

A
Thesis Report
On

**Investigation of Elastic Properties of CNT Reinforced Multi-scale
Composites and Comparative Study of Different Models to Evaluate
Properties**

*Submitted in partial fulfillment of the requirement for the award of the
degree of*

Master of Engineering

IN

PRODUCTION & INDUSTRIAL ENGINEERING

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ACKNOWLEDGEMENT

I am highly grateful to the authorities of Thapar University, Patiala for providing this opportunity to carry out the thesis work.

It is a great pleasure to express my great sincere gratitude and profound regards to **Mr. Gagandeep Bhardwaj**, Lecturer and **Mr. Lalit Kumar** Lecturer in Mechanical Engineering Department, Thapar University, Patiala for their constant encouragement, invaluable guidance and help during the course of the work. They have not only taught, guided like a parent, but criticized in making mistakes with sensible thoughts and conversations, which enabled me to stand up to the mark i.e. towards perfection. I am sure that no other person can do what they have done for me. Words are inadequate to acknowledge the great care and keen interest taken by him in all aspect of the present work. My association with them throughout the thesis activity was a great process of learning.

Gratitude is also expressed to **Prof. Ajay Batish**, Head of Mechanical Engineering Department for providing facility and advice needed to complete the work.

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Abstract

Carbon nanotubes have a high potential to improve the mechanical, physical and electrical properties of polymers. The objective of the present work is to evaluate the elastic Properties of CNT Reinforced Multi-Scale composites considering the effect of CNT % and aspect Ratio and the comparative study of different models to evaluate the elastic properties. The Halpin T-sai Model, Modified Series Model and Mori-Tanaka Model are used to evaluate elastic properties of multi-scale composites. Firstly, CNT dispersed in an isotropic manner into the matrix and the improved elastic properties of polymer matrix are obtained by using the different Models (Halpin-Tsai Model, Modified Series Model and Mori-Tanaka Method). Then, CNT reinforced Polymer matrix treated as a new matrix and E-Glass fibers are reinforced in an orthotropic manner into the matrix. Micromechanics approach is used to determine the Mechanical Properties of Multi-scale composite. The effect of SWCNT (Single-Walled carbon Nanotube), MWCNT (Multi-Walled carbon Nanotube) and the proportions of SWCNT/MWCNT on the elastic Properties of Multi-Scale Composites is also investigated.

Abbreviations

CNT	Carbon Nanotube
SWCNT	Single Walled Carbon Nanotubes
MWCNT	Multiwalled Carbon Nanotubes
CVD	Chemical Vapour Deposition
OOF	Object Oriented Finite
AR	Aspect Ratio
HDPE	High Density Polyethylene

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CHAPTER 1

Introduction

1.1 Carbon Nanotubes:

The field of Nano science has blossomed over the last twenty years, and the importance for nanotechnology will increase as miniaturization becomes more important in areas such as computing, sensors, biomedical and many other applications. Advancement in these disciplines depends largely on the ability to synthesize nanoparticles of various materials, sizes and shapes as well as assemble them efficiently into complex architectures . The discovery of polymer nanocomposite by the Toyota research group has opened a new dimension in the field of materials science. In particular, the use of inorganic nanomaterials as a filler in the preparation of polymer/inorganic composites have attracted increasing interest owing to their unique properties and numerous potential applications in the automotive, aerospace, construction and electronic industries [34]. The only drawback of CNTs as nanofiller is their higher production cost . Therefore the mass production of CNT based composite materials is very difficult [6].

The Japanese scientist Sumio Iijima discovered fullerene- related carbon nanotubes in 1991 [18]. CNTs are allotropes of carbon, Graphene is the basic structural unit of some carbon allotropes, including graphite, carbon nanotubes and fullerenes. It is believed to be composed of benzene rings stripped of their hydrogen atoms. The rolling up of a graphene along a given direction can produce a carbon nanotube. A zero dimensional fullerene can be obtained by wrapping up graphene. Graphene is considered to be two dimensional carbon nanofiller with a one atom thick planner sheet of sp^2 bonded carbon atoms that are densely packed in honeycomb crystal lattice. It is regarded as “thinnest material in the universe” with tremendous application potential. A single wall CNT is a one atom thick sheet of graphite (called graphene) rolled up in to a seamless cylinder with diameter of the order of a nanometer [34]. Nanotubes are distinguished from other carbon forms by their unique morphology, dimensions and defects. The exceptionally high modulus, electrical

and thermal conductivity and elasticity of planer graphite are all reflected in the inherent properties of nanotubes. These results in nanostructure are the potentially useful in many applications in nanotechnology, electronics, optics and other fields of material science[17]. They exhibit extraordinary strength and unique electrical properties, and are efficient conductor of heat. Inorganic have also been synthesized. Carbon nanotube-infused polyimides are being investigated for a wide range of industrial, micro-electromechanical systems (MEMS), aeronautic, and aerospace applications[33]. Polyimides are a class of polymers that provide enhanced radiation robustness in addition to being lightweight, flexible, and strong. In isolation, carbon nanotubes provide unique mechanical and electrical attributes due to their highly periodic atomic structure. When infused in polyimides, the electromechanical attributes of the nanotubes provide the capability for enhancing the polymer stiffness, providing electrical conductivity in normally non-conductive materials, and providing the capability for both actuation and sensing[34]. As actuators and sensors, nanotube-infused polyimides are lightweight, flexible, and provide broadband input capabilities. Additionally, unique attributes include temperature, chemical, and radiation stability as well as highly controlled mechanical properties. Specific aerospace applications include high strength composites, nanometer-sized semiconductor and superconductor devices, nanowires, reflector/collector inflatable antennas, solar arrays, radiometers, and probes[33] . NASA has invested large sums of money to develop carbon nanotube-based composites for applications such as the Mars mission . The material flexibility enables the spacecraft to withstand the packaging process without breaking[33].

1.2 Types of carbon nanotubes:

1.2.1 Single Walled Carbon Nanotube

1.2.2 Multi Walled Carbon Nanotube

1.2.1 Single Walled Carbon Nanotube:

SWCNTs consist of a single sheet of carbon rolled up into a cylinder and typically have diameter from 0.5-5 nm. Most single-walled Nanotubes (SWCNT) have a diameter of close to 1 nanometer, with a tube length that can be many thousands of time longer [2]. The

structure of a SWCNT can be conceptualized by wrapping a one atom thick layer of graphite sheet called graphene in to a seamless cylinder[33].

Single walled carbon nanotubes are a very important variety of carbon nanotubes because they exhibit important properties that are not shared by the multi walled carbon nanotube variants. Single walled nanotubes possess better properties than multiwalled nanotubes, but the relative simplicity in preparation of multiwalled nanotubes and ease in its isolation and purification makes it more economical for most applications including dispersing in ceramic matrix. MWNT whose modulus is comparable to that of diamond (1.2 TPa), are reported to have strengths 10- 100 times higher than the strongest steel at a fraction of the weight [33]. The schematic arrangement of single walled carbon nanotube is shown in the Fig. 1.1

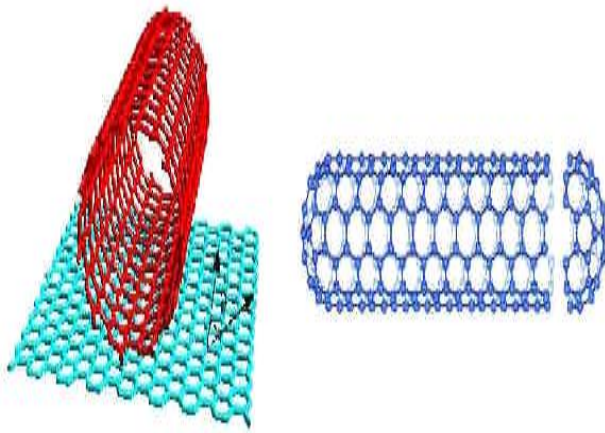


Fig. 1.1: Single Walled Carbon Nanotube (SWCNT)[36]

1.2.2 Multi walled Carbon Nanotubes:

Multi-walled Carbon Nanotubes (MWCNT) consists of a multiple layers of graphite sheet rolled in on themselves to form a tube shape. MWCNTs have an arrangement of coaxial tubes of carbon sheets forming a tube-like structure. Each MWCNT consists of 2-50 of these tubes. Usually MWCNTs have inner diameter of 1.5-15 nm and outer diameters of 2.5-30 nm [2] .The MWCNT can come in an even more complex array of form because each concentric SWCNT have different properties. There are two models which can be used to describe the structure of multi walled carbon nanotubes. The interlayer distance in multi-

walled carbon nanotubes is closed to distance between graphene layers probably if graphite length to diameter ratio exceeds 10,000. Such cylindrical carbon molecules have excellent novel properties [5]. The multi-walled carbon nanotubes with a diametrical range of 5-40 nm are known for their exceptional mechanical properties [32]. Generally Multi-walled nanotube (MWNT) has Young's modulus of 270-950 GPa while a single-walled nanotube (SWNT) has Young's modulus of 1-1.2 TPa [24]. The schematic arrangement of multi walled carbon nanotube is shown in the Fig. 1.2

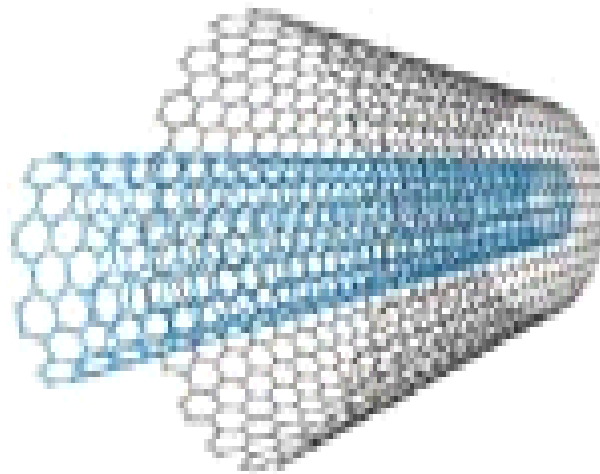


Fig. 1.2(a) Double walled CNT'S [36]

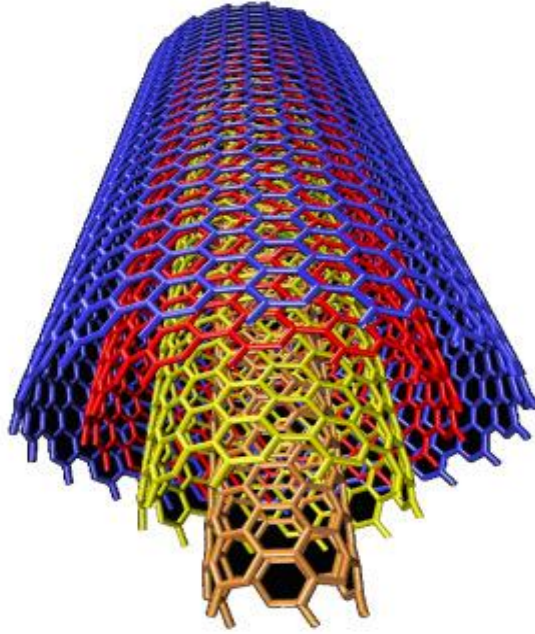


Fig. 1.2 (b) Multi walled CNTs (MWCNT) [33].

1.3 Structure of Carbon Nanotubes:

Depending on structure CNT can be divided into three categories:

1.3.1 Armchair type:

1.3.2 Zig-Zag type:

1.3.3 Chiral type:

A single wall carbon Nanotube can be described as a graphene sheet rolled into a cylindrical shape so that the structure is one-dimensional with axial symmetry and in general exhibiting a spiral conformation called chirality. The cylindrical graphene sheet of most of the observed single wall Nanotubes have diameter < 2 nm. If the two ends of a carbon nanotube are neglected and focus is on the large aspect ratio of the cylinder (i.e., length/diameter that can be as large as 10⁴-10⁵), these Nanotubes can be considered as one dimensional nanostructure [2]. Fig. 1.3 shows a classification of Nanotubes. An important fact about the structure of a carbon nanotube is the orientation of six member carbon rings in the honeycomb lattice relative to the axis of nanotube. The direction of the six- member ring in the honeycomb lattice can be taken almost arbitrarily, without any

distortion of the hexagons except for the distortion due to the curvature of the carbon nanotube [33]. This fact provides many possible structures for carbon nanotubes, even though the basic shape of the carbon nanotube wall is a cylinder. Additionally, CNTs can be classified into Single wall CNTs (SWCNT) and Multi Wall CNTs (MWCNTs). Another structural aspect of CNTs is their ability to self-organize themselves into ropes. These ropes consist of many tubes (typically 10-100) running together along their length [2].

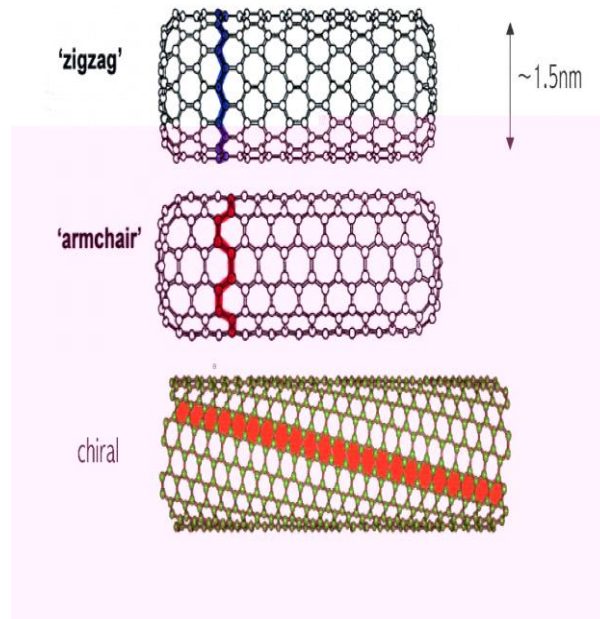


Fig. 1.3 Structure of CNT's[36]

1.4 Geometric Characteristic of CNT:

Carbon nanotubes (CNTs) are cylindrical macromolecules consisting of carbon atoms in a periodic hexagonal structure. This atomic structure imbues them with unique mechanical, physical, chemical, and electronic properties. Advantageous mechanical properties include exceptionally high longitudinal stiffness, strength, and resilience. Their high aspect ratio and low density allows CNTs to be flexible and are ideal for reinforcing fibers in nanocomposites. Other advantage of CNTs are their response to electromagnetic radiation over a broad range of frequencies and conductivity properties. The metallic nature of CNTs dissipates energy that would otherwise build up on nonconducting surfaces. CNTs may also

be embedded into polymers to gain active properties. By applying a field, the CNTs align changing the stiffness of the composite. A single nanotube can be viewed as a rolled one atom-thick sheet of hexagonal bonded carbon densely packed in a crystal lattice; i.e. graphene. Starting from a graphene sheet, two lattice vectors a_1 and a_2 ... are defined to determine the chiral vector [2]

$$C_h = na_1 + ma_2$$

where n and m are integers and generally $n > m$ as shown in Figure . If $n-m$ is divisible by three, the nanotube is considered metallic; otherwise, the nanotube is semiconducting. Special cases include armchair, (n,m) , and zigzag, $(n,0)$ configurations; otherwise, nanotubes are said to have chiral configurations as shown in Figure 1.4. In armchair configurations, the hexagonal carbon rings are aligned along the length and radially. In zigzag configurations, the carbon rings are aligned radially but not along the length. The carbon rings are not aligned along the length or radially for chiral configurations.

The nanotube diameter and chiral angle are obtained by using the following relations:

$$D = \frac{a_{C-C} \sqrt{3(n^2 + nm + m^2)}}{\pi} \quad (1.1)$$

$$\tan \theta = \frac{\sqrt{3}m}{2n + m} \quad (1.2)$$

Where n, m is integers used to represent the CNT geometry explained in the Fig. where $\theta = 0$ corresponds to zigzag, $\theta = 30$ corresponds to armchair, and $0 < \theta < 30$ corresponds to a chiral configuration [2].

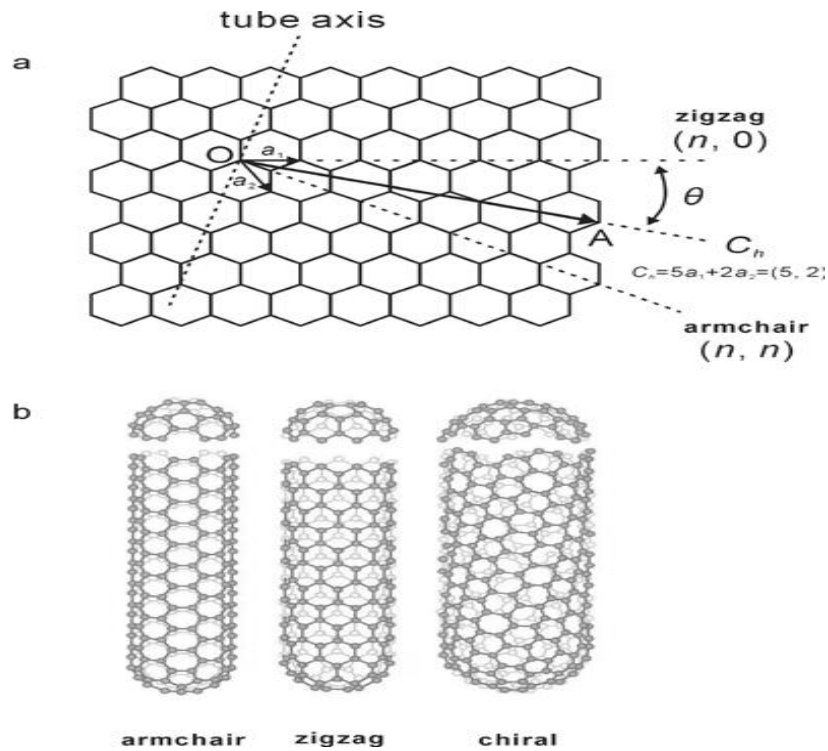


Fig. 1.4 Classification of CNT's Structure[36]

1.5 Properties of CNT [3]

1. High Electrical Conductivity
2. Very High Tensile Strength
3. Highly Flexible- can be bent considerably without damage
4. High Resilience
5. Very Elastic ~18% elongation to failure
6. High Thermal Conductivity
7. Low Thermal Expansion Coefficient
8. Good Field Emission of Electrons
9. Highly Absorbent
10. High Aspect Ratio (length = ~1000 x diameter)

1.6 Mechanical Properties of CNT:

The structural properties of CNTs with strong bonds between the carbon atoms give nanotube a very high Young's modulus and tensile strength. The strength of the carbon-carbon bonds in-plane, along the cylinder axis, retains the structure exceptionally strong resistance to carry failure. CNTs also have very good elasto-mechanical properties. The two dimensional (2D) arrangement of the carbon atoms in a graphene sheet permits a large out-of-plane distortion. The mechanical properties are strongly dependent on the structure of the nanotubes. This is due to the high anisotropy of graphite [2].

