (l)= 25μm, diameter of CNT (d)= 1.4nm, $\upsilon_f$=0.3 $\rho$ =1350kg/m3 wt%=.2

- *Mwcnt:*

$E_{cnt}$=400 GPa, length of CNT (l)= 50μm, diameter of CNT (d)= 20nm, $\upsilon_f$=0.3 $\rho$ =1350kg/m3 wt%=.1

- *Carbon Fiber properties:*

$E_a$=294 GPa, $E_t$=18.5 GPa, $\upsilon_a$=0.27, $\upsilon_t$=0.3, G=25 GPa

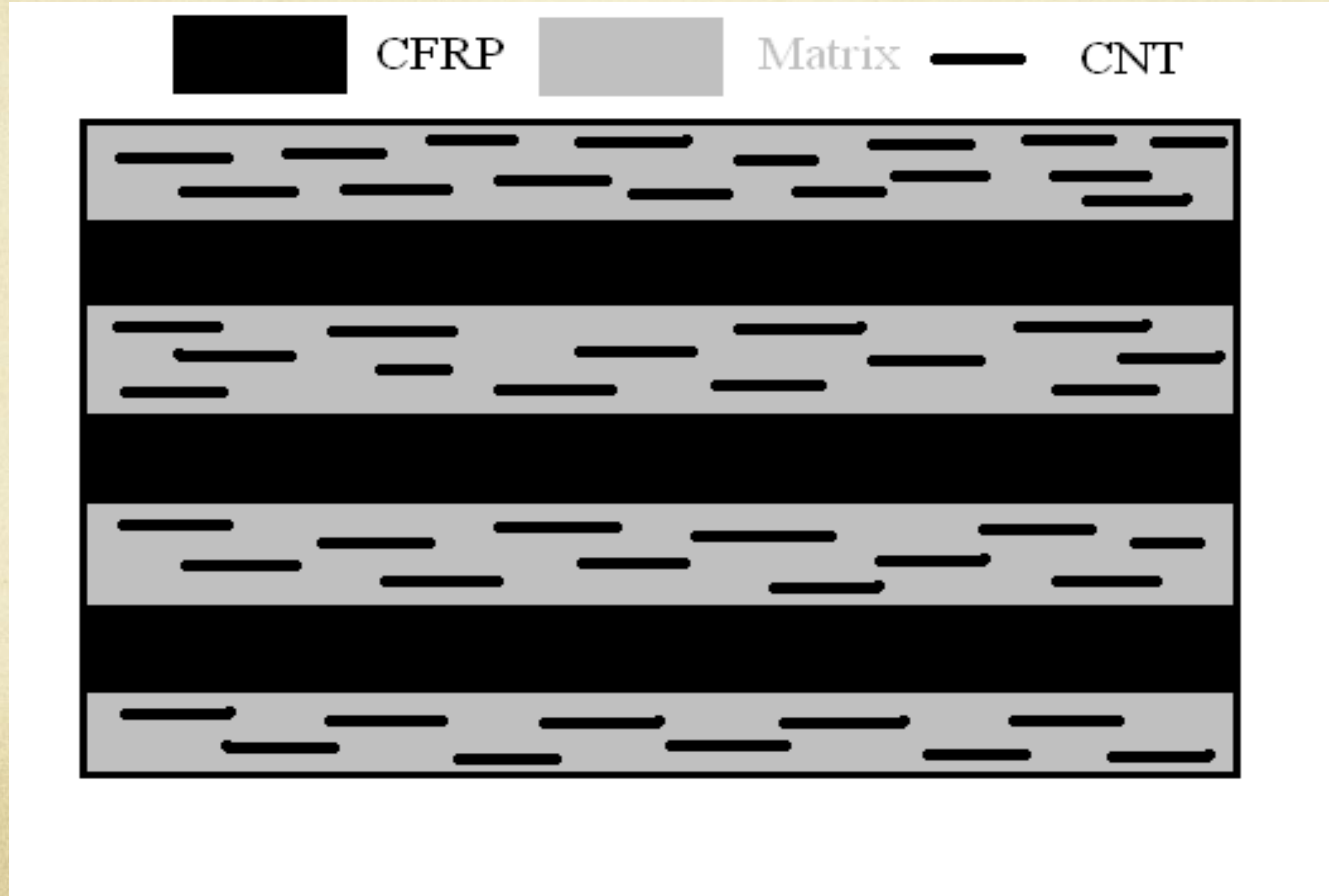
**Results:**

- **$E_{MOC\text{-}Hybrid}$ = 235.81 (Longitudenal modulus)**
- **$E_{th}$ = 221.4 (deviation= 6.50%)**

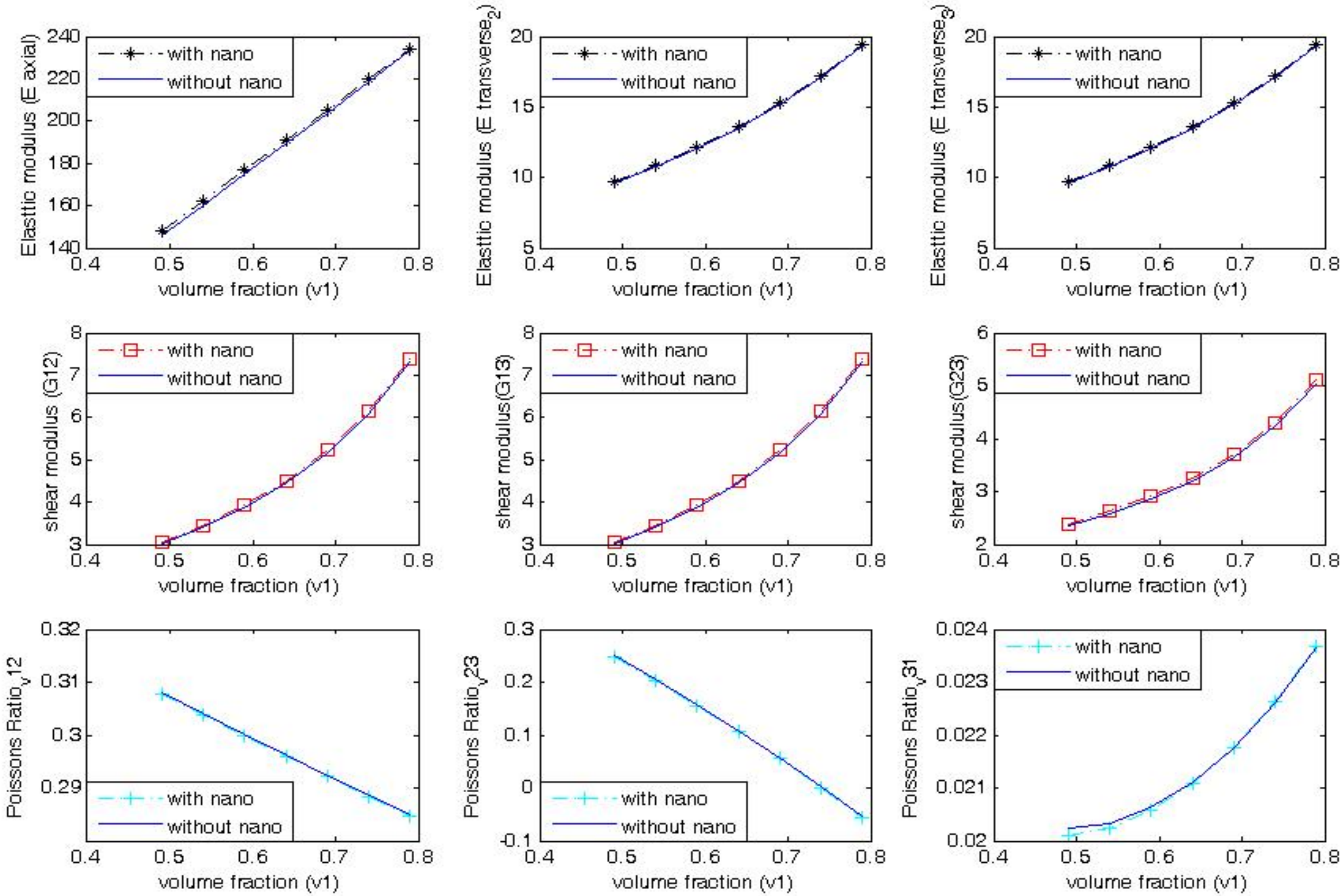
# Conclusions

- Method of cells predicts the in-plane effective properties accurately .
- It shows significant deviation from experimental and FEM values in case of out of plane properties like $E_{33}$ , $G_{23}$ , $v_{13}$ , $v_{23}$ .
- Probable reason for such behavior is the 1st order displacement relations used in MOC.
- Nevertheless for studying the Effective properties of Laminate where only in-plane properties are required , MOC can be used.

