Chapter 1
Introduction

1.1. Overview

In this chapter, a brief introduction to the various types of composite plate, sandwich plate, and carbon nanotubes reinforced composite plates and their mechanical behavior followed by the modeling approaches and the fabrication techniques are studied in detail. Also, the overview of the structural use of carbon nanotube reinforced composite plate followed by its elastic medium interaction is presented along with its various modeling approaches which includes analytical and finite element approach is discussed here. Further, a review on finite element method, modeling of CNTs and selection of element types and material properties are also discussed. We also discussed the challenges associated with modeling of CNT reinforced composite plates, including the effects of CNT orientation and interfacial bonding.

1.2. Composite and sandwich plates

A composite is a structural material that consists of mainly two parts i.e. reinforcement and matrix. The reinforcement is present in the form of fiber and typical fibers include graphite, boron, cellulose, CNTs and, glass, etc. The matrix is present in the form of continuous and typical matrix materials are epoxies, polyimides, titanium, PMMA, PmPV and aluminium, etc. The reinforcement and matrix are combined at a macroscopic level and not soluble in each other, due to which this combination at the macroscopic label creates a new material with advanced properties, unlike the parent constituent materials. In today’s modern science and technology industry, composite materials are widely used because of its enhanced property like light weight, high flexural stiffness, good fatigue, thermal and damping resistance.

The composite material is classified as follows:

- Natural composite materials
- Manmade composite materials

The natural composite materials are present in the nature and develop by itself as time passes. The typical natural composite materials are human bone and teeth, wood, pearls, mother of pearl and related shell structures etc. The manmade composite materials are developed by human. The typical manmade composite materials are sporting goods, wind turbine blades, aircraft structures, and automobile structures etc.

The composite materials are formed in following ways:

- Fibrous composites
- Particulate composites
- Laminated composites

The fibrous composite consist of reinforced material which is selected in such a way that it has lightweight and high modulus. The selected reinforced material is embedded in the matrix to produce the fibrous composite. Typical examples of fibrous composites include fiberglass and wood. The properties of aligned fibrous composite materials are highly anisotropic i.e. the properties of the composites can be varied by changing the direction of the reinforcement. The longitudinal tensile strength will be high whereas the transverse tensile strength can be much less than even the matrix tensile strength. Fibrous composite materials are widely used in the mechanical, aerospace, and naval industries, because of the high stiffness and strength. A particulate composite is characterized as being composed of particles suspended in a matrix. Particles can have virtually any shape, size or configuration. A popular example of particulate composite is concrete. The main benefit of particle-reinforced composites is their low cost and ease of production and forming compared to fiber-reinforced ones. In particular, particulate-reinforced composites find applications where high levels of wear-resistance are required such as road surfaces. To achieve the required engineering properties the fibrous composite stacked together in the thickness direction which is referred as the laminate composite. The single particulate composite is referred as lamina. The fibers in the lamina can be continuous or discontinuous, unidirectional, bi-directional, and woven. The difference between the continuous and discontinuous fibers is that continuous fibers have a long aspect ratio and generally have a preferred orientation while the discontinuous fibers have a short aspect ratio and have random orientations. Like the fibrous composite, in laminate composite the properties of aligned fibrous composite materials are highly anisotropic i.e. the properties of the composites can be varied by changing the direction of the reinforcement. The longitudinal tensile strength will be high whereas the transverse tensile strength can be much less than even the matrix tensile strength.

A sandwich structure is also a composite material that is fabricated by combining a lightweight and thick core which generally has a low strength material and its thickness provides higher bending stiffness with overall low density with stiff and strong upper and lower face sheet. The materials used in the core are structured foams like polyvinylchloride, polystyrene, polyethylene, polyurethane, polyethersulfone, balsa woods and syntactic foams, etc. The materials used in face sheets are the carbon or glass fiber-reinforced. In today’s modern science and technology industry, sandwich composite materials are widely used because of its enhanced properties like light weight, high bending stiffness and high strength-to-weight ratio. The upper and lower face sheets take over the bending loads whereas, the core carries the shear loads on the structure.

1.3. Carbon nano tubes

Carbon nanotubes (CNTs) have been extensively studied over the last few decades due to their exceptional mechanical and electrical properties. These properties make them an ideal material for a wide range of applications, such as nanoelectronics, energy storage devices, and reinforced composites. In this section, we will explore the recent developments in the synthesis and functionalization of CNTs for their various applications. We will also discuss the recent progress in the fabrication of CNT-reinforced composites and their mechanical behavior.