The mechanical properties of a solid must ultimately depend on the strength of its interatomic bonds. With knowledge of known properties of crystal graphite the mechanical properties of carbon nanotubes can be predicted with some confidence . Experimental and theoretical results have shown an elastic modulus of greater than 1 TPa (that of a diamond is 1.2 TPa) and have reported strengths 10–100 times higher than the strongest steel at a fraction of the weight . It has been predicted that carbon nanotubes have the highest Young's modulus of all different types of composite tubes such as BN, BC₃, BC₂N, C₃N₄ [23].

1.7 Electrical Properties of CNT:

Carbon nanotubes possess unique electrical properties. The diameter being in the nanometer range gives rise to quantum effects. The differences in the conducting properties are caused by the molecular structure. CNTs can either be conducting or semiconducting, depending on their chirality. They are metallic if the integers of equation [2].

$$C_h = na_1 + ma_2$$

are: $n=m$ (the armchair structure) and $n-m=3i$ (where i is an integer). All other structures are predicted to be semiconducting . The geometry of the nanotubes determines band structures and thus the energy band gap. The energy band gap of semiconducting CNTs highly depends on the nanotube diameter and is given by:

$$E_{gap} = \frac{2\gamma_0 a_{C-C}}{d}$$

where γ_0 denotes the C-C tight binding overlap energy (2.45 eV), a_{C-C} the nearest neighbor C-C distance ($\sim 1.42 \text{ \AA}$), and d is the diameter of a nanotube. Multiwall carbon nanotubes are expected to behave like quantum wires due to the confinement effects on the tube circumferences. The conductance for carbon nanotubes is given by:

$$G = G_0 M = (2e^2/h)M$$

where $G_0 = (2e^2/h) = 1/(12.9 \text{ k}\Omega)$ is the quantum unit of the conductance, e is electron charge, h is Planck's constant, M is an apparent number of conducting channels including electron-electron coupling and intertube coupling effects in addition to intrinsic channels. In general, MWNTs are quite often found to be one-dimensional conductors with a high electrical conductivity. The metallic properties of the MWCNTs are due to their multiple-shell structure consisting of tubes with various electrical properties, where additional electronic coupling between shells takes place. Moreover, MWCNTs are predicted to have ballistic electron transport at room temperature. The electrical current that could be passed through a multiwall nanotube corresponds to a current density in excess of 107 A/cm^2 . If nanotubes were classical resistors, the power dissipated by such a current would heat the nanotube so much that it would vaporize. The fact that this does not happen suggests that the electrons in nanotubes are strongly decoupled from the lattice [2].

1.8 Elastic Properties of CNT:

A variety of outstanding experimental results on the elucidation of the elastic properties of carbon nanotubes are fast appearing. These are based mainly on the techniques of high resolution transmission electron microscopy (HRTEM) and atomic force microscopy (AFM) to determine the Young's moduli of single-wall nanotube bundles and multi-walled nanotubes, prepared by a number of methods. These results are confirming the theoretical predictions that carbon nanotubes have high strength plus extraordinary flexibility and resilience [19]. Elastic properties of both multi and single-walled nanotubes (SWNT) have been investigated extensively through experimentation and theoretical approaches. SWNTs are remarkably stiff and strong [10]. The tensile modulus and strength

of nanotubes have been reported to range from 0.27 TPa to 3.6 TPa and 11 to 200 GPa, respectively. For small single walled nanotubes, although some results indicated that elastic properties are insensitive to the size of nanotubes, quantum mechanics based computations have shown that Young's modulus increases with the tube diameter [22].

1.9 Polymer/Graphene composite:

The development of the nano level dispersion of graphene particles in a polymer matrix has opened a new and interesting area in materials science in recent years. These nanohybrid materials show considerable improvement in properties that cannot be obtained normally by using conventional composites or virgin polymers. The extent of the improvement is related directly to the degree of the dispersion of the nanofiller in the polymer matrix. It has been observed that with the dispersion of nanofiller in the matrix, there has been drastic improvement in the properties of matrix [1]. Depending on the interphase, the composite can be divided into three different categories:

Hard Interphase: If the Young's modulus of interphase is greater than the Young's modulus of matrix, the interphase is known as hard interphase [1].

Soft Interphase: If the Young's modulus of interphase is less than the Young's modulus of matrix, the interphase is known as soft interphase [1].

No Interphase: If the Young's modulus of interphase is equal to the Young's modulus of matrix, there is no interphase between the CNT and matrix [1].

1.10 Multiscale composite:

The multi-scale composites are relatively new area of research field. The nanofiller are dispersed in a matrix to obtain the improved properties of matrix. The CNT may be dispersed as a randomly/properly aligned in a matrix resulting in a new matrix with the improved properties. The fibers are added into new matrix with improved properties in an orthotropic manner to evaluate the elastic properties of multi-scale composite [26]. Structural materials can be divided into four basic categories: metals,

polymers, ceramics and composites. Composites which consist of two or more separate materials are combined in a macroscopic structural unit, are made from various combinations of other three materials [1]. Composites are generally used because they have desirable properties which could not be achieved by either of the constituent materials acting alone. Generally CNT is added to matrix material to form new matrix, after this fibers are reinforced into new matrix and formed multiscale composites. In matrix-based structural composites, the matrix serves two paramount purposes viz., binding the reinforcement phases in place and deforming to distribute the stresses among the constituent reinforcement materials under an applied force [3]. The demands on matrices are many. They may need to temperature variations, be conductors or resistors of electricity, have moisture sensitivity etc. This may offer weight advantages, ease of handling and other merits which may also become applicable depending on the purpose for which matrices are chosen. Solids that accommodate stress to incorporate other constituents provide strong bonds for the reinforcing phase are potential matrix materials. A few inorganic materials, polymers and metals have found applications as matrix materials in the designing of structural composites, with commendable success. These materials remain elastic till failure occurs and show decreased failure strain, when loaded in tension and compression [1].

1.11 Functions of Matrices [3]

1. Holds the fibres together
2. Protects the fibres from environment.
3. Distributes the loads evenly between fibres so that all fibres are subjected to the same amount of strain.
4. Enhances transverse properties of a laminate.
5. Improves impact and fracture resistance of a component.
6. Helps to avoid propagation of crack growth through the fibers by providing alternate failure path along the interface between the fibres and the matrix.

1.12 Properties of Matrix [3]

The needs or desired properties of the matrix which are important for a composite structure are as follows:

1. Reduced moisture absorption.
2. Low shrinkage.
3. Low coefficient of thermal expansion.
4. Good flow characteristics so that it penetrates the fibre bundles completely and eliminates voids during the compacting/curing process.
5. Reasonable strength, modulus and elongation (elongation should be greater than fibre).
6. Must be elastic to transfer load to fibres.
7. Strength at elevated temperature (depending on application).
8. Low temperature capability (depending on application).
9. Excellent chemical resistance (depending on application).

1.13 Types of Matrix Materials [3]

1. Polymer matrix materials
2. Metal matrix materials
3. Ceramic matrix materials
4. Carbon matrix materials
5. Glass matrix materials

1. Polymer Matrix Materials:

Polymers make ideal materials as they can be processed easily, possess lightweight, and desirable mechanical properties. It follows, therefore, that high temperature resins are extensively used in aeronautical applications. Two main kinds of polymers are thermosets and thermoplastics. Thermosets have qualities such as a well-bonded three-dimensional molecular structure after curing. They decompose instead of melting on hardening. Merely changing the basic composition of the resin is enough to alter the conditions suitably for curing and determine its other characteristics. They can be retained in a partially cured

condition too over prolonged periods of time, rendering Thermosets very flexible. Thus, they are most suited as matrix bases for advanced conditions fiber reinforced composites. Thermosets find wide ranging applications in the chopped fiber composites form particularly when a premixed or moulding compound with fibers of specific quality and aspect ratio happens to be starting material as in epoxy, polymer and phenolic polyamide resins [3].

2. Metal Matrix Materials:

Metal matrix composites, at present though generating a wide interest in research fraternity, are not as widely in use as their plastic counterparts. High strength, fracture toughness and stiffness are offered by metal matrices than those offered by their polymer counterparts. They can withstand elevated temperature in corrosive environment than polymer composites. Most metals and alloys could be used as matrices and they require reinforcement materials which need to be stable over a range of temperature and non-reactive too. However the guiding aspect for the choice depends essentially on the matrix material. Light metals form the matrix for temperature application and the reinforcements in addition to the aforementioned reasons are characterized by high moduli. Most metals and alloys make good matrices. However, practically, the choices for low temperature applications are not many. Only light metals are responsive, with their low density proving an advantage. Titanium, Aluminium and magnesium are the popular matrix metals currently in vogue, which are particularly useful for aircraft applications. If metallic matrix materials have to offer high strength, they require high modulus reinforcements. The strength-to-weight ratios of resulting composites can be higher than most alloys. The melting point, physical and mechanical properties of the composite at various temperatures determine the service temperature of composites. Most metals, ceramics and compounds can be used with matrices of low melting point alloys. The choice of reinforcements becomes more stunted with increase in the melting temperature of matrix materials [3].

3. Ceramics Matrix Materials:

Ceramics can be described as solid materials which exhibit very strong ionic bonding in general and in few cases covalent bonding. High melting points, good corrosion resistance, stability at elevated temperatures and high compressive strength, render ceramic-based matrix materials a favourite for applications requiring a structural material that doesn't give way at temperatures above 1500°C. Naturally, ceramic matrices are the obvious choice for high temperature applications. High modulus of elasticity and low tensile strain, which most ceramics possess, have combined to cause the failure of attempts to add reinforcements to obtain strength improvement. This is because at the stress levels at which ceramics rupture, there is insufficient elongation of the matrix which keeps composite from transferring an effective quantum of load to the reinforcement and the composite may fail unless the percentage of fiber volume is high enough. A material is reinforcement to utilize the higher tensile strength of the fiber, to produce an increase in load bearing capacity of the matrix. Addition of high-strength fiber to a weaker ceramic has not always been successful and often the resultant composite has proved to be weaker. The use of reinforcement with high modulus of elasticity may take care of the problem to some extent and presents pre-stressing of the fiber in the ceramic matrix is being increasingly resorted to as an option. When ceramics have a higher thermal expansion coefficient than reinforcement materials, the resultant composite is unlikely to have a superior level of strength. In that case, the composite will develop strength within ceramic at the time of cooling resulting in microcracks extending from fiber to fiber within the matrix. Microcracking can result in a composite with tensile strength lower than that of the matrix[3].

4. Carbon Matrix:

Carbon and graphite have a special place in composite materials options, both being highly superior, high temperature materials with strengths and rigidity that are not affected by temperature up to 2300°C. This carbon-carbon composite is fabricated through compaction of carbon or multiple impregnations of porous frames with liquid carboniser precursors and subsequent pyrolyzation. They can also be manufactured through chemical vapour deposition of pyrolytic carbon. Carbon-carbon composites are not be applied in

elevated temperatures, as many composites have proved to be far superior at these temperatures. However, their capacity to retain their properties at room temperature as well as at temperature in the range of 2400°C and their dimensional stability make them the obvious choice in a number of applications related to aeronautics, military, industry and space [3].

5. Glass Matrix Materials:

In comparison to ceramics and even considered on their own merit, glass matrices are found to be more reinforcement-friendly. The various manufacturing methods of polymers can be used for glass matrices. Glasses are meant to improve upon performance of several applications. Glass matrix composite with high strength and modulus can be obtained and they can be maintained up to temperature of the order of 650°C. Composites with glass matrices are considered superior in dimensions to polymer or metal system, due to the low thermal expansion behaviour [3].

1.14 Types of Composites Materials

1.14.1 Isotropic

1.14.2 Orthotropic

1.14.3 Anisotropic

1.14.1 Isotropic Materials

An isotropic material is one which looks the same in every direction. We cannot define any special direction using the material properties. In other words, none of the properties depend the orientation; it is perfectly rotationally symmetric. Note that in order to be isotropic the material must be homogenous on the length scale of interest, i.e. the same at every point in the material [3]. Most metallic alloys and thermoset polymers are considered isotropic, where by definition the material properties are independent of direction. Such materials have only 2 independent variables (i.e. Elastic constants) in their stiffness and compliance matrices, as opposed to the 21 elastic constants in general anisotropic case. The two elastic constants are usually expressed as the Young's modulus E and the Poisson's ratio ν . However, the alternative elastic constants K (bulk

modulus) and/or G (shear modulus) can also be used. For isotropic materials, G and K can be found from E and ν by a set of equations, and vice-versa [1].

1.14.2. Orthotropic Materials :

An **orthotropic material** has two or three mutually orthogonal two fold axes of rotational symmetry so that its mechanical properties are, in general, different along each axis. Orthotropic materials are thus anisotropic; their properties depend on the direction in which they are measured. An isotropic material, in contrast, has the same properties in every direction. One common example of an orthotropic material with two axis of symmetry would be a polymer reinforced by parallel glass or graphite fibers. The strength and stiffness of such a composite material will usually be greater in a direction parallel to the fibers than in the transverse direction [1]. Another example would be a biological membrane, in which the properties in the plane of the membrane will be different from those in the perpendicular direction. Such materials are sometimes called **transverse isotropic**. An **orthotropic material** has two or three mutually orthogonal two fold axes of rotational symmetry so that its mechanical properties are, in general, different along each axis. Orthotropic materials are thus anisotropic; their properties depend on the direction in which they are measured. An isotropic material, in contrast, has the same properties in every direction [3].

1.14.3. Anisotropic Materials:

In a single crystal, the physical and mechanical properties often differ with orientation. It can be seen from looking at our models of crystalline structure that atoms should be able to slip over one another or distort in relation to one another easier in some directions than others. When the properties of a material vary with different crystallographic orientations, the material is said to be **anisotropic**. The main difference between anisotropic and orthotropic materials is that in case of anisotropic, properties of material is different in every plane while in case of orthotropic, the properties of materials are different at every point . There are 21 engineering constants in case of anisotropic materials [1].

1.15 Fiber Reinforcement

Fibers are the important class of reinforcements, as they satisfy the desired conditions and transfer strength to the matrix constituent influencing and enhancing their properties as desired glass fibers are the earliest known fibers used to reinforce materials [5]. Ceramic and metal fibers are subsequently found out and put to extensive use, to render composites stiffer more resistant to heat fibers fall short of ideal performance due to several factors [11]. The performance of a fiber composite is judged by its length, shape, orientation, composition of the fibers and the mechanical properties of the matrix [17]. The orientation of the fiber in the matrix is an indication of the strength of the composite and the strength is greatest along the longitudinal directional of fiber. This doesn't mean the longitudinal fibers can take the same quantum of load irrespective of the direction in which it is applied. Optimum performance from longitudinal fibers can be obtained if the load is applied along its direction. The slightest shift in the angle of loading may drastically reduce the strength of the composite [11]. Unidirectional loading is found in few structures and hence it is prudent to give a mix of orientations for fibers in composites particularly where the load is expected to be the heaviest. Monolayer tapes consisting of continuous or discontinuous fibers can be oriented unidirectional stacked into plies containing layers of filaments also oriented in the same direction. More complicated orientations are possible too and nowadays, computers are used to make projections of such variations to suit specific needs. In short, in planar composites, strength can be changed from unidirectional fiber oriented composites that result in composites with nearly isotropic properties of angle-ply composites which are not quasi-isotropic may vary with the number of plies and their orientations. Composite variables in such composites are assumed to have a constant ratio and the matrices are considered relatively weaker than the fibers [33]. The strength of the fiber in any one of the three axes would, therefore be one-third the unidirectional fiber composite, assuming that the volume percentage is equal in all three axes. However, orientation of short fibers by different methods is also possible like random orientations by sprinkling on to given plane or addition of matrix in liquid or solid state before or after the fiber deposition. Most fibers in use currently are solids which are easy to produce and handle, having a circular cross-section, although a few non-conventional

shaped and hollow fibers show signs of capabilities that can improve the mechanical qualities of the composites. The main dispersion methods for the distribution of CNT in polymer are sonication, extrusion and kneading [10].