**CFRP composites with CNTs aligned in longitudinal direction**



# Elastic constants at wt%=2.0 & Aspect Ratio=1000

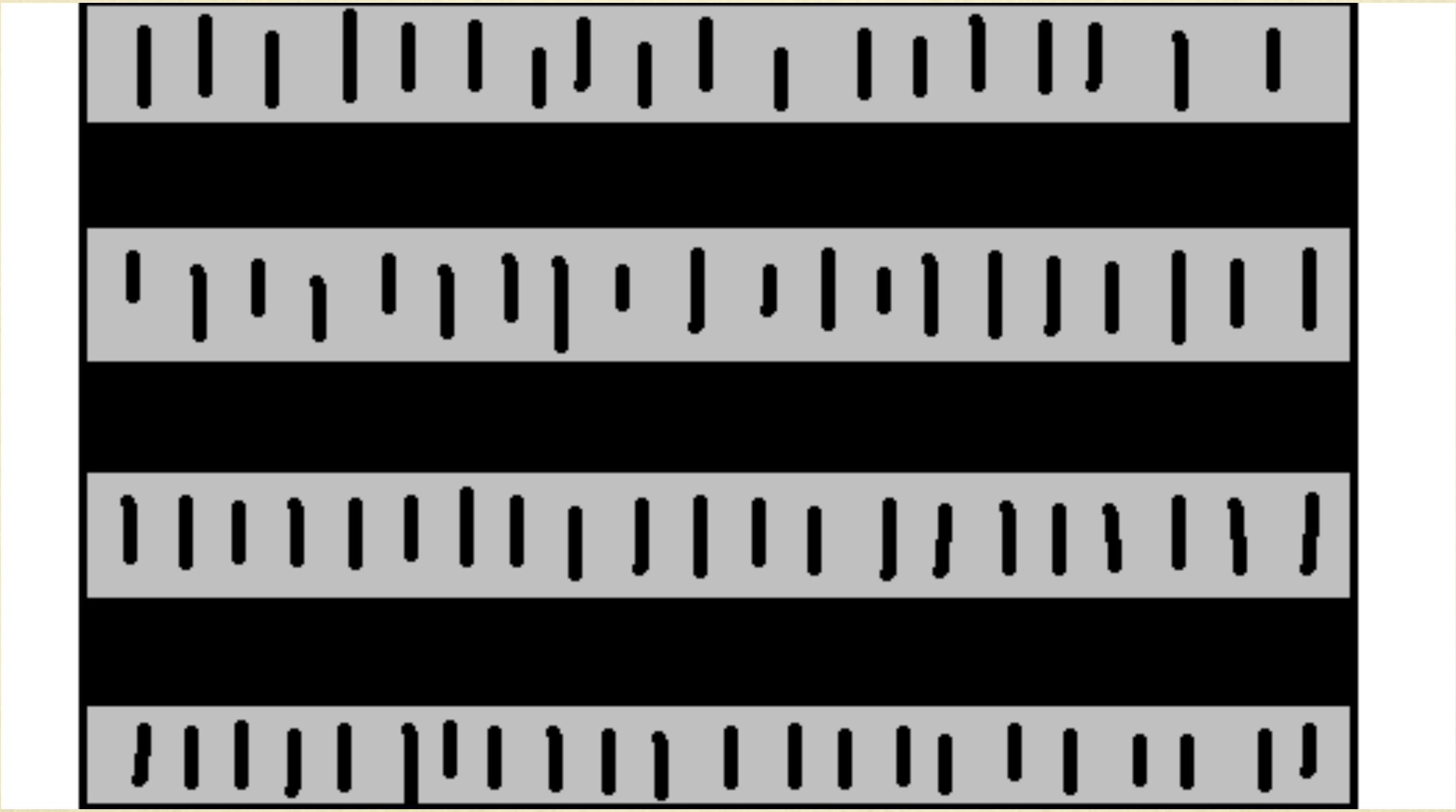


**CFRP composites with CNTs aligned in longitudinal direction**

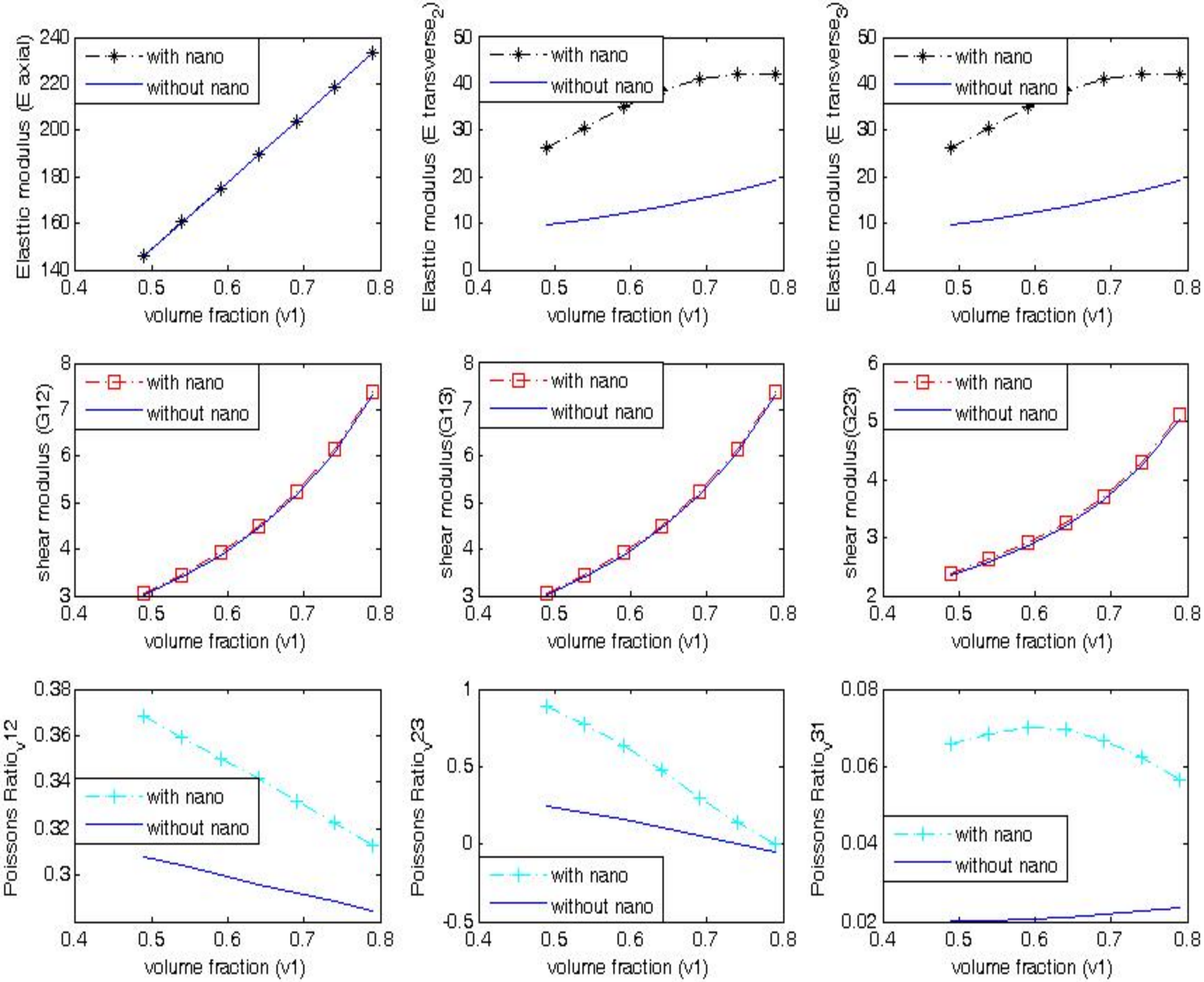
Observations

- With CNTs aligned in longitudinal direction, there is no significant change in elastic constants because the properties are fiber dominated.
- The material is transversely isotropic.