As mentioned in the section 1.3, CNTs have a high strength-to-weight ratio, high thermal conductivity, and excellent electrical conductivity. Therefore, they have been incorporated into polymer matrices to form CNT-reinforced polymer composites, which have improved mechanical, thermal, and electrical properties over conventional composites. The mechanical behavior of CNTs has been investigated both experimentally and theoretically. The mechanical properties of CNTs, such as their high stiffness and strength, have been shown to be transferred to the composite matrix, resulting in enhanced mechanical properties. In addition, the interaction between the CNTs and the matrix has been shown to play a significant role in determining the mechanical behavior of the composite. This interaction can be enhanced through functionalization or surface modification of the CNTs. One of the challenges in designing CNT-reinforced composites is to optimize the distribution of the CNTs within the matrix. The distribution of the CNTs can significantly affect the mechanical behavior of the composite. Therefore, various techniques has been developed to improve the dispersion of the CNTs within the matrix, such as sonication, shear mixing, and electrospinning.

The synthesis of CNTs has been a challenging task due to their small size and high aspect ratio. Several methods have been developed for the synthesis of CNTs, including chemical vapor deposition (CVD), arc discharge, laser ablation, and high-pressure carbon monoxide (HiPCO) method. Among these methods, CVD is the most widely used method for the synthesis of high-quality CNTs. Recently; efforts have been made to improve the synthesis of CNTs by controlling the growth conditions and using different catalysts. The use of different catalysts, such as nickel, iron, and cobalt, has been investigated to improve the selectivity and yield of CNTs. In addition, the use of different carbon sources, such as methane and ethylene, has been investigated to control the morphology and structure of CNTs. Functionalization of CNTs involves modifying their surface chemistry to improve their dispersibility in different solvents and matrices. The functionalization of CNTs has been shown to improve their mechanical and electrical properties and enable their use in various applications. Several methods has been developed for the functionalization of CNTs, including covalent functionalization, non-covalent functionalization, and electrostatic assembly. Covalent functionalization involves the chemical modification of the CNT surface by attaching functional groups, such as carboxylic acids or amines, to the surface of the CNTs. Non-covalent functionalization involves the adsorption of molecules onto the CNT surface through van der Waals interactions. Electrostatic assembly involves the deposition of charged molecules onto the CNT surface through electrostatic interactions. CNTs have been incorporated into polymer matrices to form CNT-reinforced composites, which have improved mechanical, thermal, and electrical properties over conventional composites. Chemical and physical processes are used to synthetize nanoparticles with specific intended properties. Fullerene (C60), fullerenes C20, C240, C540…, carbon nanotube, graphene, carbon nanotorus, carbon nanobud, peapod, cup-stacked carbon nanotube, nanodiamond, amorphous carbon, diamond, graphite, lonsdaleite and carbon nano-onions are some well-known forms of carbon allotropes. The carbon is a tetravalent chemical element has atomic number 6 has four electrons available to form covalent chemical bonds. The electrons of the carbon are arranged in $1s^2 2s^2 2p^2$ atomic orbital. The hybridization of carbon is sp, sp^2, or sp^3. Iijima (1991) deals with the formulation of needle type tube structure by arc-discharge method, which is referred as the CNTs. CNTs are the allotropes of carbon which has high aspect ratio Iijima *et al.* (1991). Single-layer of carbon atoms are referred as the graphene sheet, that rolled-up sheets of graphene in the form of the cylindrical molecules is addressed as the CNTs. Carbon nanotubes attract the attention it is the strongest material known which is generally considered as weightless material and possess very high flexibility.

Techniques use for the synthesis of the CNTs

- Arc discharge method
- Laser ablation method
- Chemical vapour deposition method

Arc discharge method is the elderly and famous process of the synthesis of the CNTs. At the high temperature of 1700^{o}C, low pressure and using expensive noble gases, carbon atoms transformed into plasma providing the growth of CNTs. Laser ablation method is very much interesting for the synthesis of the single walled carbon nanotubes (SWCNTs). In the synthesis of the SWCNTs, laser with the noble gases is passed with the quartz tube and hit the target at the high temperature in the range (800-1400°C) along with the pressure in the range of (200-400 Torr). Different Chemical vapour deposition methods are plasma enhanced chemical vapour deposition method (PECVD), microwave plasma chemical vapour deposition method (MPECVD), radiofrequency chemical vapour deposition method (RF-CVD), hot-filament chemical vapour deposition method (HFCVD), oxygen assisted chemical vapour deposition method, water assisted chemical vapour deposition method, and floating catalyst chemical vapour deposition method (FCCVD).