1.16 Types of Fibers :

Organic and inorganic fibers are used to reinforce composite materials. Almost all organic fibers have low density, flexibility, and elasticity. Inorganic fibers are of high modulus, high thermal stability and possess greater rigidity than organic fibers and not withstanding the diverse advantages of organic fibers which render the composites in which they are used. Mainly, the following different types of fibers namely, glass fibers, silicon carbide fibers, high silica and quartz fibers, alumina fibers, metal fibers and wires, graphite fibers, boron fibers, aramid fibers and multiphase fibers are used. Among the glass fibers, it is again classified into E-glass, A-glass, R-glass etc. The potential of fibers of graphite, silica carbide and boron are also exercising the scientific mind due to their applications in advanced composites [3].

1. Glass Fibers:

Over 95% of the fibers used in reinforced plastics are glass fibers, as they are inexpensive, easy to manufacture and possess high strength and stiffness with respect to the plastics with which they are reinforced. Their low density, resistance to chemicals, insulation capacity are other bonus characteristics, although the one major disadvantage in glass is that it is prone to break when subjected to high tensile stress for a long time. However, it remains break-resistant at higher stress-levels in shorter time frames. This property mitigates the effective strength of glass especially when glass is expected to sustain loads for many months or years continuously [3].

2. Metals Fibers:

As reinforcement, metal fibers have many advantages. They are easily produced using several fabrication processes and are more ductile, apart from being not too sensitive to surface damage and possess high strengths and temperature resistance. However, their weight and the tendency to react each other through alloying mechanisms are major disadvantages. Metal wires, of the continuous version, also reinforce plastics like

polyethylene and epoxy. Such combinations ensure high strength, light weight and good fatigue resistance [3].

3. Alumina Fibers:

Alumina aluminium oxide fibers, basically developed for use in metal matrices are considered a potential resin-matrix composite reinforcement. It offers good compressive strength rather than tensile strength. It's important property is it's high melting point of about 2000^oc and the composite can be successfully used at temperature up to about 1000^oc. Magnesium and aluminum matrices frequently use alumina fiber reinforced composites as they do not damage the fiber even in the liquid state [3].

4. Boron Fibers:

Boron-tungsten fibers are obtained by allowing hot tungsten filament through a mixture of gases. Boron is deposited on tungsten and the process continued until the thickness is achieved. The tungsten however remains constant in its thickness. Properties of boron fibers generally change with the diameter, because of the changing ratio of boron to tungsten and the surface defects that change according to size. However, they are known for their remarkable stiffness and strength. Their strengths often compare with those of glass fibers, but their tensile modulus is high, almost four to five that of glass. Boron coated carbons are much cheaper to make than boron tungsten fiber. But is low modulus of elasticity often works against it [3].

5. Silicon Carbide Fibers:

Silicon carbide can be coated over a few metals and their room temperature tensile strengths and tensile moduli are like those boron-tungsten. The advantages of silicon carbide-tungsten are several and are more desirable than uncoated boron tungsten fibers. Elevated temperature performance and the fact that they reported only a 35% loss of strength at 1350^oc are their best qualities. Silicon carbide-tungsten and silicon carbide-carbon have both been seen to have very high stress-rupture strength at 1100^oc and 1300^oc. Uncoated boron-tungsten fibers do not react with molten aluminum, unlike uncoated boron and they also withstand high temperatures used in hot-press titanium matrices [3].

1.17 Methods for Synthesis of Carbon Nanotubes:

1.17.1 Arc Discharge Method:

The first method that was successfully used to synthesize CNTs in small quantities was the arc discharge method [22]. Opposing anode and cathode terminals made of 6-mm and 9-mm graphite rods respectively are placed in an inert environment (He or Ar at ~500 Torr). A strong current, typically around 100 A (DC or AC), is passed between the terminals generating arc-induced plasma that evaporates the carbon atoms in the graphite. The nanotubes grow from the surface of these terminals. A catalyst can be introduced into the graphite terminal. Although MWCNTs can be formed without a catalyst, it has been found that SWCNTs can only be formed with the use of a metal catalyst such as iron or cobalt [7].

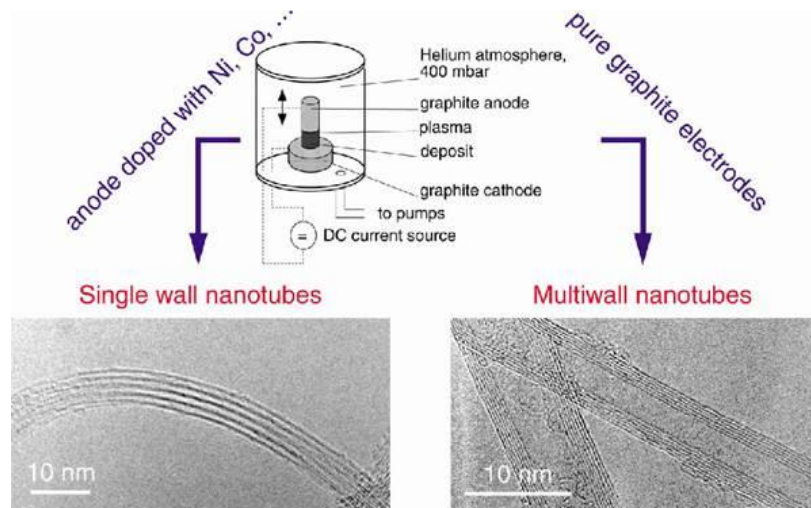


Fig.1.5 Arc Discharge Method[36]

1.17.2. Laser Ablation Method:

A process called Laser Ablation, first developed in 1995, uses a similar principle to produce nanotubes. Carbon is evaporated at high temperatures from a graphite target using a powerful and focused laser beam. In the most basic laser ablation technique, a 1.25-cm diameter graphite target is placed in a 2.5-cm diameter, 50-cm long quartz tube in a furnace controlled at 1200°C and filled with 99.99% pure argon to a pressure of 500 Torr. A pulsed Nd:Yag laser beam at 250 mJ (10 Hz) is focused using a circular lens and the beam is

swept uniformly across the graphite target surface [7]. The nanotubes, mixed with undesired amorphous carbon, are collected on a cooled substrate at the end of the chamber. Both of these methods have limited potential for scale-up. Solid graphite must be evaporated at $>3000^{\circ}\text{C}$ to source the carbon needed, the nanotubes produced are in an entangled form, and extensive purification is required to remove the amorphous carbon and fullerenes that are naturally produced in the process. This process is known to produce carbon nanotubes with the highest quality and high purity of single walls [21].

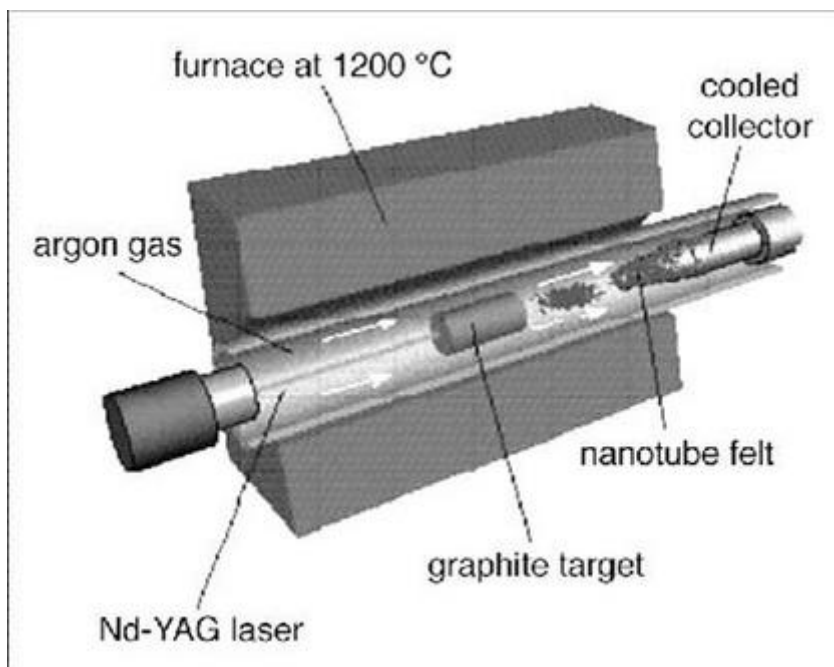


Fig.1.6 Laser Ablation Method [7]

1.17.3. Chemical Vapour Deposition:

Chemical Vapour Deposition (CVD) has the highest potential for mass production of carbon nanotubes [8]. It is a versatile method that can produce bulk amounts of defect-free CNTs at relatively low temperatures. The generalized process for producing CNTs using CVD is outlined here. A substrate material (e.g. Alumina, quartz), is cleaned in preparation for the catalyst deposition [21]. A porous substrate may be desired, so electrochemical etching with a hydrofluoric acid/methanol solution may be performed. Nanotubes can grow at a higher rate on a porous substrate, suggesting that carbon can

diffuse through the porous substrate layer and feed growing nanotubes [8]. A catalyst (e.g. Iron, nickel) is deposited onto the substrate by thermal evaporation. The furnace is raised to a temperature between 500-1200°C and a hydrocarbon gas such as acetylene, ethylene, or carbon monoxide is slowly pumped into the reactor. At these high temperatures carbon dissociates from the feedstock molecules and diffuses onto the catalyst [21]. The atoms arrange themselves into a sheet of nanotubes on the substrate, combined with impurities such as amorphous carbon, fullerenes, as well as the catalyst material. In most cases these impurities must be removed using a purification step[7].

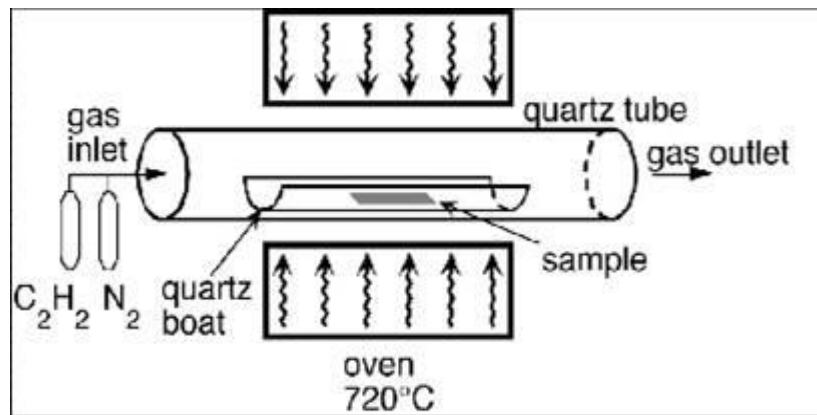


Fig. 1.7 Chemical vapour deposition method [36]

1.18 Potential Applications of Composites:-

The major structural application of fiber-reinforced composites and the expected applications of nanocomposite are in field of military and commercial aircraft, for which weight reduction is critical for higher speeds and increased payloads. Ever since the production application of boron fiber-reinforced epoxy skin for F-14 horizontal stabilizers in 1969, the use of fiber-reinforced polymers has experienced a steady growth in aircraft industry. Carbon fiber, either alone or in hybridization with Kevlar 49 fibers, have becomes the primary material in many wing, fuselage, and empennage components. The structural integrity and durability of these components have built up confidence in their performance and prompted developments of other structural aircraft components. Fiber-reinforced epoxies are used in rotor blades for many military and commercial helicopters. Besides the weight reduction, one significant advantage of using composite materials is the ability to

tailor the dynamic frequencies of the blades to its operating parameters. The critical flopping and twisting frequencies of the blade can be controlled and turned by the classical method of mass distribution as well as orientation of fibers along the blade length. Another advantage of fiber-reinforced composites in blade application is the manufacturing flexibility of these materials. Fiber-reinforced composites are selected in missile structure for the purpose of weight reduction, which in turn increases the missile range as well as its payload capacity. Application of fiber-reinforced composites in the automotive industry can be classified in to three groups: body components, chassis components and engine components [3]. Over the last few years, fiber-reinforced polymeric composites have experienced a substantial usage in the sporting goods industry. The advantages of using fiber-reinforced polymers are weight reduction, vibration damping, and design flexibility. Glass fiber-reinforced polyester laminates have found wide use in marine applications ever since their introduction as commercial materials [6]. Potential practical applications have been reported such as chemical sensors, field emission materials , catalyst support ,electronic devices , high sensitivity nanobalance for nanoscopic particles , nanotweezers , reinforcements in high performance composites, and as nanoprobes in meteorology and biomedical and chemical investigations, anode for lithium ion in batteries, nanoelectronic devices , supercapacitors and hydrogen storage New applications are likely in the diamond industry [23].

1.19 Software Used:

1.19.1 Material Studio Software[39]:

Materials Studio is software for simulating and modeling materials developed and distributed by accelrys, a company specializing in research software for computational chemistry, bioinformatics, cheminformatics, molecular simulation, and quantum mechanics. This software is used in advanced research of various materials: polymers, nanotubes, catalysts, metals, ceramics, and so on, by universities, research centres and hi-Tec companies (e.g., in nanotechnology research by ST Microelectronics) Materials Studio is a client–server software with Microsoft Windows-

based PC clients and Windows and Linux-based servers running on pcs, Linux IA-64 workstations (including Silicon Graphics (SGI) and HP XC clusters.

Software Components: X-Cell, indexing for medium- to high-quality powder diffraction data from X-ray, neutron, and electron radiation sources.

Adsorption Locator, to find the most stable adsorption sites for various materials, including zeolites, carbon nanotubes, silica gel, and activated carbon

CASTEP, to predict electronic, optical, and structural properties

ONETEP, to perform linear-scaling density functional theory simulations

QSAR /QSAR Plus to identify compounds with optimal physicochemical properties.

Polymers and Classical Simulation, to construct and characterize models of isolated chains or bulk polymers and predict their properties.

Materials Visualizer is used to construct/import graphical models of materials accurate structure is determined by quantum mechanical, semi-empirical, or classical simulation

1.19.2 Object Oriented finite software[40]:

OOF2 is an object oriented program. The term “object oriented” means different things to different people. OO programming involves writing descriptions of things, such as finite elements, or colors. A *class* describes the data associated with a thing and the functions that operate on that data. . For example, a color class could contain storage for the red, green, and blue components, functions for setting those components, and a function for returning the equivalent gray value. The fundamental objects that OOF2 manipulates microstructures, images skeltons, Meshes, and Subproblems, are nested. Microstructure contains images and skeltons and skeltons contains meshes. Meshes are divided into subproblems. The objects are all given identifying names when they are created. These names are assigned by user or generated automatically by the program if the user declines to specify a name. No two microstructure can have the same name and within a microstructure no two images can have the same name.

Advantages of oof2 over oof1

1. OOF2 is much more flexible and expandable than OOF1.
2. OOF2 can solve the heat equation, mechanical force balance, and the Coulomb equation. It includes material properties for linear elasticity, body forces (gravity), thermal conductivity, heat sources, dielectric permittivity, space charge (in an approximation in which charges interact only with the local polarization field, not with other charges at a distance), thermal expansion, and piezoelectricity.
3. OOF2 contains a more powerful set of finite elements than OOF1.
4. OOF2 has 3 noded triangles, 4 node quadrilaterals, 6 noded subparametric triangles, and 8 noded subparametric quadrilaterals. Adding new element types in C++ is easy.
5. OOF2 generates and refines triangular, quadrilateral, and mixed meshes from image data. Element order is specified independently from element geometry.
6. OOF2 is threaded, meaning that it can perform multiple calculations simultaneously, unlike OOF1.
7. OOF2 has more flexible graphical output than OOF1.
8. OOF2 will eventually become OOF3, which will solve 3 dimensional problems. The primary difficulties here will involve image based mesh generation and user interfaces. The finite element and material definition machinery will carry over from OOF2

1.20. Organisation of Thesis:

The aim of the thesis is to evaluate the effect of CNT reinforced Multi-scale materials on the static and dynamic behaviour of composite laminated plate. The effect of the boundary conditions, effect of aspect ratio of plate, effect of aspect ratio of CNT, content of CNT % on the nonlinear static and dynamic behaviour of composite laminated plate is evaluated.

Chapter 1 deals with the brief introduction of problem highlighting the importance of the problem. This chapter also includes the brief introduction of CNT and its applications. In

this chapter we describe the different types of matrices materials, types of fibres and different methods for synthesis of CNT'S .

Chapter 2 presents the review of literature on the modern techniques for predicting the mechanical behaviour of CNT, potential of CNT fillers , processing, characterization, and modelling of carbon nanotubes-reinforced multi-scale composites, effect of nanotubes geometry on the elastic properties of nano composites, critical review of interaction between carbon nanotubes and polymers ,and the objective of the present investigation is presented.

Chapter 3 deals with the mathematical modeling of the problem in details. The different models are described which are used to determine the improved properties of matrix by dispersing CNT in the matrix in an aligned/ random manner. Then the micromechanics approach is described which is used to determine the elastic properties of multi-scale composites.

Chapter 4 presents the evaluation of the elastic properties of CNT reinforced multi-scale composites. The different models Halpin-Tsai model, Modified series model and Mori-Tanaka methods are used for evaluating the improved elastic properties of the matrix by dispersing CNT in a random manner in to the matrix. Then the micromechanics approach will be used to evaluate the elastic properties of carbon nanotubes reinforced multi-scale composite, the fibers are reinforced in an orthotropic manner in to the matrix. The influence of CNT % and aspect ratio on the elastic properties of multi-scale composite will be studied.

Chapter 5 presents the conclusions of the present thesis work. The essential contribution is to evaluate the elastic properties of CNT reinforce multi-scale composites. Several new results have been reported.

CHAPTER 2

Litrature Review

2.1 Introduction:

The research in the area of carbon Nanotubes has increased tremendously in last few years. A brief review of research concerned with CNT reinforced multi-scale composites and their response is presented herein.