**CFRP composites with CNTs aligned in transverse direction**



# Elastic constants at wt%=2.0 & Aspect Ratio=1000

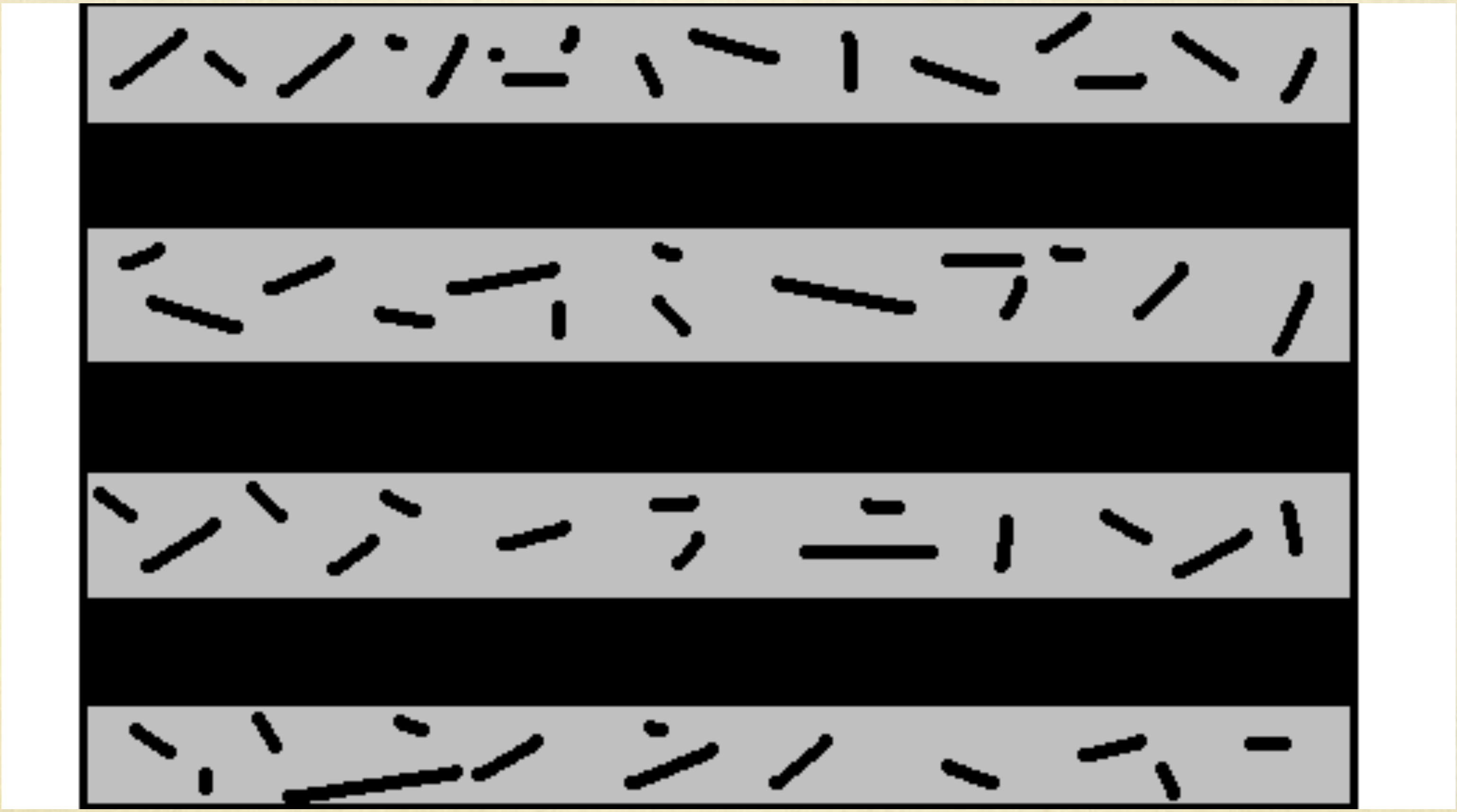


**CFRP composites with CNTs aligned in transverse direction**

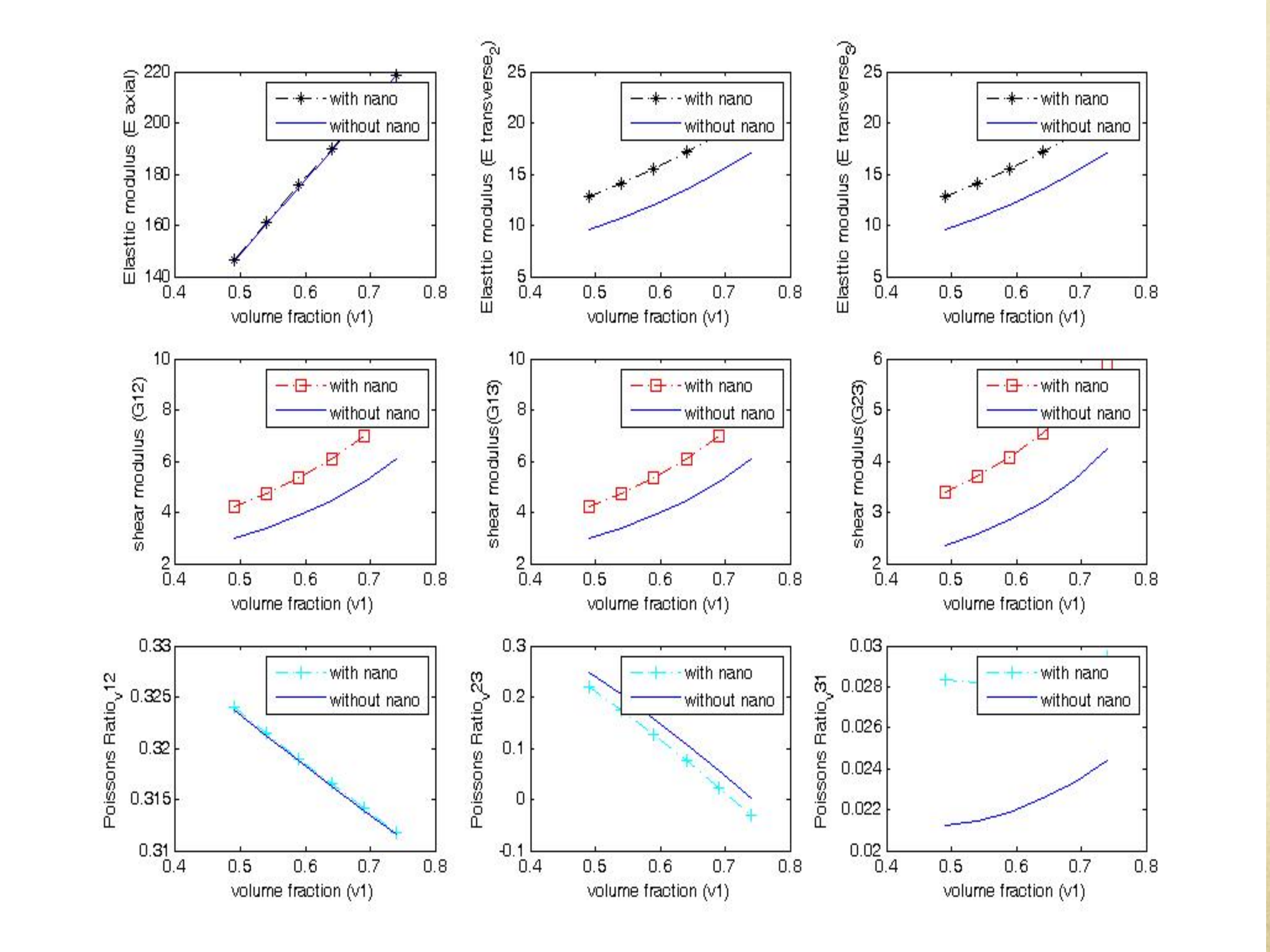
Observations

- With CNTs aligned in transverse direction, there is significant improvement in transverse modulus
- At a particular volume fraction of CF and/or particular weight percentage or aspect ratio of CNT, transverse modulus starts to deteriorate
- The material is transversely isotropic

CFRP composites with CNTs randomly aligned



# Elastic constants at wt%=2.0 & Aspect Ratio=1000



**CFRP composites with CNTs randomly aligned**

Observations

- There is significant increase in transverse and shear modulus with randomly oriented CNT inclusions
- The material is transversely isotropic

# Problem Definition

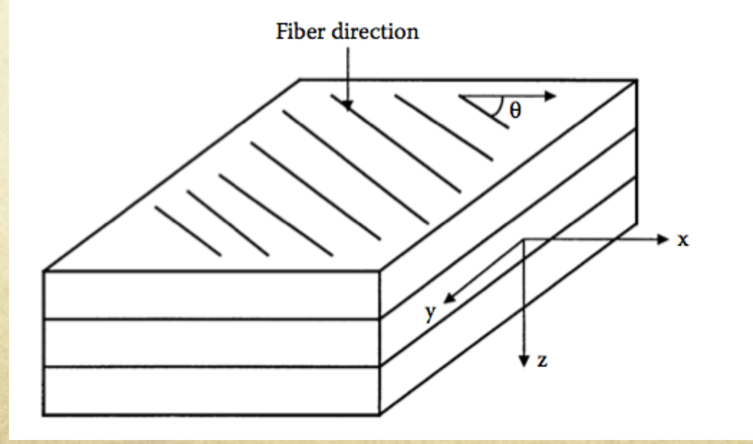
**1.** Develop a constitutive model to predict the composite properties of Hybrid composite system.

**2.** *Find Effective properties of CFRP laminates after nano-inclusion*

**3.** Find the changes in Interlaminar shear stress of CFRP laminates after nano-inclusion

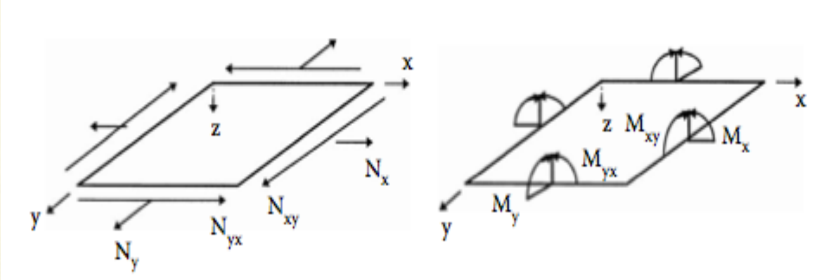
# Need for Laminates

- A real structure will not consist of a single lamina but a laminate consisting of more than one lamina bonded together through their thickness since lamina thicknesses are on the order of 0.125 mm and several laminae will be required to take realistic loads.
- The mechanical properties of a typical unidirectional lamina are severely limited in the transverse direction . This problem can be overcome by making a laminate with layers stacked at different angles .