Types of Carbon Nanotubes

Carbon nanotubes can be single-walled (SWCNTs) or multi-walled (MWCNTs), depending on the number of graphene sheets rolled up. CNTs have a high strength-to-weight ratio, high stiffness, and excellent electrical and thermal conductivity. These properties make them an ideal material for reinforcement in polymer matrices. The Single-walled Carbon nanotubes are an 1-D structure formed by rolling-up the sheets of graphene in the form of the cylindrical molecules. Chiral, achiral, armchair and zig-zag are some popular forms of the SWCNT. Chiral SWCNT is handed and mirror is absent where as in the case of the achiral SWCNT it is non-handed and mirror is present. Armchair and zig-zag are the special case of the achiral SWCNT. The types discussed can be easily understood by the help of the vector which is referring as the chiral vector.

$$\vec{C} = n\vec{a}_1 + m\vec{a}_2$$

For Chiral SWCNT ($n \neq m \neq 0$), for armchair SWCNT ($n = m \neq 0$), and for zig-zag SWCNT ($n = 0$).

Properties of Single-walled Carbon Nanotubes are:

- The diameter of Single-walled Carbon nanotubes is 2nm.
- The length of Single-walled Carbon nanotubes is around 2 micrometres.
- SWCNTs exist in a one-dimensional structure. Therefore, it is also known as a nanowire.
- Electronics can be miniaturized by using a Single-walled Carbon nanotube.

- SWCNTs band gap varies from 0-2 electron volts (eV).
- SWCNTs show conductivity like a semiconductor.

It is composed of several nested carbon nanotubes. These type of nanotubes has two diameters, one is known as outer diameter and another one is known as inner diameter. Russian doll and parchment are the popular forms of the MWCNT. In case of Russian doll MWCNT, more than one sheet of graphen with inter layer separation of the 3.4 angstrom (A^o) are rolled together in the cylindrical form whereas, in the case of parchment one single sheet of graphen is rolled in the form of the parchment.

Properties of Multi-walled Carbon Nanotubes are given below:

- The outer diameter of Multi-walled Carbon nanotubes is around 2-20 nanometres.
- The inner diameter of Multi-walled Carbon nanotubes is 1-3 nm.
- The length of Multi-walled Carbon nanotubes is around 5-6 micrometres.
- Carbon nanotubes are stiff. They are as stiff as a diamond (the hardest natural material in nature).
- The gravitational weight of the nanotube is very low.
- The density of the carbon nanotubes is one-fourth of that of steel.
- Carbon nanotubes are stronger than steel. They exhibit extraordinary mechanical properties. Carbon nanotubes are ten times stronger than steel.
- Carbon nanotubes have a high thermal capacity. Generally, it is twenty times stronger than steel.
- In carbon nanotubes, each carbon atom is surrounded by three other carbon atoms through covalent bonds. These carbon-carbon covalent bonds form lattices in the shape of hexagons.
- The crystalline structure of carbon nanotubes exists in the form of regular hexagons.
- Carbon nanotubes are elastic.

- Carbon nanotubes are good conductors of heat.
- Carbon nanotubes have good electrical conductivity.
- The young's modulus is high. The young’s modulus of carbon nanotubes is around 1 terra Pascal which makes carbon nanotubes ten times stronger than steel.
- Carbon nanotubes are chemically neutral which make them chemically stable. Therefore, carbon nanotubes resist corrosion.