A.Hernandez, et al. [4] evaluated the effective properties of multiwalled carbon nanotube/epoxy composites using two different tubes. For this purpose they experimentally investigate mechanical, thermo-mechanical, and electrical properties of a brittle epoxy matrix reinforced with two different types of multiwalled carbon nanotubes. The nanotubes investigated have significantly different aspect ratios and slightly different content of metal impurities. The results indicate that the nanotube morphology and impurity content can significantly affect the effective properties of the resulting composite.

A. Martone, et al. [5] presented reinforcement efficiency of multi-walled carbon nanotube/epoxy nano composites. Mechanical reinforcement of polymer matrices loaded by carbon nanotubes is expected to benefited both by the high aspect ratio and the very high modulus of such nanofillers and, consequently, it depends not only their content within the hosting system but also by the state of dispersion. In this paper, they analyses the effect on the bending modulus of dispersed multi-walled carbon nanotube (MWCNT) into an epoxy system. At the end they concluded that reinforcement efficiency is characterised by two limiting behaviours whose transition region coincides with the development of a percolative network of nanotubes

Amal, et al. [6] evaluates the technical and economic feasibility of using carbon nanotubes in reinforcing polymer composites. They concluded that carbon nanotubes can be used in conjunction with carbon fibers in a hybrid composite in order to achieve elastic modulus values in the range 170–450 GPa. These conclusions are confirmed by a case study to select the optimum material for a tennis racket using the analytic hierarchy process. In this

paper they also observed that CNT should need to be produced in larger quantities at a lower cost, they need to be synthesized in longer lengths, and improved techniques are required to align and evenly distribute them in the matrix.

Chunyu Li [8] presented Multiscale modeling of compressive behavior of carbon nanotube/polymer composites. This paper reports a multiscale modeling of the compressive behavior of carbon nanotube/polymer composites. The nanotube is modeled at the atomistic scale, and the matrix deformation is analyzed by the continuum finite element method. The nanotube and polymer matrix are assumed to be bonded by van der Waals interactions at the interface. The results indicate that continuous nanotubes can most effectively enhance the composite buckling resistance.

E. Bekyarova, et al. [9] presented an approach to the development of advanced structural composites based on engineering multiscale carbon nanotube-carbon fiber reinforcement. The carbon nanotube/carbon fiber performs successfully infiltrated with epoxy resin using the vacuumassisted resin transfer molding (VARTM) method. This leads to multiscale hybrid composites with enhanced out-of-plane mechanical and electrical properties

Shady and Gowayed [10] presented the Effect of nanotube geometry on the elastic properties of nanocomposites. In this work, the nanotube geometry in 3D is included in the calculation of the elastic properties of a modified effective fiber. The impact of the nanotube curvature on the elastic properties of nanocomposites is studied utilizing the modified fiber model and the approach developed by Mori-Tanaka. They concluded that for a low weight fraction of nanotubes the effect of curvature seems to be minor and as the weight fraction increases, the effect of nanotube curvature becomes critical.

F.H. Gojny, et al. [11] investigated about mechanical properties of carbon nanotube-reinforced epoxy composites at low nanotube content. A standard shear-mixing technique calendaring is applied in order to disperse double-wall nanotubes in an epoxy resin. The prepared nanocomposites is investigated by transmission- and scanning-electron microscopy in order to receive information concerning the achieved dispersion and the CNT-epoxy interface. The addition of only small amounts of carbon nanotubes leads to improved mechanical properties like strength, stiffness, fracture toughness.

G.I.Giannopoulos, et al. [12] described a micromechanical finite element approach for the estimation of the effective Young's modulus of single-walled carbon nanotube reinforced composites. They estimated Young's modulus of nanocomposite by considering representative cylindrical volume element. The numerical results are compared with experimental and analytical predictions.

IndraVir Singh, et al [13] presented Effect of interface on the thermal conductivity of carbon nanotube composites. They used element free Galerkin method as a numerical tool to evaluate the thermal conductivity of the composites. The numerical results have been obtained using continuum mechanics approach for a model composite problem, also they concluded that the interface has a major effect on the thermal conductivity of the composites. They resulted that the effect of interface on the effective conductivity of the composite is small for short nanotubes as compared to long nanotubes and interface thickness also plays an important role on the effective thermal conductivity of the composite.

J. Cho, et al. [14] presented the mechanical properties of nano composites consisting epoxy matrix reinforced with randomly oriented platelets are studied by Mori-Tonka approach in conjunction with molecular mechanics. In this paper they concluded that modulus of nano composites is strongly dependent on the aspect ratio of the reinforcing particles, not on their size.

J.P. Salvetat, et al. [16] studied about the mechanical properties of carbon nanotubes. High-resolution transmission electron microscopy (HRTEM) and atomic force microscopy (AFM) techniques are used to determine the Young's moduli of single-wall nanotube bundles and multi-walled nanotubes. The results from these techniques are confirming the theoretical predictions that carbon nanotubes have high strength plus extraordinary flexibility and resilience. They also concluded that composites will benefit from the exceptional mechanical properties of carbon nanotubes, but that the major outstanding problem of load transfer efficiency must be overcome before suitable engineering materials can be produced.

Jia-LinTsai, et al.[17] presented Characterizing elastic properties of carbon nanotubes/polyimide nanocomposites using multi-scale simulation. The elastic properties of the CNT nanocomposites are predicted by a three-phase micromechanical model in

which the equivalent solid cylinder of CNTs, polyimide matrix, and the effective interphase is included. Results indicated that the longitudinal moduli of the nanocomposites obtained based on the three-phase model are in good agreement with those calculated from MD simulation

Kim, et al. [18] presented effect of surface modification on mechanical and physical properties on CNT/epoxy composites. They investigated that physical and mechanical properties of CNT/Epoxy can not improved significantly because interfacial bonding between CNT's and polymer matrix is weak. They concluded that mechanical and physical properties can improved if CNT'S are treated by acidic solutions to remove impurities and modified subsequently by amine treatment or plasma oxidation to improve interfacial bonding and dispersion of nanotubes in the epoxy matrix.

M. SATO [19] studied the elastic and plastic deformation of carbon nanotubes. It has been broadly accepted that mechanical deformation of a carbon nanotube causes significant changes in its physical and chemical properties. Precise knowledge of its deformation mechanism and available geometry is, therefore, crucial for understanding the precise physics of CNT systems and in developing CNT-based applications. This paper introduced such remarkable elastic and plastic deformation properties of CNTs, as well as recent theoretical and experimental progresses in the field of many excellent CNT researches.

M.Tehrani, et al. [20] presented Nanocharacterization of creep behavior of multiwall carbon nanotubes/epoxy nanocomposite. High temperature instrumented indentation testing is used to evaluate the mechanical properties of multiwall carbon nanotubes/epoxy nanocomposite system. They investigated that improvements in the properties are not as high as anticipated through the use of mixture rule, indicating insufficient dispersion. The analysis of the creep strain rate sensitivity clearly revealed that the addition of MWCNTs to a commercial epoxy reduced the creep rate

Shokrieh, et al. [21] studied the tensile behavior of embedded short carbon nanotubes(CNTs) in a polymer matrix in presence of van der Waals (vdW) interaction as inter-phase region. They investigated nanotube length effect on the reinforcement efficiency in carbon nanotube based composites. Furthermore, a comparison between results obtained for short carbon nanotubes and long carbon nanotube is presented.

Mandar Kulkarni, et al. [22] studied about the elastic response of a carbon nanotube fiber reinforced polymeric composite. The carbon nanotubes increase the effective diameter of the fiber and provide a larger interface area for the polymeric matrix to wet the fiber. A study is conducted by them to numerically predict the elastic properties of the nano reinforced composites. A multiscale modeling approach and the Finite Element Method were used to evaluate the effective mechanical properties of the nano reinforced laminated composite. An experimental program is also conducted to evaluate the elastic moduli of the nanoreinforced laminated composite and correlate them with the numerical values.

Melissa Paradise and Tarun Goswami [23] showed the CNT effect on production and industrial applications. In this paper the production methods, properties and industrial applications of carbon nanotubes are specifically reviewed. Production methods include classical approaches such as the arc method, chemical vapor deposition, laser ablation, and electric arc discharge along with new methods which are being tested such as through solar energy, plasma and microgravity environments.

Meng-Kao, et al. [24] studied the mechanical behavior of phenolic-based composites reinforced with multi-walled carbon nanotubes. Two types of carbon nanotubes (CNTs), the network multi-walled nanotubes (MWNTs) and the dispersed MWNTs, used for fabricating MWNTs/phenolic composites. The MWNTs are synthesized using the floating catalyst method through the chemical vapor deposition process. Modified Halpin-Tsai equation is proposed to evaluate the Young's modulus and tensile strength of the MWNTs/phenolic composites by adopting an orientation factor and an exponential shape factor in the equation.

Rahmat, Hubert [25] presented a critical review of interaction between carbon nanotubes and polymers. In this paper, they described various techniques of interaction measurements, including experimental and modelling studies. From the experimental approaches, they discuss about wetting, spectroscopy and probe microscopy techniques in detail. Finally, they concluded that an optimum carbon nanotube-polymer interaction is a key factor towards reaching the full potential of carbon nanotubes in nanocomposites.

Kim, Park, et al. [26] presented processing, characterization, and modeling of carbon nanotube-reinforced multiscale composites. In this paper, they studied about the effect of

sonication on mechanical properties of multiscale composites which contains reinforcements at varying scale. A combination of Halpin–Tsai equations and woven fiber micromechanics is also used by them to predict the mechanical properties of multiscale composites .

P.K. Valavala and G.M. Odegard [27] presented a review for modeling techniques for predicting the mechanical behaviour of carbon nanocomposites. A detailed discussions of computational chemistry and computational mechanics modelling techniques are given. The approaches like Ab initio simulation, Molecular Dynamics, Montecarlo, Analytical micromechanics, Finite element method and Boundary element method are also discussed.

R.Andrews and M.C. Weisenberger [28] presented state of research into carbon nanotube/polymer–matrix composites for mechanical reinforcement. Particular interest is also given to interfacial bonding of carbon nanotubes to polymer matrices as it applies to stress transfer from the matrix to the CNT.

R.J. Mora, et al. [29] presented properties of composites of carbon nano tube fibers. This paper reports the properties of epoxy matrix reinforced with fibres of carbon nanotubes (CNTs) which, in many ways, are similar to standard composites reinforced with commercial fibres. They used thermogravimetric analysis (TGA) for measurement of fibre density and volume fraction. Tensile and compression tests suggest that the composite stiffness and fibre volume fraction are related to each other . At the end results show that CNT-fibres provide good reinforcement in compression as well as in tension.

S.Kanagraj,et al [30] studied mechanical properties of high density polyethylene and carbon nanotube composites. They observed that mechanical properties of materials are increased when volume fraction of CNT is increased. They used Halphin Tsai and modified series model to predict the young’s modulus of CNT-HDPE composites. They also observed that melting point and oxidation temperature of the composites are not affected by the addition of CNT.

S.V. Ahir [31] presented a review on Polymers with aligned carbon nanotubes. This paper is focus on the emerging trends in nanocomposite actuators, in particular, photo-stimulated mechanical response. He studied how photo-actuation in nanocomposites depend on nanotube concentration, alignment and entanglement, and examine possible mechanisms

that could lead to this effect. Properties of pure carbon nanotube networks, in form of materials or fibers are also discussed.

Shiren Wang, et al.[32] presented dispersion and thermal conductivity of carbon nanotube composites. A mechanical method is used to shorten carbon nanotubes (CNTs) for improving dispersion without reducing their thermal conductivity. Single walled carbon nanotubes (SWCNTs) are mechanically cut to produce short and open-ended fullerene pipes. These shortened SWCNTs are then used in polymer composites. Both atomic force microscopy and scanning electron microscopy characterizations suggested that nanotube shortening significantly improved CNT dispersion. Thermal conductivity of composites containing short CNTs are found to be much better than those containing pristine CNTs.

Subhrnshu Sekhar, et al.[33] presented the overview of recent advances reported in literature in ceramics matrix composites research in the context of reinforcement with carbon nanotubes. Their research has indicated the potential of these nano compsite and challenges in processing and improving properties.

Xiao-Lin Xie, et al. [37] presented a review of dispersion and alignment of carbon nano tubes in polymer matrix. They resulted that Optimum physical blending, in situ polymerization and chemical functionalization could improve the dispersion of CNTs. The alignment of CNTs in a polymer matrix could be increased by ex situ alignment due to force, electrical and magnetic field-induced methods, and liquid crystalline phase could also induce the orientation of CNTs along the direction of the applied field. In this paper, discussions on mechanical, thermal, electrical, electrochemical, optical and super-hydrophobic properties; and applications of polymer/CNT composites are also included.

Yijun Liu[38] presented modeling of carbon-nanotube composites by a fast multipole boundary element method. In this paper, a new continuum model of the CNT-based composites is developed for large-scale analysis at the micro-scale in order to characterize such composites. For this purpose CNTs are treated as rigid fibers in the elastic matrix, due to its high stiffness that are at least two orders higher than those of most polymer matrices. They resulted that effectiveness, efficiency and promises of the developed fast multipole BEM as a fast and first-order numerical tool for large-scale characterizations of the carbon-nanotube composites.

2.2 Objective:

The objective of the present work will be to evaluate the elastic Properties of CNT Reinforced Multi-Scale composites considering the effect of CNT % and Aspect Ratio .Firstly, CNT is dispersed in an isotropic manner in a matrix and the improved elastic properties of polymer matrix are obtained by using the different Models (Halpin-Tsai Model, Modified Series Model and Mori-Tanaka Method). Then, CNT reinforced Polymer matrix is treated as a new matrix and E-Glass fibers are reinforced in an orthotropic manner into the matrix. Micromechanics approach is used to determine the Mechanical Properties of Multi-scale composite. The effect of SWCNT (Single-Walled carbon Nanotubes), MWCNT (Multi-Walled carbon Nanotubes) on the elastic Properties of Multi-Scale Composites is investigated. So our main objective is the comparative study of different models to investigate elastic properties of multi-scale composites.

Chapter 3

Mathematical Modeling

Firstly, CNT is dispersed in an isotropic manner in a matrix and the improved elastic properties of polymer matrix are obtained by using the different Models (Halpin-Tsai Model, Modified Series Model and Mori-Tanaka Method). Then, CNT reinforced Polymer matrix is treated as a new matrix and E-Glass fibers are reinforced in an orthotropic manner into the matrix. Micromechanics approach is used to evaluate the Mechanical Properties of Multi-scale composite.

Multi-scale Micro Mechanics Modeling

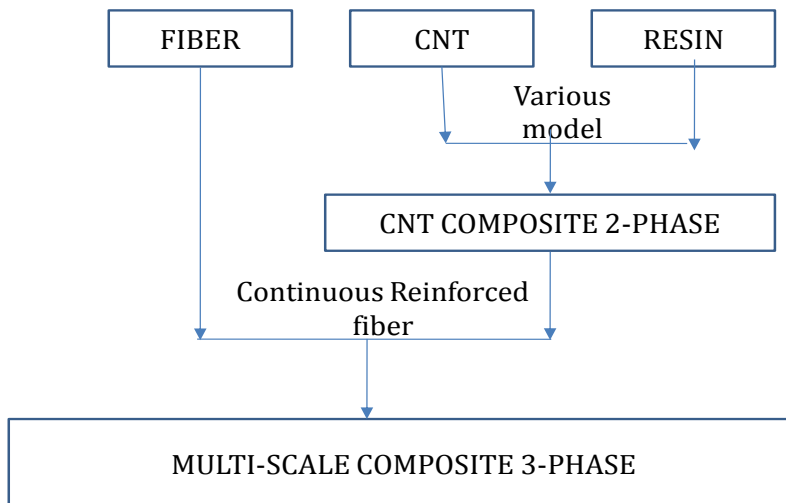


Fig. 3.1: Layout for evaluating the elastic properties of CNT Reinforced multi-scale composites [26] .

3.1. Halpin-Tsai Model for Randomly Oriented Nanotube [26] :

To evaluate the mechanical properties of carbon nanotube composite, Halpin-Tsai Model is also used. In this model both the volume fraction and aspect ratio of CNT in the nanocomposite can be varied for determining the elastic properties of carbon nanocomposite. This model is used for determining the elastic properties of nanocomposite for short as well as long CNT. The Halpin-Tsai model determines the tensile modulus of nanocomposite, and expressed [26]:

$$\mathbf{E}_{NC} = \left[\frac{3}{8} \times \frac{1 + 2(l_{NT}/d_{NT})\eta_L V_{NT}}{1 - \eta_L V_{NT}} + \frac{5}{8} \times \frac{1 + 2\eta_D V_{NT}}{1 - \eta_D V_{NT}} \right] \mathbf{E}_{epoxy} \quad (3.1)$$

$$\eta_L = \frac{(E_{NT}/E_{epoxy}) - (d_{NT}/4t)}{(E_{NT}/E_{epoxy}) + (l_{NT}/2t)} \quad (3.2)$$

$$\eta_D = \frac{(E_{NT}/E_{epoxy}) - (d_{NT}/4t)}{(E_{NT}/E_{epoxy}) + (d_{NT}/2t)} \quad (3.3)$$

Where E , l_{NT} , d_{NT} , V_{NT} and t are represents the tensile modulus, length, diameter, and volume fraction of nanotube and thickness of graphite layer respectively. Based on isotropic assumption, the shear modulus can be calculated as follows:

$$G_{NC} = \frac{E_{NC}}{2(1 + \nu)} \quad (3.4)$$

3.2. Modified Series Model for Randomly oriented nanotube [30]:

The Modified Series Model is used to determine the properties of CNT reinforced composite in a randomly oriented manner. Then the improved Properties of matrix are obtained. The Modified Series Model is quietly used for determining the mechanical properties of the carbon nanotube composite. In this model, both the volume fraction and aspect ratio can be varied for determining the elastic properties of carbon nanotube composite. Thus the Modified Series Model is used for determining the elastic properties of carbon nanotube composite for short as well as long CNT.