# Laminate Theory

- In order to calculate the effective moduli of a composite laminate system such as nano-CFRP hybrid laminate, the mechanics of the system needs to be understood.
- For 2-d lamina under axial load and bending load




- ABD matrix

$$\left[\frac{N}{M}\right] = \left[\frac{A}{B} \,\middle|\, \frac{B}{D}\right]\left[\frac{\varepsilon^0}{K}\right]$$

- Only for a special case of symmetric laminate the inplane effective moduli can be calculated, since the coupling matrix vanishes.
-

$$E_x = \frac{1}{hA^*_{11}}$$

$$E_y = \frac{1}{hA^*_{22}}$$

$$G_{xy} = \frac{1}{hA^*_{66}}$$

$$V_{xy} = -\frac{A^*_{12}}{A^{\&*}_{11}}$$

$$V_{yx} = -\frac{A^*_{12}}{A_{22}{}^*}$$

where $\left[A^*\right] = A^{-1}$.

# Simulations

- With an aim of Enhancing Transverse plane properties $E_{22}$ ,$G_{12}$ ,$V_{12}$ combinations of the various parameters like types of inclusions , orientation of lamina , lamina order were carried out

- Orientation 1: (ort-1)

  *Top lamina*: angle =(0:5:90)

  *Middle lamina*: angle=0

  *Bottom lamina*: angle=(0:5:90)

- Orientation 2: (ort-2)

  *Top lamina:* angle =0

  *Middle lamina:* angle=(0:5:90)

  *Bottom lamina:* angle=0

- Type of Lamina

  CFRP with longitudinally aligned cnt

  CFRP with transversely aligned cnt

  CFRP with Randomly oriented cnt

- Example : Laminate [1 2 1]

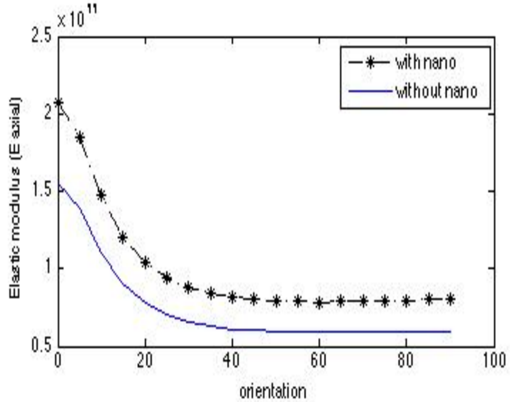
  Top lamina= CFRP with longitudinally aligned cnt

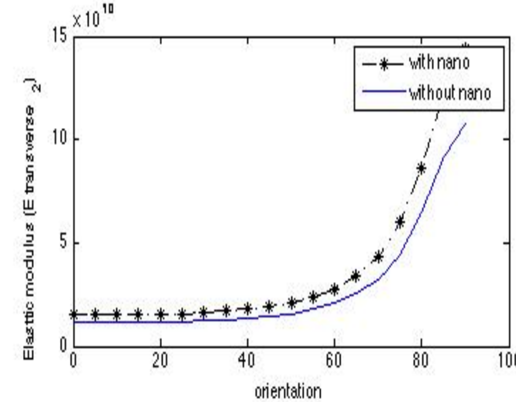
  Middle lamina= CFRP with transversely aligned cnt

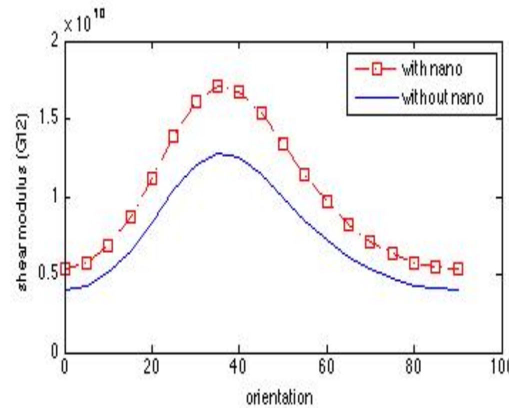
  Bottom lamina= CFRP with Randomly oriented cnt