Applications of Carbon Nanotubes

Carbon nanotube reinforced composites have emerged as a promising material for structural applications due to their exceptional mechanical properties. By incorporating CNTs into a polymer matrix, the resulting composite material can exhibit improved strength, stiffness, and toughness, making it suitable for a wide range of structural applications. One area where CNT reinforced composites have shown particular promise is in the design of lightweight and high-strength structural components such as plates. The use of these materials has the potential to significantly reduce the weight of structural components while maintaining or even improving their strength and stiffness, which is particularly important in industries such as aerospace, automotive, and marine. In this context, the structural use of CNT reinforced composite plates has gained significant attention in recent years. Researchers have explored various fabrication techniques and composite designs to optimize the mechanical properties of these plates, and have demonstrated their potential in applications such as load-bearing structures, vibration damping, and impact-resistant panels. Overall, the use of CNT reinforced composites in structural applications, particularly in the form of plates, represents a promising avenue for the development of lightweight and high-performance materials. Ongoing research in this field is expected to yield further advancements in the design and fabrication of CNT reinforced composite plates, paving the way for their widespread use in a variety of structural applications. CNT reinforced composites have been extensively studied over the past few decades, and have been identified as promising materials for structural applications. Due to their excellent mechanical properties, including high strength, stiffness, and toughness, CNT reinforced composites have the potential to replace traditional materials such as metals and alloys in various structural applications. In recent years, the use of CNT reinforced composites in structural plates has gained considerable attention. This is because structural plates are widely used in various applications such as bridges, aircraft, spacecraft, and automobiles, where they must withstand significant loads and stresses. The addition of CNTs to the polymer matrix of the composite plates can improve their mechanical properties, making them stronger, stiffer, and more resistant to impact, fatigue, and wear. Another aspect that can affect the mechanical behavior of structural plates is their foundation. In many cases, structural plates rest on an elastic foundation, which can have a significant impact on their deformation, stresses, and stability. Therefore, studying the behavior of CNT reinforced composite plates on an elastic foundation is essential for understanding their mechanical properties and designing them for various structural applications. The various applications of CNTs are mentioned below:

- Breast cancer tumour destruction: Nanotubes are used to destroy breast cancer tumours. They play with an antibody. The antibody along with nanotubes is attracted to the proteins by cancer cells in the body and nanotubes absorb the laser beam killing the bacteria of the tumour.
- Windmill blades: Hollow tubes are also used in the windmill blades because of their low weight. It increases the efficiency of the windmill and helps to produce more electricity at a faster rate.

- Filtration: Carbon nanotubes can be used to separate particles of size greater than the diameter of carbon nanotubes during filtration through them. They can also be used to trap smaller sized ions from a solution.
- Carbon nanotubes as Nano cylinders: Gas like H_2, for energy, battery for vehicles can be safely stored inside the carbon nanotubes and the problem of H_2 storage hazards can be solved. Carbon nanotubes have also been shown to absorb infrared light and may have applications in the IR optics industry.
- Aircraft stress reduction: Nanotubes are also used in space and aircraft to reduce the weight and stress of the various components working together.
- Other uses of carbon nanotubes – they are used as catalysts in some reactions. They are also used in drug delivery systems and in applications related to conductivity in electronics.
- Composite materials containing carbon nanotubes are being used in sporting goods.
- Carbon nanotubes are used to make bullet- proof jackets.
- Carbon nanotubes can be used to make aircraft and spacecraft bodies.
- Carbon nanotubes can be used to build high-performance nanoscaled thin-film transistors to replace silicon-based transistors because of the semiconducting properties of carbon nanotubes.
- Carbon nanotubes can be used to make biosensors and electrochemical sensors.
- Carbon nanotubes are used in making electrodes to study electrochemical reactions because of their excellent electrical properties.

Carbon nanofibres are represented as CNFs. Carbon nanofibres have a diameter of around 200 nm. Carbon nanofibres are not hollow from the inside. The lattice structure of the carbon nanotubes and carbon nanofibres are completely different. In Multi-walled Carbon nanotubes, the nano ranged tubes are arranged concentrically but they are hollow from inside. Therefore, Multi-walled Carbon nanotubes are different from carbon nanofibres. Carbon nanofibers have been in use for several decades to strengthen the compounds. In real the hallow carbon nanotubes are packed using the cap of fullerene at the top and bottom of the carbon nanotubes.