In case of CNT-HDPE (High Density Poly Ethylene) composites, it is considered as randomly oriented short fiber arrangement. Based on the Modified form of rule of mixtures for series model, the composite Modulus is [29]:

$$E_c = (\eta_l \eta_o E_{CNT} - E_{HDPE}) V_{CNT} + E_{HDPE} \quad (3.5)$$

Where,
$$\eta_l = 1 - \frac{\text{Tanh}(a.(l/d))}{a.(l/d)} \quad (3.6)$$

$$a = \sqrt{\frac{-3E_{HDPE}}{2E_{CNT} \ln(V_{CNT})}} \quad (3.7)$$

$$\eta_o = 0.2$$

Where, η_l = Length Efficiency Factor,

η_o = Orientation efficiency factor for randomly oriented fiber

l/d = Aspect Ratio

3.3. Mori-Tanaka Method for Randomly Oriented Nanotube J. Wuite [15]:

The mechanical properties of composite are evaluated by dispersing the CNTs in a randomly oriented (isotropic) manner in a matrix. The improved properties of matrix are determined using the Mori-Tanaka Method for randomly oriented Nanotube. The effect of the percentage content of CNT on the mechanical properties of composite is investigated for randomly oriented Nanotube. This method is valid for short fibers only and the effect of aspect ratio on the mechanical properties of Nano composite cannot be studied using this method. The derived expression for the Bulk Modulus K and Shear Modulus G of a composite reinforced with randomly oriented, straight Nanotube using the Mori- Tanaka method which are given as:

$$K = K_m + \frac{C_r (C - 3K_m A)}{3(C_m + C_r A)} \quad (3.8)$$

$$G = G_m + \frac{C_r (D - 2G_m B)}{2(C_m + C_r B)} \quad (3.9)$$

Where,

$$A = \frac{3(K_m + G_m) + k_r - l_r}{3(G_m + k_r)}$$

$$B = \frac{1}{5} \left\{ \frac{4G_m + 2k_r + l_r}{3(G_m + k_r)} + \frac{4G_m}{G_m + p_r} + \frac{2[G_m(3K_m + G_m) + G_m(3K_m + 7G_m)]}{G_m(3K_m + G_m) + m_r(3K_m + 7G_m)} \right\}$$

$$C = \frac{1}{3} \left[n_r + 2l_r + \frac{(2k_r + l_r)(3K_m + 2G_m - l_r)}{(G_m + k_r)} \right]$$

$$D = \frac{1}{5} \left[\frac{2}{3}(n_r - l_r) + \frac{8G_m p_r}{G_m + p_r} + \frac{2(k_r - l_r)(2G_m + l_r)}{3(G_m + k_r)} + \frac{8m_r G_m (3K_m + 4G_m)}{3K_m(m_r + G_m) + G_m(7m_r + G_m)} \right]$$

Where K_m and G_m are the bulk and shear modulus of the matrix. The effective young's Modulus E and the Poisson's ratio of the material are given by the following relationship [3].

$$E = \frac{9KG}{3K + G} \quad (3.10)$$

$$\nu = \frac{3K - 2G}{6K + 2G} \quad (3.11)$$

Where k_r , m_r , l_r , n_r and p_r are the Hill's elastic Moduli for the Reinforcing phase

3.4. Multi-Scale Composite (CNT + Matrix + Fiber)

The properties of Nanocomposites are used as the elastic properties of the matrix and the fibers are reinforced into the matrix in an orthotropic way to determine the mechanical properties of multi-scale composites. Following equations reported by R. F.Gibson [1] are used in this study:

The longitudinal modulus of composite is determined by the following relationships [1]:

$$E_1 = E_f V_f + E_m V_m \quad (3.15)$$

The transverse modulus of composite is determined by using the Halpin-Tsai relationships [1]:

$$\frac{E_2}{E_m} = \frac{1 + \xi\eta V_f}{1 - \eta V_f} \quad (3.16)$$

Where,

$$\eta = \frac{(E_f / E_m) - 1}{(E_f / E_m) + \xi} \quad (3.17)$$

The in plane shear modulus is determined by using the following relationship [1]:

$$\frac{G_{12}}{G_m} = \frac{1 + \xi\eta V_f}{1 - \eta V_f} \quad (3.18)$$

Where,

$$\eta = \frac{G_{12f} / G_m - 1}{G_{12f} / G_m + \xi} \quad (3.19)$$

Where,

E_f, E_m = Young's Modulus of fiber and Matrix.

V_f, V_m = Volume fraction of fiber and matrix.

G_f, G_m = Shear Modulus of fiber and matrix.

ξ = Curvature fitting parameter.

3.5. Limitations of Mori-Tanka Model [36]:

1. Mori-Tanka method used for inclusion only.
2. We can not vary the aspect ratio in Mori-Tanka method while aspect ratio can be vary in Halpin T-sai model and Modified series model.

Due to these reasons we can not used Mori-Tanka method to find out elastic properties of Multi-scale composites.

Evaluation of Elastic Properties of Multi-scale Composites

4.1 Introduction:

This chapter deals with the evaluation of the elastic properties of CNT reinforced multi-scale composite. First step is to validate the elastic properties of CNT reinforced polymer by using different models (Halpin-Tsai model and Modified series model). Firstly, CNT is dispersed in an isotropic manner in a matrix and the improved elastic properties of matrix are obtained by using the Halpin-Tsai model. Then, CNT reinforced polymer matrix is treated as a new matrix and E-Glass fibers are reinforced in an orthotropic manner into the matrix. Micromechanics approach is used to determine the elastic properties of multi-scale composites. The effects of single-walled carbon nanotubes (SWCNT) and multi-walled carbon nanotubes (MWCNT) on the elastic properties of Multi-scale composites are investigated

4.2 Validation:

To compare different models, following properties of matrix and CNT reported by Kanagaraj [30] are used:

Poisson ratio of nano tube=0.33, Young's modulus of CNT=910 GPa

Young's modulus of HDPE=1.0935 GPa, Aspect ratio of CNT=86

The values of the Young's modulus of CNT reinforced matrix are calculated using Halpin-Tsai model and Modified series model and compare with the results due to S.Kanagaraj[30]. The effect of CNT% on the Young's modulus of matrix from different models are calculated for different CNT% content by keeping the aspect ratio constant(86)[30]. It has been observed that Halpin-Tsai model gives closer values to the experimental values as compare to Modified series model as shown in Fig. 4.1. So we will use Halpin T-sai model to evaluate the elastic properties of multi-scale composites.

Table 4.1: Comparison of Young's modulus of randomly oriented CNT

CNT%	Kanagaraj(2007) [30]	Halpin-Tsai Model [26]	Modified series Model[30]
0	1.095	1.095	1.095
.11	1.169	1.1651	1.1674
.22	1.228	1.2353	1.2488
.33	1.287	1.3056	1.3344
.44	1.338	1.3761	1.4229

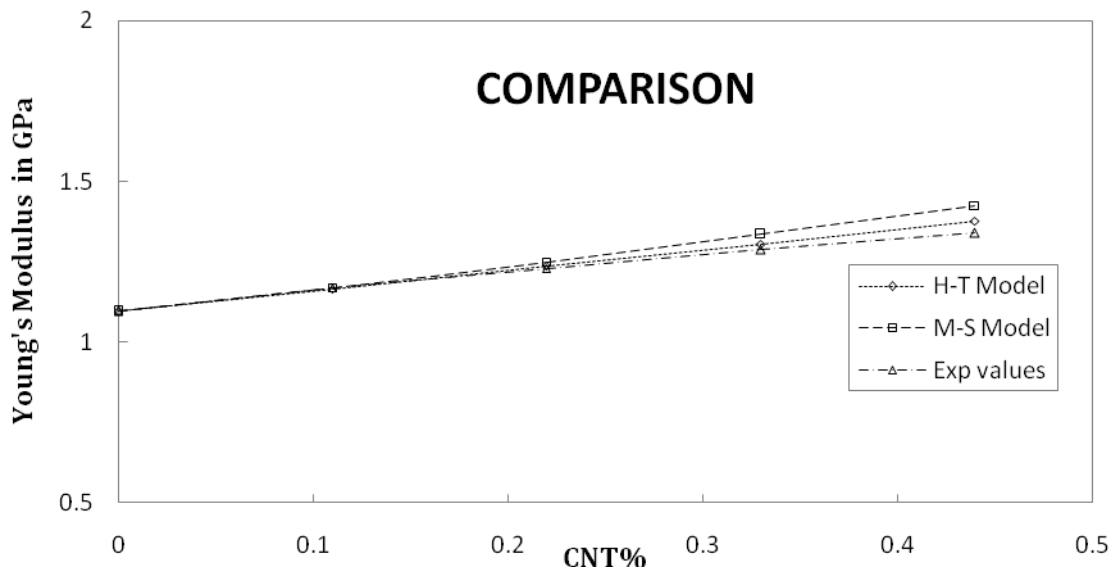


Fig 4.1 :- Effect of CNT% on Young's Modulus of CNT reinforced polymer by different Models

4.3. Results and Discussion:

Following elastic properties of SWCNT and MWCNT are taken for further evaluation of the multi-scale composites properties (Kim, et al.) [26]

Table 4.2: Properties of SWCNT and MWCNT

S.No.	Property	SWCNT's	MWCNT's
1.	Diameter	1.4nm	20nm
2.	Length	25 μ m	50 μ m
3.	Young's modulus	640GPa	400GPa

Density of CNT= 1.35g/cc

Density of epoxy = 1.2g/cc

Tensile modulus of epoxy= 2.72 GPa

Poisson's ratio of nanotube =0.33

Thickness of nano tube= 0.34

Volume of matrix = 0.2

Properties of E-Glass Fiber:

Young's modulus of fiber = 69GPa

Poisson 's ratio= 0.22

Shear modulus of fiber=28.28GPa

Volume of fiber = 0.8

The effect of CNT% and aspect ratio on the elastic properties of multi-scale composite are presented herein. Fig. 4.2 and 4.3 show the effect of CNT% (SWCNT and MWCNT) on the young's modulus and shear modulus of matrix respectively. It is observed that at 3% CNT, increase in young's modulus of matrix is due to dispersion of SWCNT and MWCNT in matrix is 50.19% and 46.62% respectively. It is observed that at 4% CNT, increase in shear modulus of matrix is due to dispersion of SWCNT and MWCNT in matrix is 67.60% and 62.76% respectively.

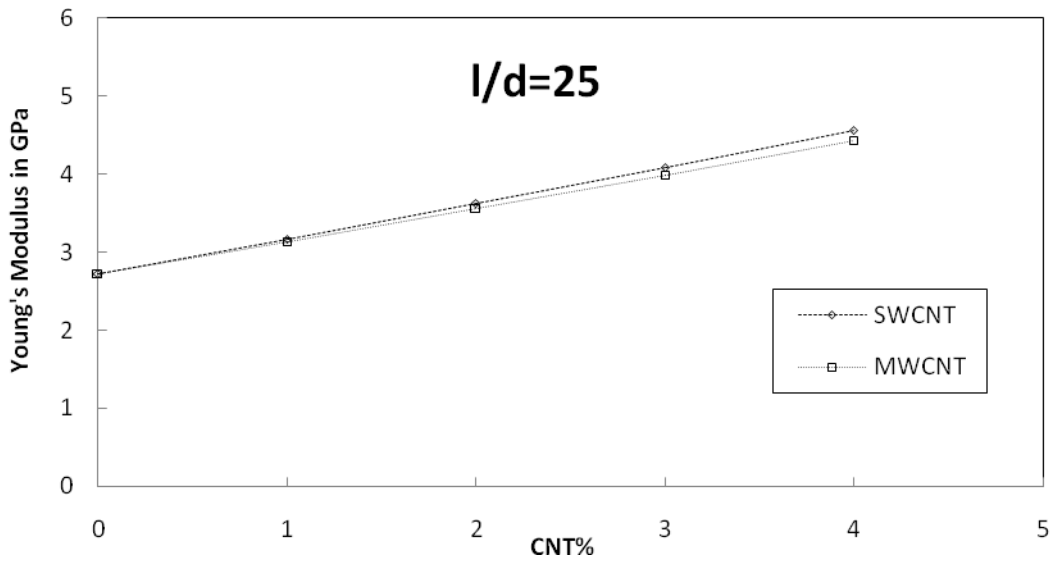


Fig. 4.2 :- Effect of CNT% on young's modulus of matrix

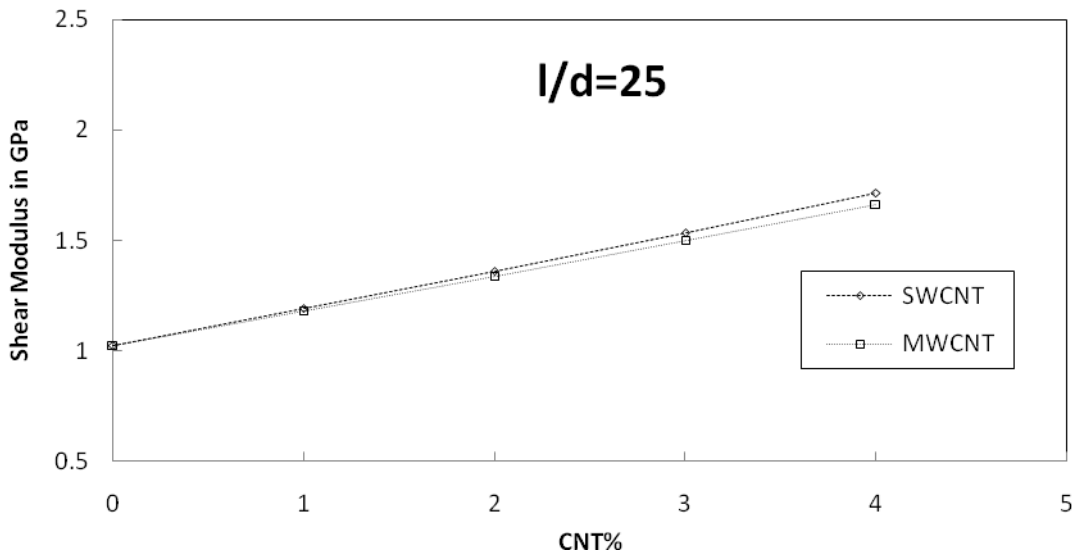


Fig. 4.3 :- Effect of CNT% on Shear modulus of matrix

Fig. 4.4 and 4.5 shows effect of CNT% (SWCNT and MWNT) on young's modulus and shear modulus of matrix respectively at aspect ratio 100. It is observed that at 2% CNT increase in young's modulus of matrix due to dispersion of SWCNT and MWCNT in matrix is 86.58% and 70.69% respectively. At 1 % CNT increase in shear modulus of matrix due to dispersion of SWCNT and MWCNT in matrix is 42.98 and 35.13 respectively