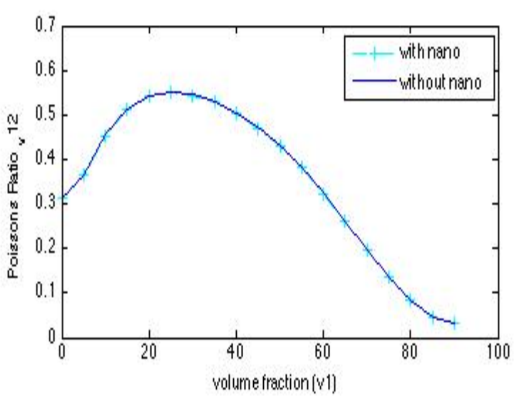
- Simulations were performed for all possible 9 cases(symmetric) ie.,

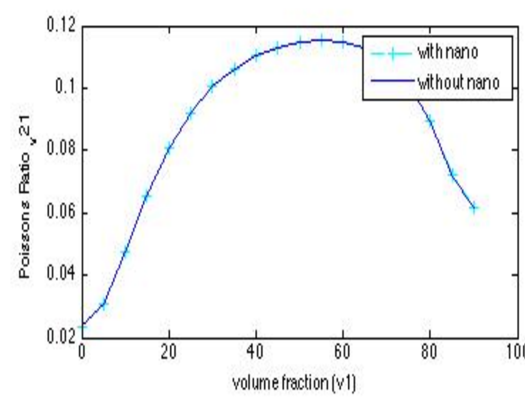
  [1 1 1] [2 2 2] [3 3 3]
  [1 2 1] [1 3 1] [2 1 2]
  [2 3 2] [3 1 3] [3 2 3]


x 10^11
with nano
without nano
Elastic modulus (E axial)
orientation


x 10^10
with nano
without nano
Elastic modulus (E transverse 2)
orientation


x 10^10
with nano
without nano
shear modulus (G12)
orientation


with nano
without nano
Poissons Ratio v 12
volume fraction (v1)


with nano
without nano
Poissons Ratio v 21
volume fraction (v1)

# Conclusions

- Maximum value of young’s modulus occurs at 35deg in contrast to 45deg for isotropic plies. This can be explained because of the transversely isotropic Nature of Long fibers in the composite.
- If improvement only in $E_{22}$ is desired 222-o2(38% improvement) is best scenario.
- If improvement only in $G_{12}$ is desired 222-o1(17% improvement) is best scenario.
- If improvement in both $E_{22}$ and $G_{12}$ is desired 222-o1(33%,17% improvement) is best scenario.

# Problem Definition

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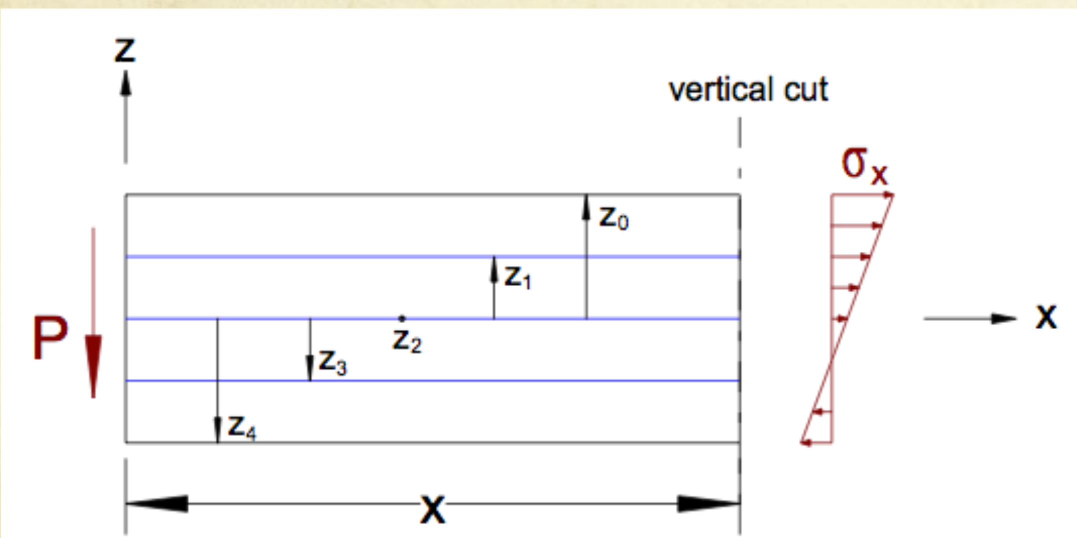
**3.** *Find the changes in Interlaminar shear stress of CFRP laminates after nano-inclusion*

# Need to study Interlaminar shear

- A commonly observed failure mode in laminated composite materials is the delamination between the composite layers which is a result from the interlaminar stresses created by impact/load.
- ILLS distributions are needed to enable design and sizing of laminates subjected to global shear loads.
- Lamination theory:-
  >Inplane stress distribution in each layer of a laminate from the knowledge of the applied force and moment resultants.
  >ply-by-ply magins can be determined
  >Cannot predict ILSS
- Higher-order plate theories provide piece-wise profiles that are discontinuous at the ply interfaces.

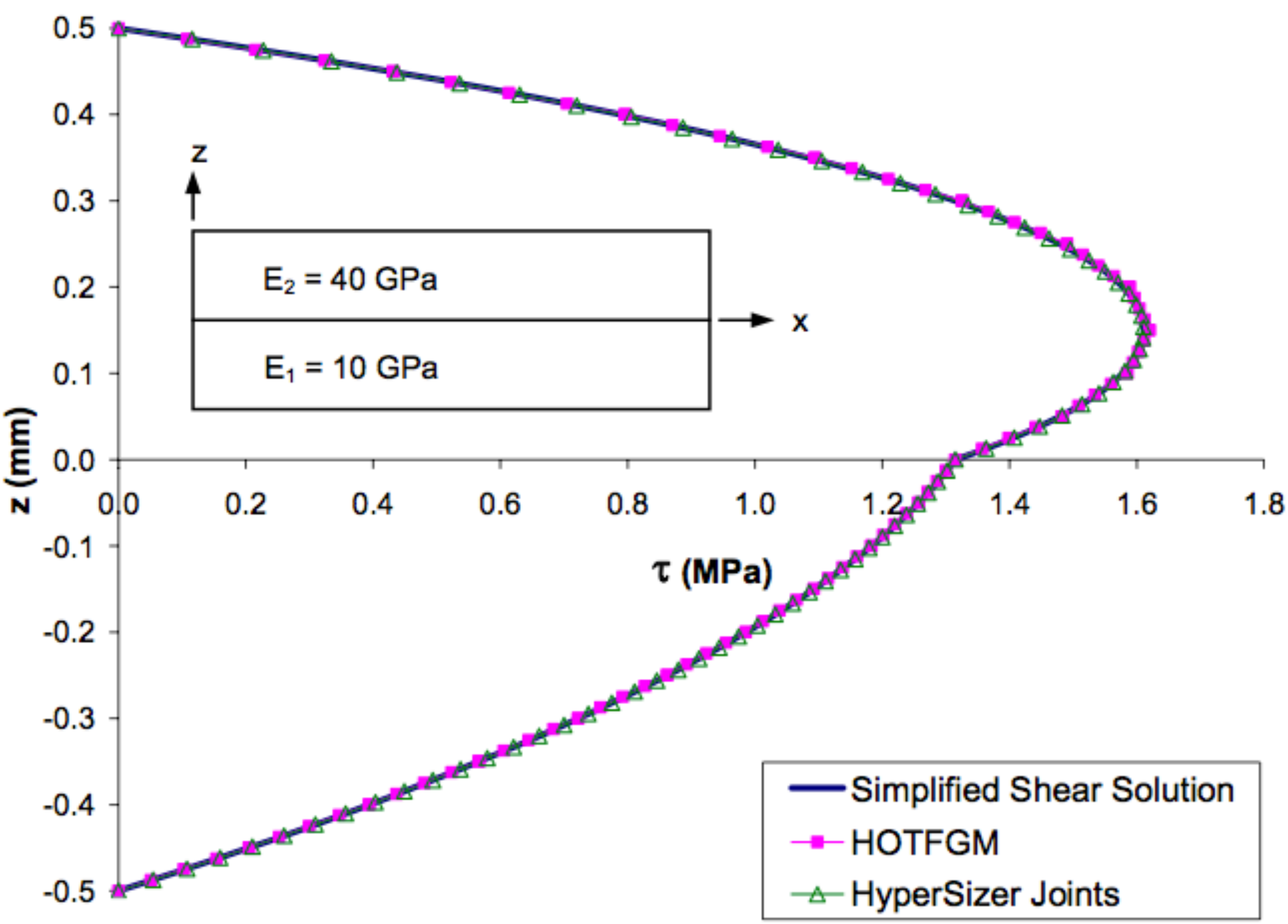
# Modeling ILSS
# Simplified Shear Model

A analytical method  based on laminated beam theory with shear loading, for determining the interlaminar shear stress distribution in a laminate from a given applied shear resultant

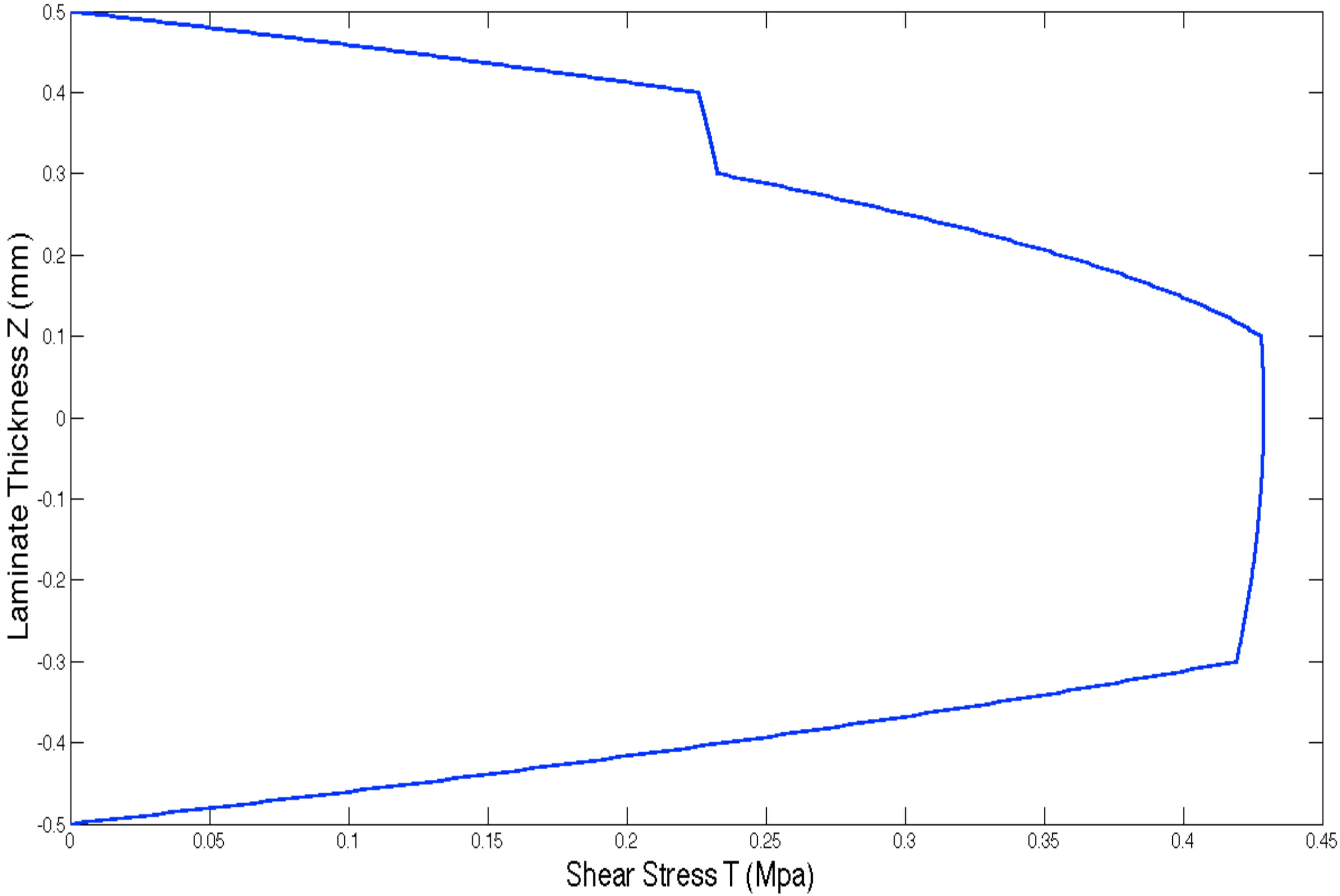



$$\tau(k,\hat{Z}) = -\frac{Q}{I}Q'(k,\hat{z})$$

# Validations



# Validations



# Damage Tolerant laminates

- Engineering Design optimizes the thickness, ply orientations for study of deflection, frequency and failure criteria .
- To enhance mechanical properties of a laminate system and to meet design requirements , parameters like thickness  number of lamina and orientation of plies are manipulated.
- A Novel method is introduced to enhance the ILSS thus making them damage tolerant by reinforcing CFRP plies with Cnts without increasing number of layers or thickness of plies

# Simulations

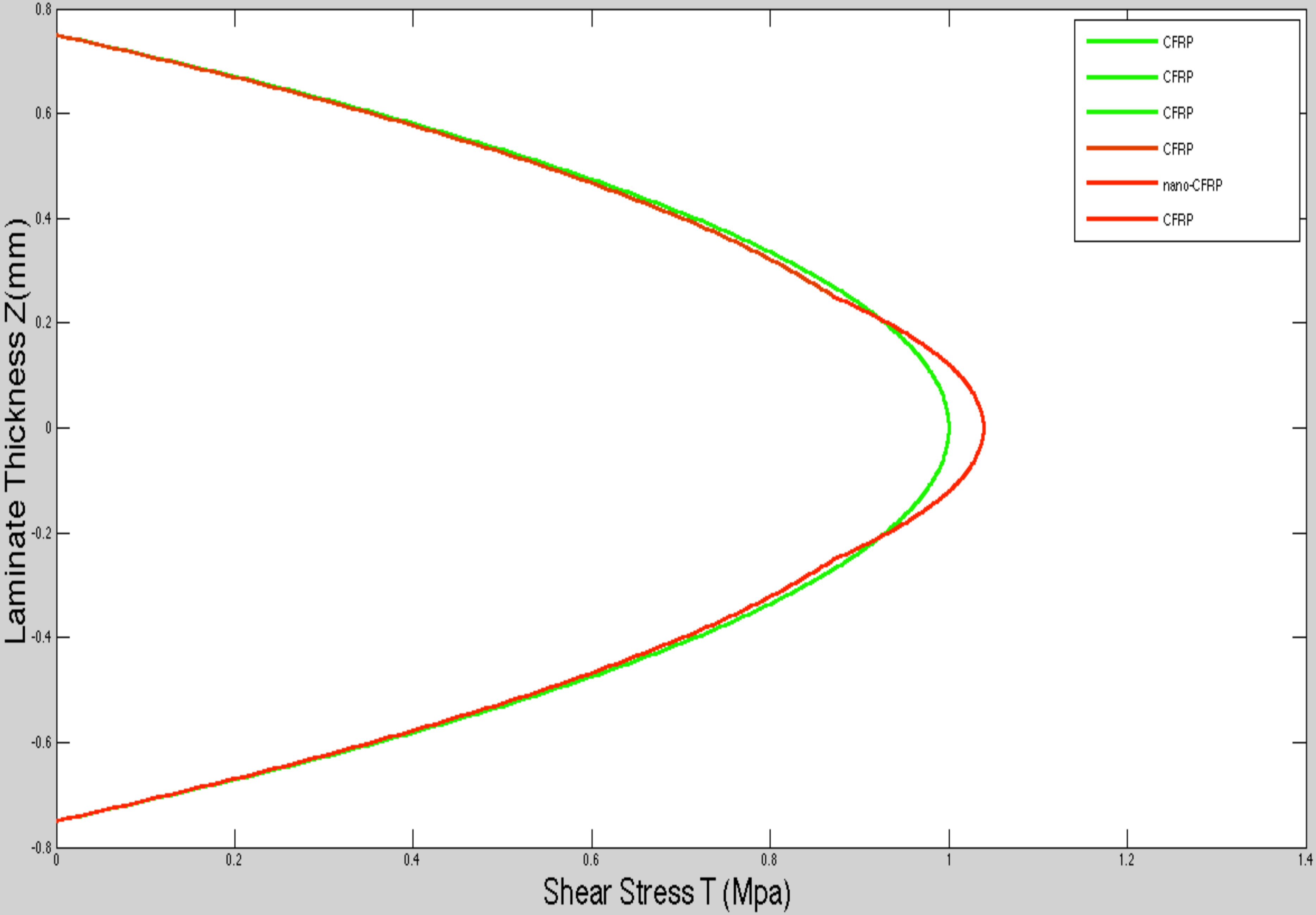
- Number of lamina =3
- Thickness of lamina = .5 mm each
- Wt% =1& 2% of cnt inclusion in each lamina
- Lamina Orientation (combinations of 0,45,90 deg orientations)