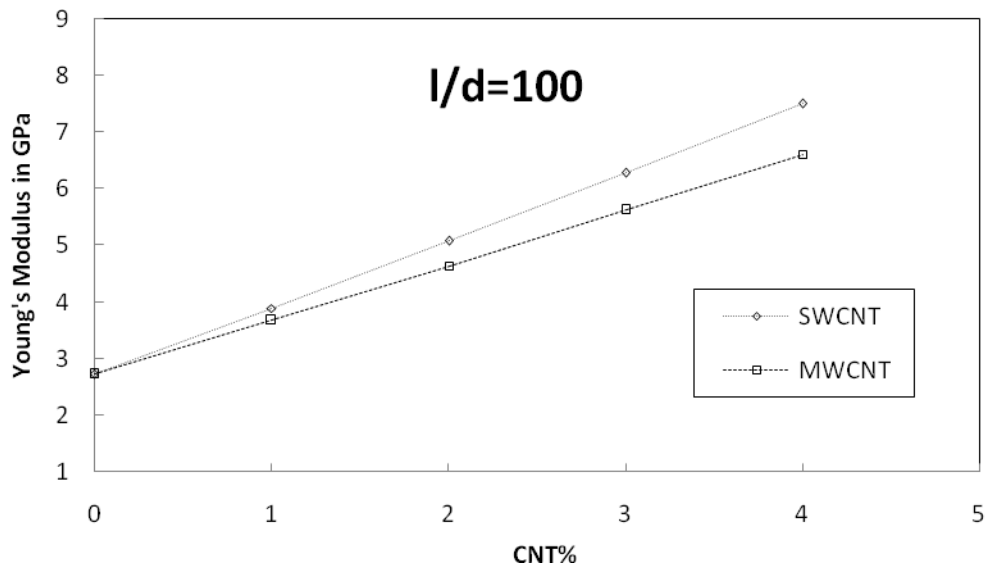


Fig. 4.4 :- Effect of CNT% on young's modulus of matrix

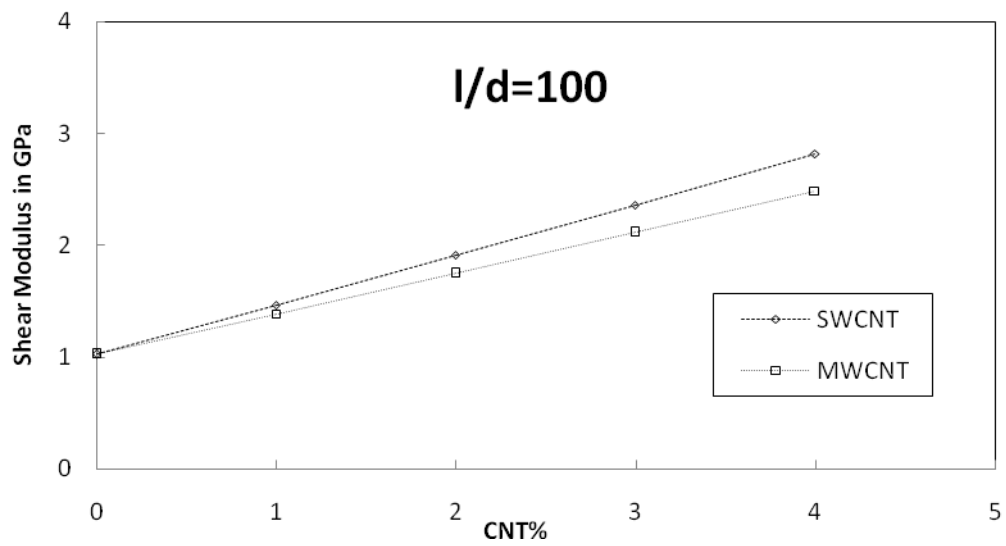


Fig. 4.5 :- Effect of CNT% on shear modulus of matrix

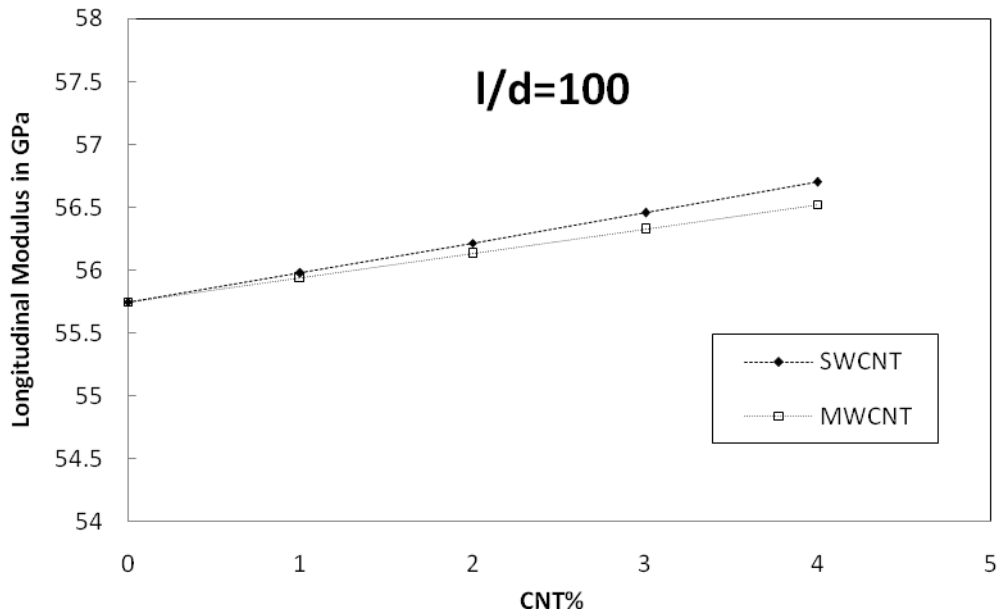


Fig. 4.6 :- Effect of CNT% on longitudinal modulus of polymer

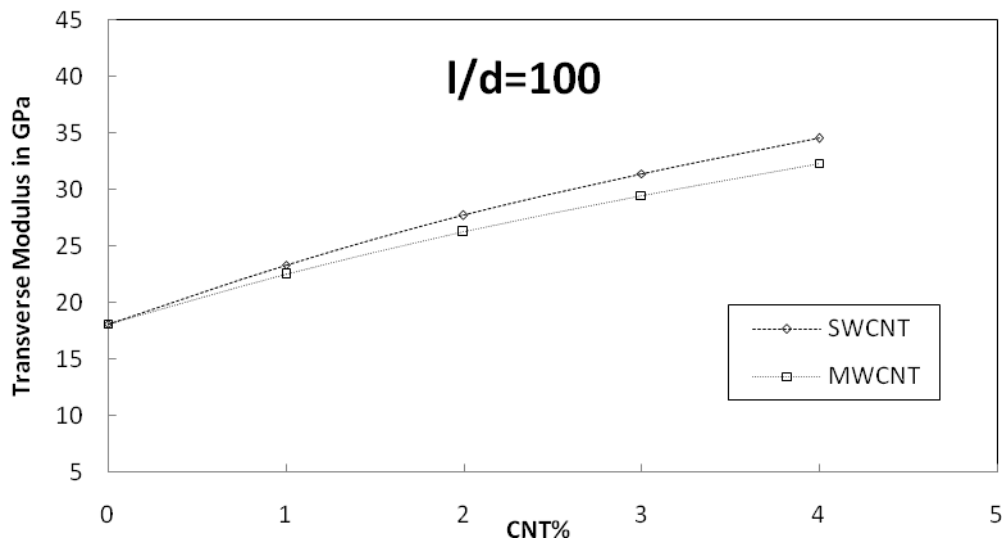


Fig. 4.7 :- Effect of CNT% on transverse modulus of polymer

Fig. 4.6 and 4.7 shows effect of CNT% (SWCNT and MWCNT) on the longitudinal modulus and transverse modulus of multi-scale composite at aspect ratio 100. It is observed that there is small variation in the longitudinal modulus of multi-scale composite , due to the fiber dominance in the longitudinal direction. It is observed that increase in value of

transverse modulus is 52.67% and 44.47% due to inclusion of 2% SWCNT and MWCNT respectively.

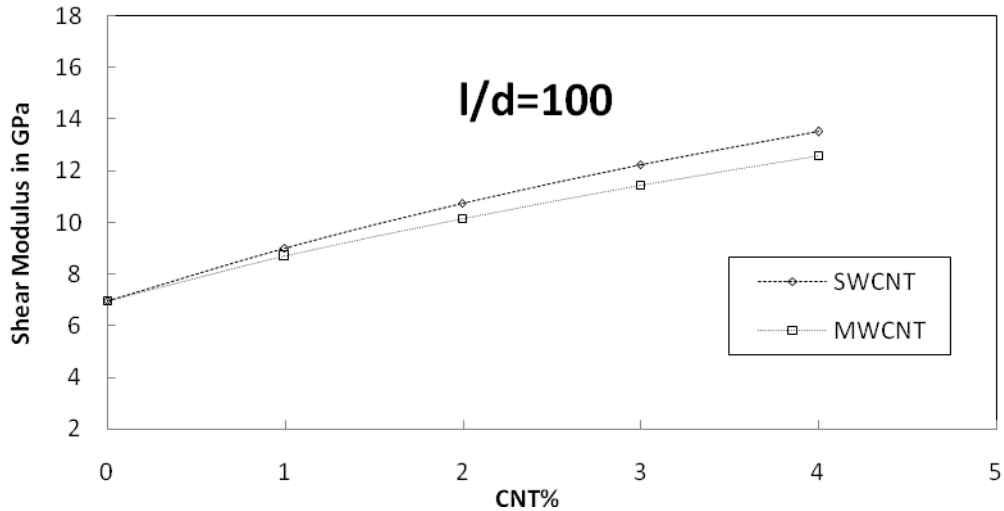


Fig 4.8 :-Effect of CNT% on shear modulus of polymer

Fig. 4.8 show the effect of CNT% (SWCNT and MWCNT) on the shear modulus of multi-scale composite. It is observed that increase in values of shear modulus is 54.39% and 45.84% due to inclusion of 2% SWCNT and MWCNT respectively.

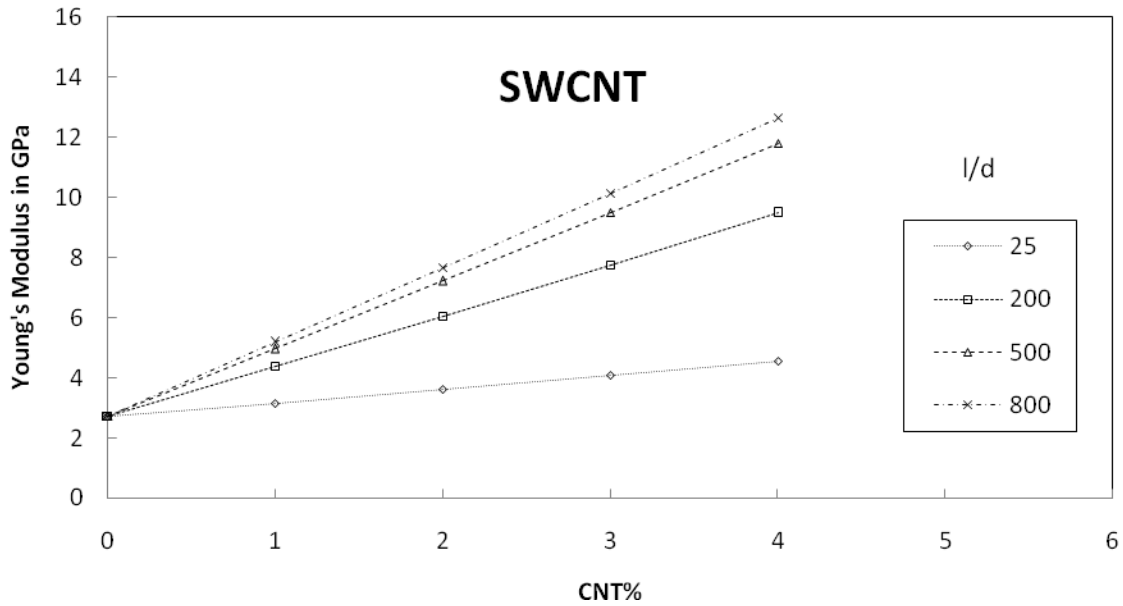


Fig. 4.9 :- Effect of CNT% on young's modulus of matrix for SWCNT

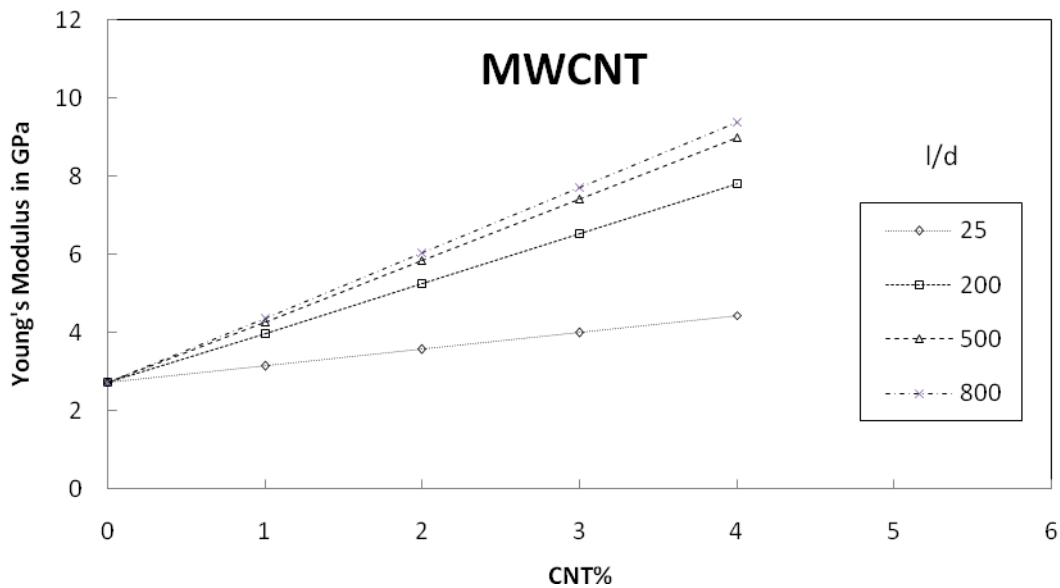


Fig. 4.10 :- Effect of CNT% on young's modulus of matrix for MWCNT

Fig. 4.9 and 4.10 show effect of CNT% on young's modulus for SWCNT and MWCNT at different aspect ratios. It shows that young's modulus of matrix is increased by increasing CNT% as well as aspect ratio. The value of young's modulus is more in case SWCNT as compare to MWCNT. By increasing 1% CNT, at aspect ratio 25 the value of young's modulus increased by 16.43% by dispersion of SWCNT while in case of MWCNT increase in value of Young's modulus is 15.28%.

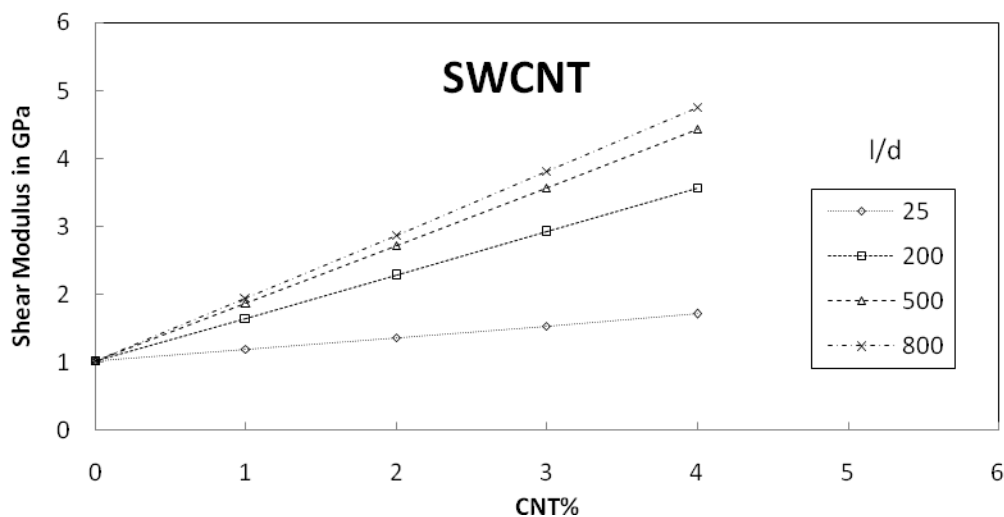


Fig. 4.11 :- Effect of CNT% on shear modulus of matrix for SWCNT

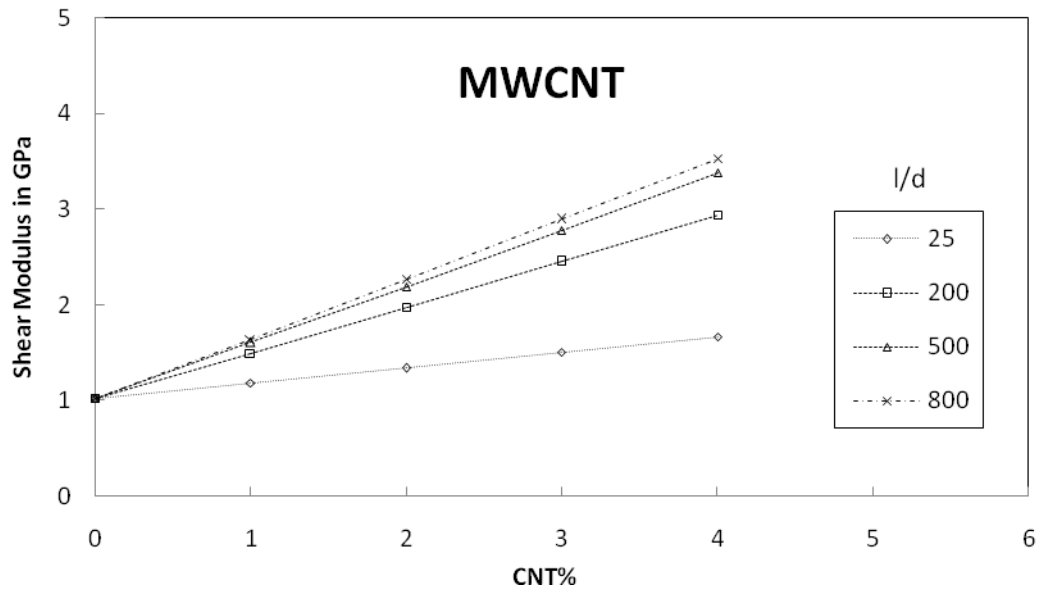


Fig. 4.12 :- Effect of CNT% on shear modulus of matrix for MWCNT

Fig. 4.11 and 4.12 show the effect of CNT% on shear modulus of matrix for SWCNT and MWCNT at different aspect ratio. It is observed that shear modulus of matrix is slightly increased with the dispersion SWCNT as compare to MWCNT. By increasing 2% CNT, at aspect ratio 25 the value of shear modulus is increased by 33.17% by dispersion of SWCNT while in case of MWCNT increase in value shear modulus is 30.83%.