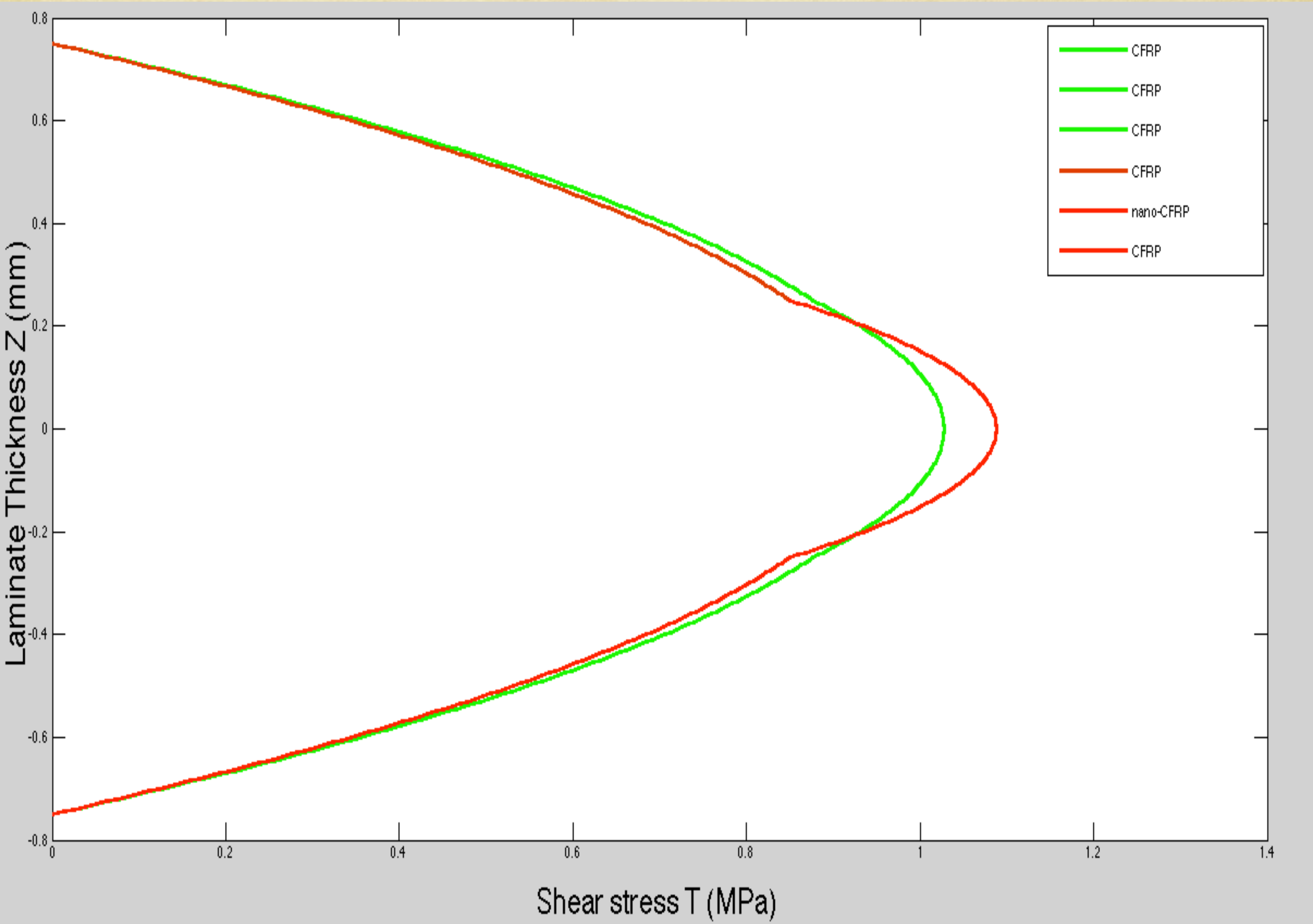
  [0 0 0 ]  [0 45 0] [45 0 45 ] [45 90 45 ] [90 45 90] [90 0 90] [0 90 0]
  [45 45 45] [90 90 90]

- Order of Lamina in Laminate

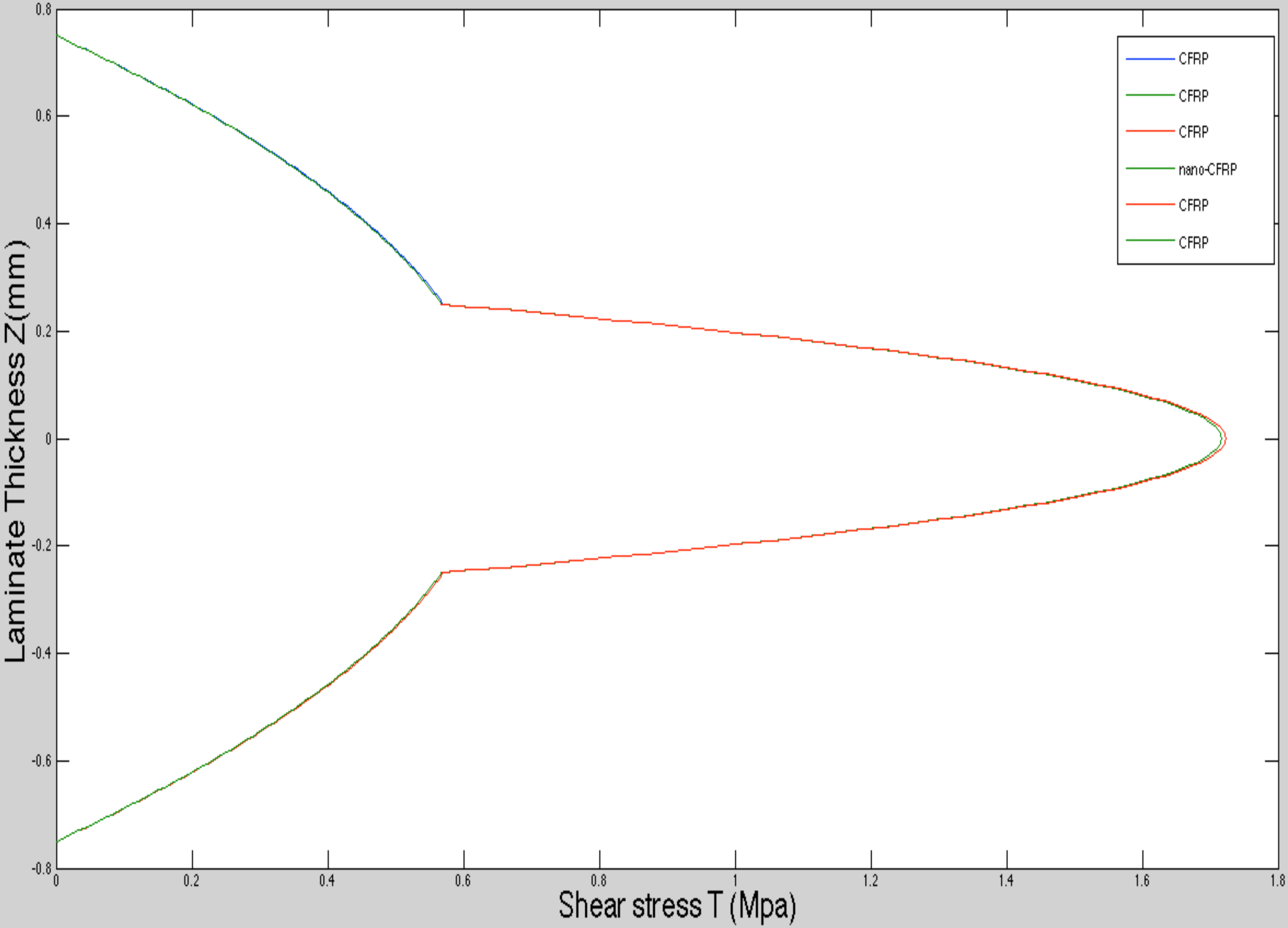
  [cfrp nano-cfrp cfrp]
  [nano-cfrp cfrp nano- cfrp]
  [nano-cfrp nano-cfrp nano-cfrp]

- Load applied is 1Mpa in Y-direction.


CFRP
CFRP
CFRP
CFRP
nano-CFRP
CFRP
Laminate Thickness Z(mm)
Shear Stress T (Mpa)
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
0
0.2
0.4
0.6
0.8
1
1.2
1.4



CFRP
CFRP
CFRP
CFRP
nano-CFRP
CFRP
Laminate Thickness Z (mm)
Shear stress T (MPa)
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
0
0.2
0.4
0.6
0.8
1
1.2
1.4


CFRP
CFRP
CFRP
nano-CFRP
CFRP
CFRP
Laminate Thickness Z(mm)
Shear stress T (Mpa)
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8

| orientation | Reference | | | Laminate : [cfrp,nano-cfrp,cfrp] | | |
|---|---|---|---|---|---|---|
| | Max.lyr-1 | Max.lyr-2 | Max.lyr-3 | Max.lyr-1 | Max.lyr-2 | Max.lyr-3 |
| [0,0,0] | .8889 | 1 | .8889 | .8534 (-3.99) | 1.0796 (7.96) | .8534 (-3.99) |
| [0,45,0] | .8766 | 1.0276 | .8766 | .8314 (-5.15) | 1.1293 (9.89) | .8314 (-5.15) |
| [45,0,45] | .8980 | .9795 | .8980 | .8715 (-2.95) | 1.0391 (6.08) | .8715 (-2.95) |
| [0,90,0] | .5705 | 1.7165 | .5705 | .5633 (-1.26) | 1.7324 (.92) | .5633 (-1.26) |

Table 8: Layer wise Maximum ILSS-$T_{yz}$ values before and after nano inclusion of [cfrp, nano-cfrp, cfrp] system. % Difference is indicated in braces.

Wt.% of cnt=2

| orientation | Reference | | | Laminate : [nano-cfrp ,cfrp,nano-cfrp] | | |
|---|---|---|---|---|---|---|
| | Max.lyr-1 | Max.lyr-2 | Max.lyr-3 | Max.lyr-1 | Max.lyr-2 | Max.lyr-3 |
| [0,0,0] | .8889 | 1 | .8889 | .90633 (1.96) | .9600 (-4) | .90633 (1.96) |
| [0,45,0] | .8766 | 1.0276 | .8766 | .9005 (2.72) | .9735 (-5.26) | .9005 (2.72) |
| [45,0,45] | .8980 | .9795 | .8980 | .9108 (1.42) | .9505 (-2.96) | .9108 (1.42) |
| [0,90,0] | .5705 | 1.7165 | .5705 | .7146 (25.25) | 1.392 (-18.90) | .7146 (25.25) |

Layer wise Maximum ILSS-$T_{yz}$ values before and after nano inclusion of [nano-cfrp, cfrp, nano-cfrp] system. % Difference is indicated in braces. Wt.% of cnt=2

| orientation | Reference | | | [nano-cfrp , nano-cfrp,nano-cfrp] | | |
|---|---|---|---|---|---|---|
| | Max.lyr-1 | Max.lyr-2 | Max.lyr-3 | Max.lyr-1 | Max.lyr-2 | Max.lyr-3 |
| [0,0,0] | .8889 | 1 | .8889 | .8889 (0) | 1 (0) | .8889 (0) |
| [0,45,0] | .8766 | 1.0276 | .8766 | .8774 (.09) | 1.0258 (-.17) | .8774 (.09) |
| [45,0,45] | .8980 | .9795 | .8980 | .8975 (-.05) | .9804 (.09) | .8975 (-.05) |
| [0,90,0] | .5705 | 1.7165 | .5705 | .7049 (23.55) | 1.403 (-18.26) | .7049 (23.55) |

Layer wise Maximum ILSS-$T_{yz}$ values before and after nano inclusion of [nano-cfrp, nano-cfrp, nano-cfrp] system. % Difference is indicated in braces. Wt.% of cnt=2

# Conclusions

- Its better to have same lamina orientation in all layers to have better load taking capability ( shear load) when compared to laminates with different ply orientations.

- when all layers are of cfrp or nano-cfrp or in short the youngs modulus E value issame for all layers ,the maximum value of ILSS obtained (.8889,1,.8889) are the upper limits of load the layers can handle. (given applied unit load).

- Even when all the layers are reinforced with cnts, ILSS of all layers is not improved .
  Thus it can be concluded that there is no use of reinforcing all layers with cnts , rather focusing on Top ,bottom and middle layers individually according to requirement of design is optimal.

- Adding cnts to cfrp lamina brings significant increase in ILSS
 1.) Unidirectional plies: 4% and 8% increase with 1% and 2% cnt addition respectively
 2.) Cross plies: upto 15% increase with 1% cnt and 25% increase with 2% addition respectively

# Summary

- A novel Multiscale micro mechanics model has been developed based on method of cells .
- Simulations have been carried out to study the effect of various reinforcement parameters such as orientation, aspect ratio, weight percentages and volume fraction of CFRP on the Elastic properties.
- Effective mechanical properties of a Laminate system were predicted using Laminate theory
- The interlaminar shear stresses in laminates were calculated using a Simplified shear model
- A Novel method was introduced to enhance the interlaminar shear stress without modifying the laminate parameters like thickness, number of layers and orientation of plies

# Acknowledgements

- I would like to thank **Dr.S. Raja**, Senior Principal Scientist & Group Head Dynamics and adaptive structures for letting me use the Aeroelasticity and smart structures lab.

- I would like to thank my PS instructor **Dr. Rakesh Mohan Jha**, Scientist G, CEM for his guidance and allotment of projects.

- I would also like to express my thanks to **Mr. Abhinav Alva, Mr. Dwarakanathan** and **Mr.Karthikeyan** and all STTD staff for their support and for helping me to carry out the project to the best of my abilities.