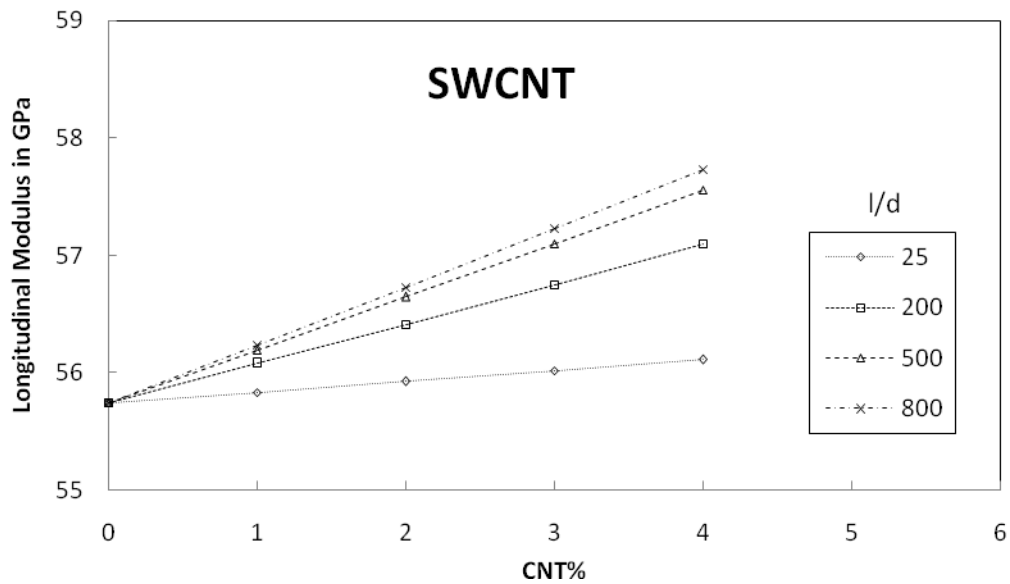


Fig 4.13:- Effect of CNT% on longitudinal modulus of polymer for SWCNT

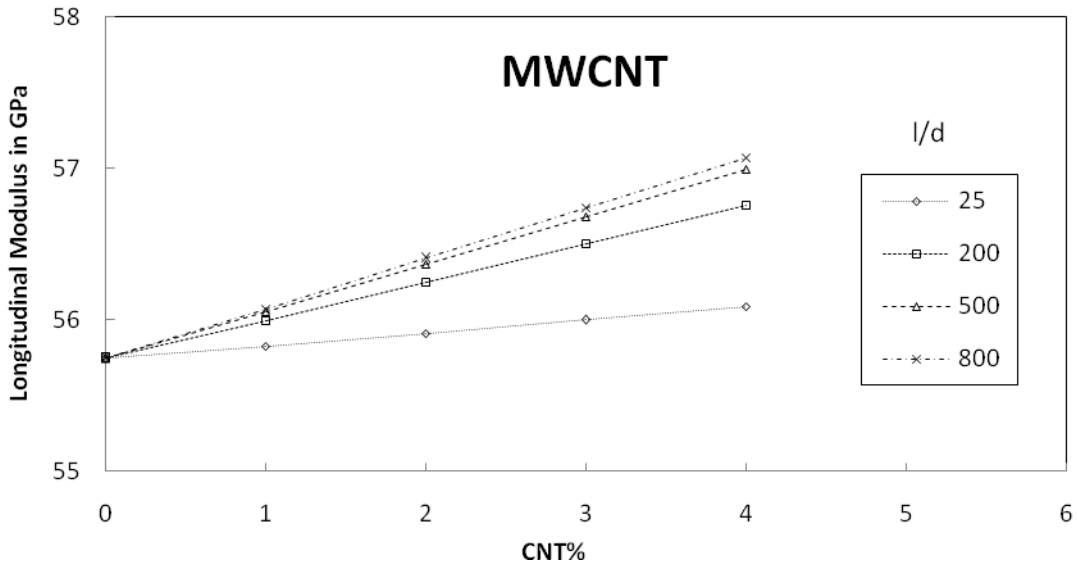


Fig. 4.14:-Effect of CNT% on longitudinal modulus of polymer for MWCNT

Fig. 4.13 and 4.14 show the effect of CNT% on longitudinal modulus of polymer for SWCNT and MWCNT at different aspect ratio. Longitudinal modulus of polymer is slightly increased by increasing CNT% and aspect ratio. The value of longitudinal modulus in case of SWCNT is slightly greater than MWCNT. By increasing 4% CNT , at aspect ratio 200 increase in value of longitudinal modulus of polymer is 2.42% by dispersion of SWCNT while by dispersion of MWCNT the increase in value of longitudinal modulus is 1.82%.

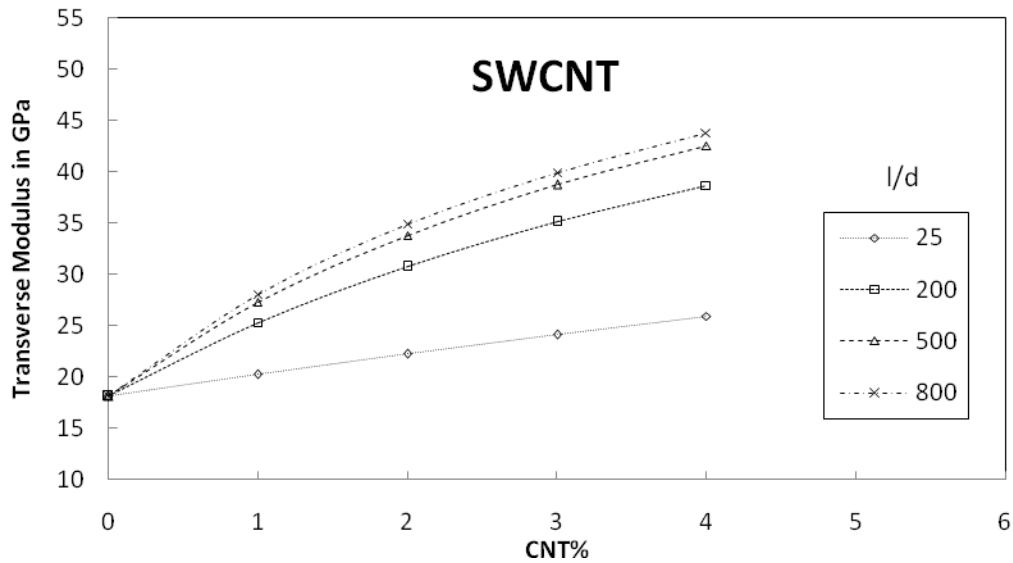


Fig. 4.15:- Effect of CNT% on transverse modulus of polymer for SWCNT

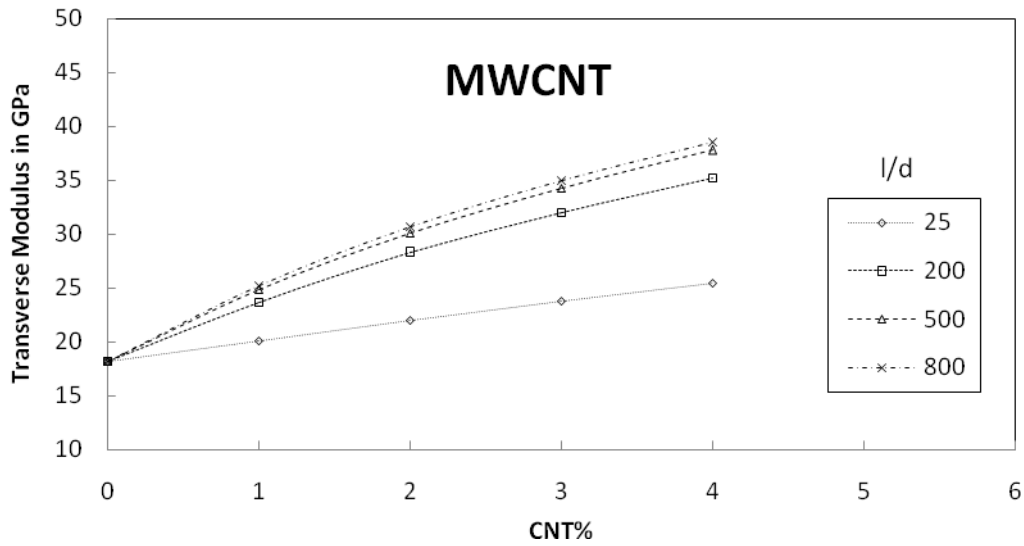


Fig. 4.16:-Effect of CNT% on transverse modulus of polymer for MWCNT

Fig. 4.15 and 4.16 show the effect of CNT% on transverse modulus of polymer for SWCNT and MWCNT at different aspect ratio. It is observed that transverse modulus of polymer is increased by increasing CNT% and aspect ratio. By increasing 1% CNT at aspect ratio 200 increase in value of transverse modulus of polymer is 39.26% by dispersion of SWCNT while by dispersion of MWCNT the increase in value of transverse modulus is 30.64%.

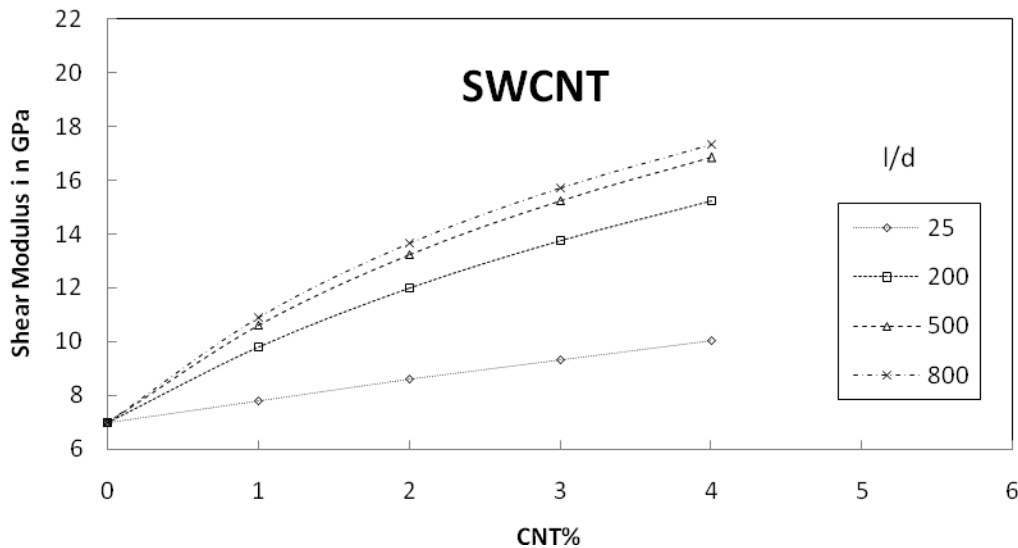


Fig. 4.17:- Effect of CNT% on shear modulus of polymer for SWCNT

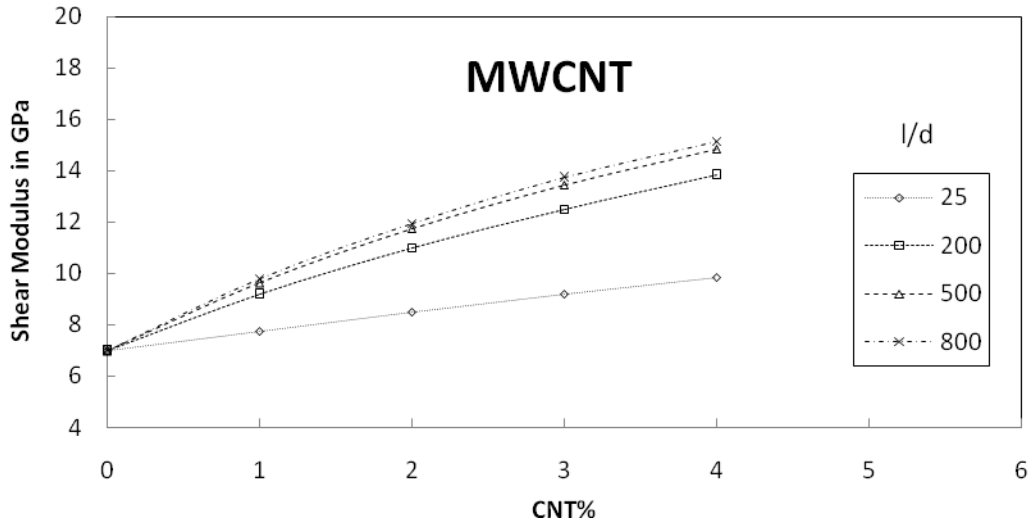


Fig. 4.18:- Effect of CNT% on shear modulus of polymer for MWCNT

Fig. 4.17 and 4.18 show the effect of CNT% on shear modulus of polymer for SWCNT and MWCNT at different aspect ratio. As shown in figures shear modulus polymer is increased by increasing CNT% as well as by increasing aspect ratio. The improvement in value of shear modulus of polymer by dispersion of SWCNT is more than dispersion of MWCNT. By increasing 1% CNT at aspect ratio 200, the increase in the value of shear modulus of polymer is 40.43% while in case of MWCNT the value of shear modulus of polymer is 31.49%

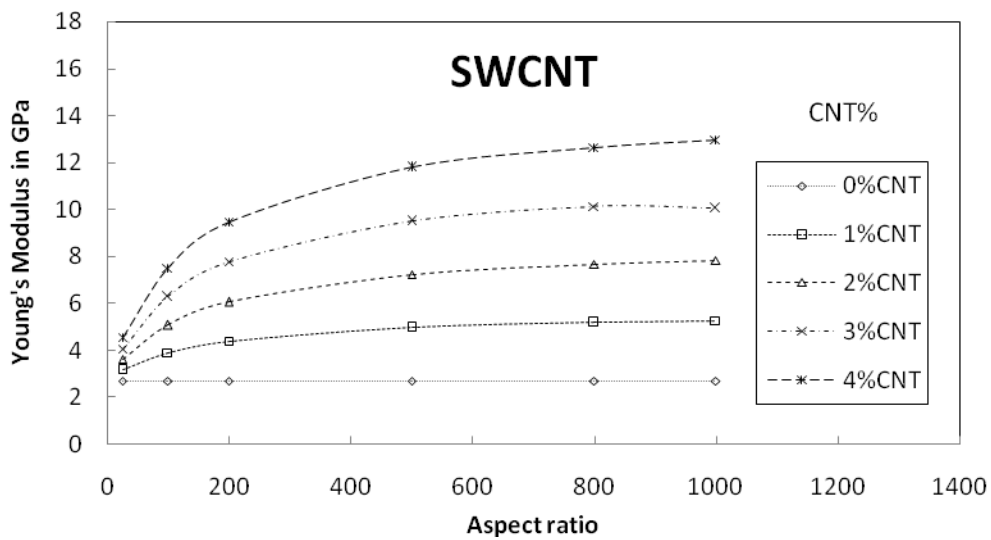


Fig. 4.19:-Effect of aspect ratio on the Young's modulus of matrix of SWCNT

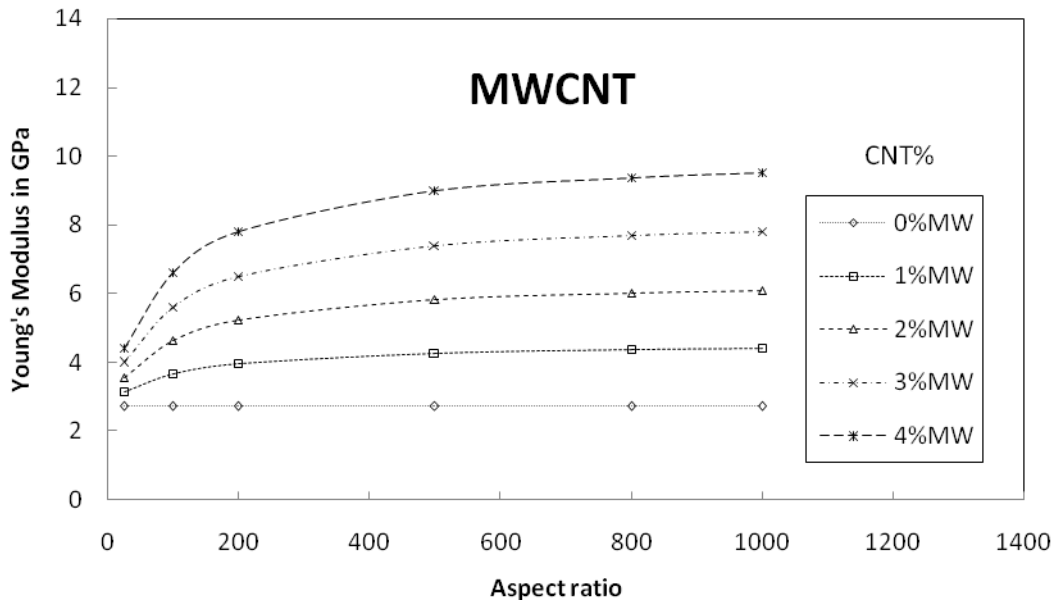


Fig. 4.20:- Effect of aspect ratio on Young's modulus of matrix of MWCNT

Fig. 4.19 and 4.20 show the effect of aspect ratio on the Young's modulus of matrix reinforced with SWCNT and MWCNT. It is observed that the effect of CNT reinforcement on the Young's modulus of matrix is notable for the aspect ratio between 200 to 400.

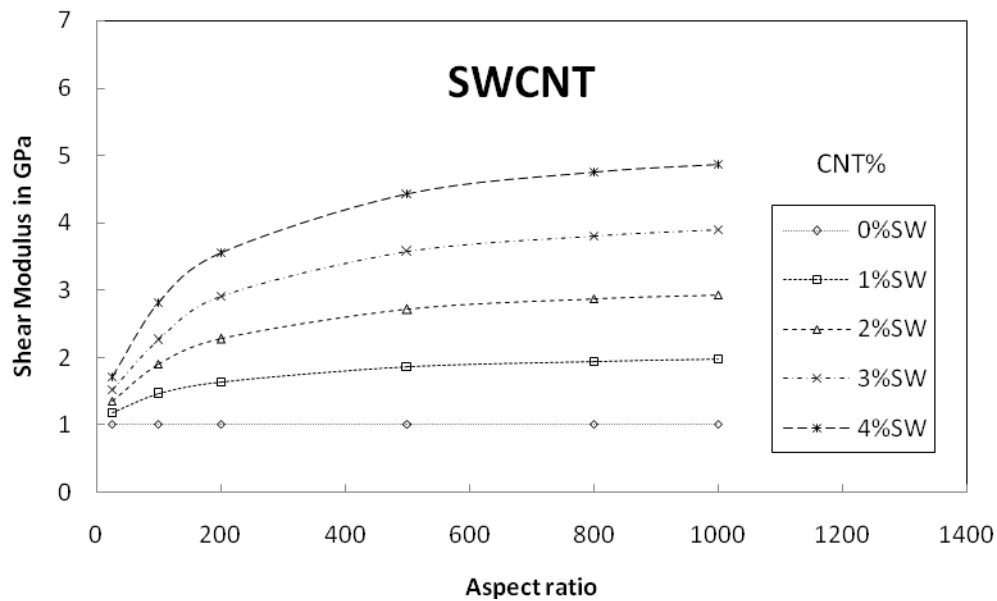


Fig. 4.21:- Effect of aspect ratio on shear modulus of matrix for SWCNT

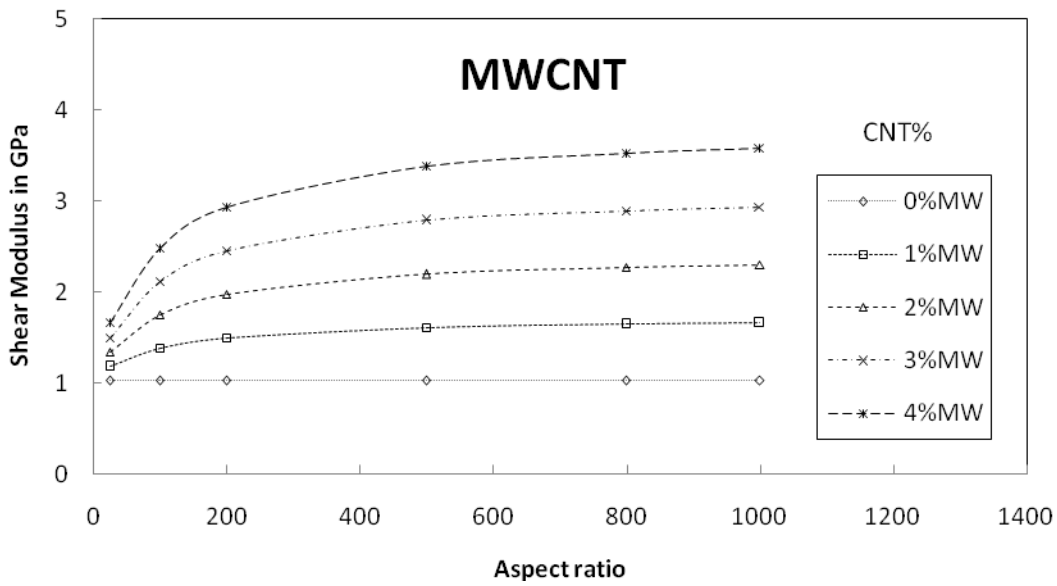


Fig. 4.22:- Effect of aspect ratio on shear modulus of matrix for MWCNT

Fig. 4.21 and 4.22 show the effect of aspect ratio on the shear modulus of matrix for the reinforcement of SWCNT and MWCNT. It is concluded that as the CNT% is increased, the improvement in the shear modulus of matrix is observed. The improved properties are obtained by dispersing more SWCNT as compare to the MWCNT.

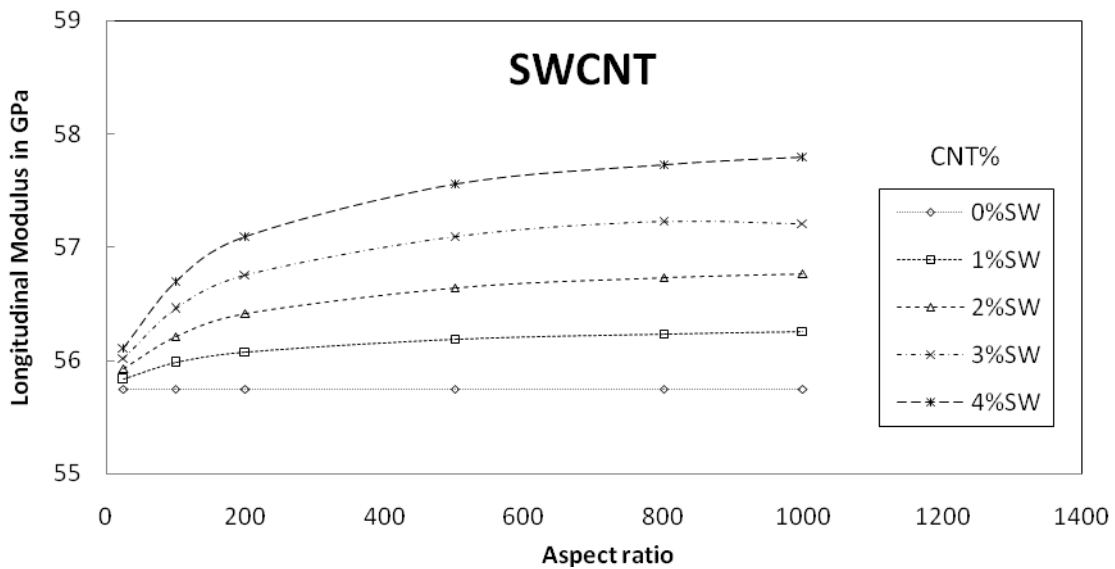


Fig. 4.23:-Effect of aspect ratio on Longitudinal modulus of multi-scale composite SWCNT dispersed

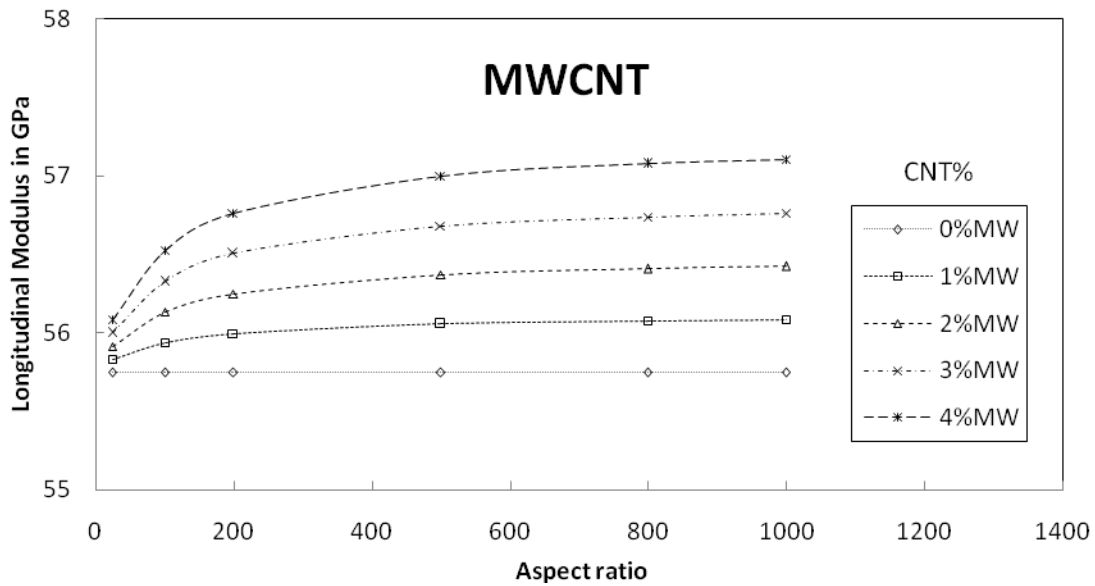


Fig 4.24:- Effect of aspect ratio on Longitudinal modulus of multi-scale composite MWCNT dispersed

Fig. 4.23 and 4.24 show the effect of aspect ratio on the longitudinal modulus of multi-scale composite for the reinforcement of SWCNT and MWCNT in multi-scale composite respectively. It is observed that there is small increment in the longitudinal modulus as with increase in the longitudinal modulus as with increase in the CNT%

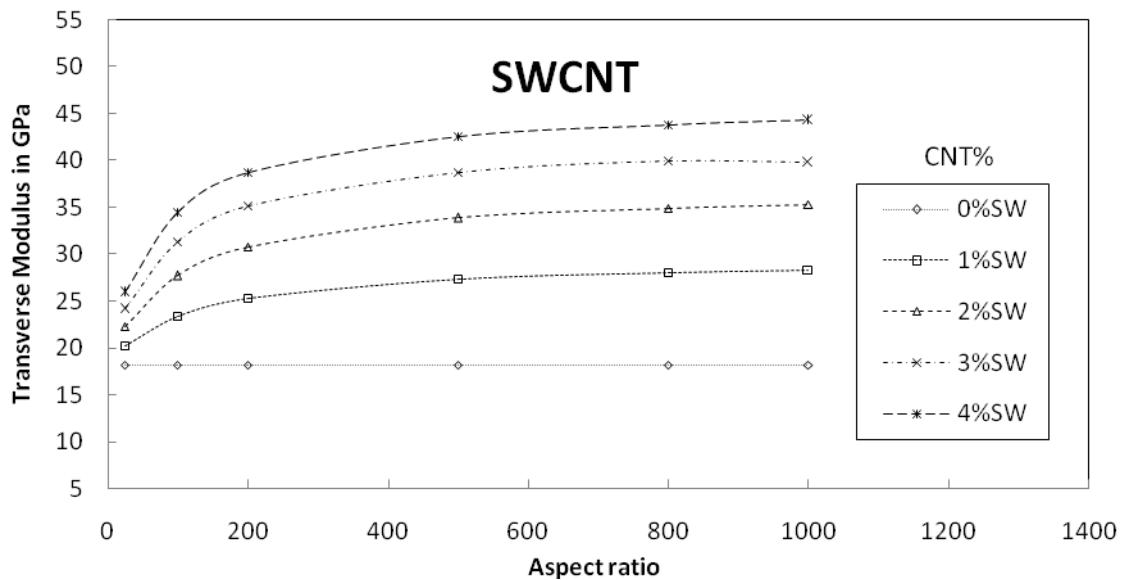


Fig. 4.25:-Effect of aspect ratio on Transverse modulus of multi-scale composite SWCNT dispersed

Fig. 4.25 and 4.26 show the effect of aspect ratio on the transverse modulus of multi-scale composite for the reinforcement of SWCNT and MWCNT in the multi-scale composite respectively. There is significant improvement in the transverse modulus value with the CNT%..

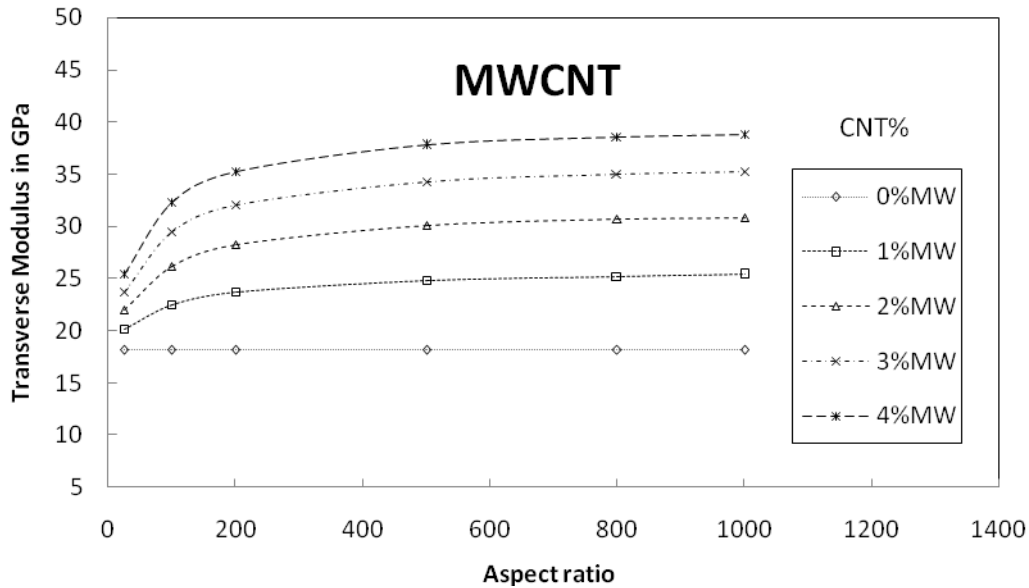


Fig. 4.26:-Effect of aspect ratio on Transverse modulus of multi-scale composite MWCNT dispersed

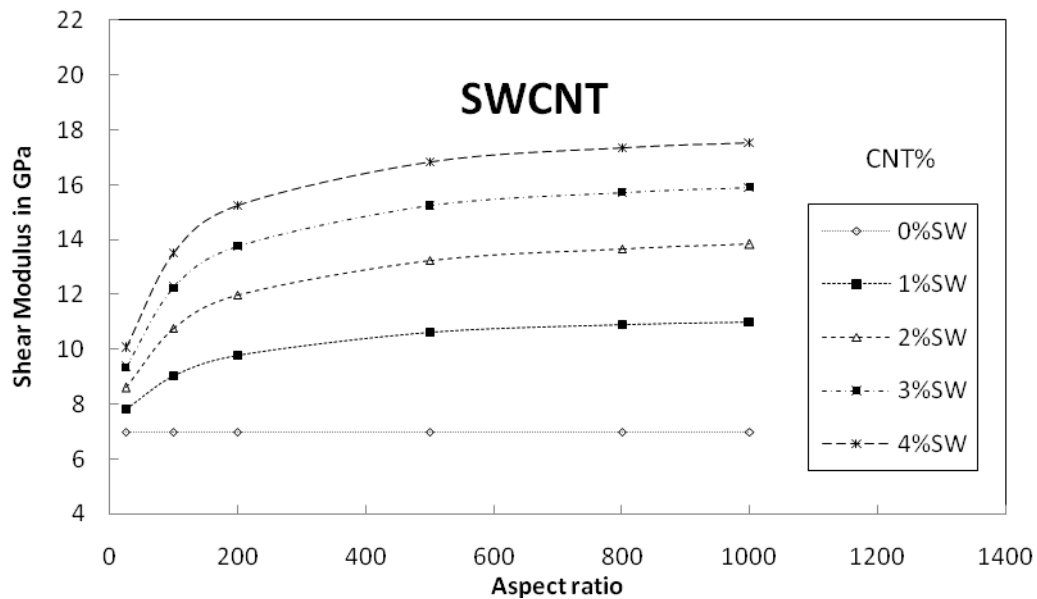


Fig. 4.27:- Effect of aspect ratio on Shear modulus of multi-scale composite SWCNT dispersed

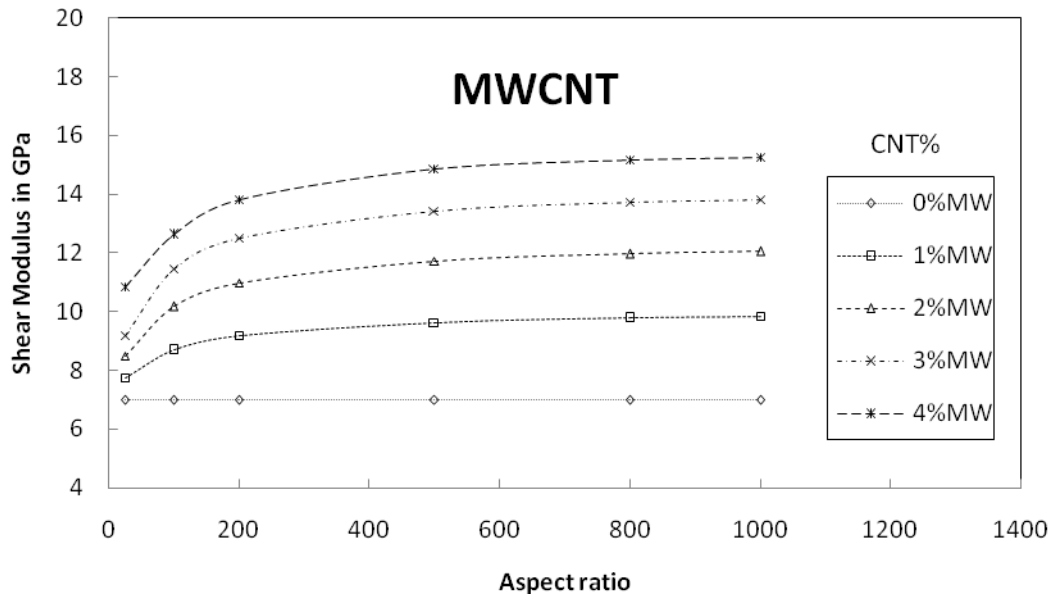


Fig. 4.28:- Effect of aspect ratio on Shear modulus of multi-scale composite MWCNT dispersed

Fig. 4.27 and 4.28 show the effect of the aspect ratio on the shear modulus of multi-scale composite for the reinforcement of SWCNT and MWCNT in a multi-scale composite, significant improvement in the shear modulus is observed.

Chapter 5

Conclusions

1. It is observed that even with the small percentage of CNT in a matrix, there is considerable improvement in the elastic properties of matrix.
2. It is observed that there is small increment in the longitudinal modulus of polymer with increase in percentage of CNT. But there is significant improvement in transverse and shear modulus of polymer with increase in percentage of CNT.
3. It is concluded that the SWCNT has more pronounced effect on the elastic properties of multiscale composites as compare to MWCNT.
4. It is observed when CNT used as inclusion in multiscale composites, no improvement in properties is observed for even large percentage content of CNT. When the aspect ratio is between 50 to 400, there is significant improvement in the elastic properties of multiscale composites.

CHAPTER 6

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