1.3.1. Carbon nano tubes reinforced composite plate

Carbon nanotube reinforced composite plate is a new type of structural material and has the potential to be used in a wide range of applications. Carbon nanotubes (CNTs) are cylindrical structures made up of graphene sheets rolled into a seamless tube. They have unique mechanical, electrical, and thermal properties, which make them one of the most promising materials for various applications, including structural materials. The mechanical properties of CNTs are particularly impressive, with tensile strengths up to 130 GPa and Young's moduli upto 1 TPa. These values are significantly higher than those of conventional materials such as steel and aluminum, making CNTs one of the strongest and stiffest materials known to date. CNT reinforced composites plate are materials that consist of CNTs embedded in a polymer matrix. The addition of CNTs to the matrix can improve the mechanical properties of the composite material, including its strength, stiffness, and toughness. The mechanical properties of CNT reinforced composites depend on various factors, such as the CNT orientation, volume fraction, and fabrication techniques. The structural use of carbon nanotube reinforced composite plates has emerged as a promising area of research due to their high strength-to-weight ratio and excellent mechanical properties. Carbon nanotubes (CNTs) are cylindrical molecules made up of carbon atoms arranged in a hexagonal lattice. They have unique mechanical, electrical, and thermal properties, making them ideal for a range of applications, including structural composites. In recent years, research has focused on using CNTs to reinforce composite materials to improve their strength, stiffness, and toughness. CNTs have a high aspect ratio, which allows them to provide reinforcement to composite materials in a way that other materials cannot. The mechanical properties of CNTs, combined with their small size, make them ideal for use in composites. Carbon nanotube reinforced composite plates have been used in various applications, including aerospace, automotive, and biomedical fields. They have the potential to reduce the weight of structures, increase their strength and stiffness, and improve their resistance to fatigue, impact, and corrosion.

Carbon nanotube reinforced composite plate has the potential to be used in many applications. The main reason for this is that it can absorb much more energy than steel, which makes it ideal for use in areas where high-impact collisions are common. CNTs are one of the strongest and stiffest materials known to date which has remarkable mechanical properties, with tensile strengths up to 100 times greater than steel, and Young's moduli up to five times greater than that of steel. These properties make CNTs ideal for use as reinforcing agents in composites, resulting in improved strength, stiffness, and toughness compared to traditional composite materials. The orientation, volume fraction, and fabrication techniques of the CNTs within the composite matrix can greatly affect its mechanical properties. For example, composites with aligned CNTs have higher stiffness and strength in the direction of alignment, while composites with randomly oriented CNTs have isotropic mechanical properties. The fabrication techniques used to produce CNT reinforced composites can also affect their mechanical properties. The most common techniques used include chemical vapor deposition, vacuum filtration, and solutions mixing techniques are discussed in detail further. Each technique has its advantages and disadvantages, and the choice of technique can greatly affect the resulting composite properties. Carbon nanotube reinforced composite plates are composed of a matrix material, such as epoxy or polymer, reinforced with carbon nanotubes. The mechanical properties of the composite depend on the properties of both the matrix material and the CNTs. The properties of the composite depend on the alignment and concentration of CNTs within the matrix material. The CNTs are aligned in the direction of the applied stress the composite exhibits higher strength and stiffness. The concentration of CNTs also affects the mechanical properties of the composite, with higher concentrations leading to increased strength and stiffness. The electrical and thermal properties of carbon nanotube reinforced composites are also of interest. CNTs have a high electrical conductivity, which allows for the production of conductive composites. The high thermal conductivity of CNTs also makes them ideal for use in thermal management applications. Current structural design is assessed by bending, free vibration and buckling. Within this finite element case study; carbon nanotube-reinforced composite plate subjected to a shaker load was built using Standard electromagnetic software to predict its mechanical behaviors. A carbon nanotube reinforced composite plate is a structural material that consists of CNTs as fiber, fibers are responsible for the strength and stiffness of the plate. The CNTs and matrix are combined at a macroscopic level and not soluble in each other, due to which this combination at the macroscopic label creates a new composite plate which is refer as the CNTRC plate.

The applications of carbon nanotube reinforced composite plates can be clearly observed in the following area:

- The aerospace industry is one of the main areas where carbon nanotube reinforced composite plates are being researched and developed. The lightweight and high strength of these materials make them ideal for use in aerospace structures, such as aircraft wings and fuselage components. The use of

CNTs in composites can also reduce the weight of aircraft, which can lead to increased fuel efficiency and reduced emissions.

- In the automotive industry, carbon nanotube reinforced composites are being used in the development of lightweight and high-strength materials for vehicle structures. The use of CNTs in composites can reduce the weight of vehicles, which can lead to improved fuel efficiency and reduced emissions. The high strength and stiffness of these materials can also improve crash resistance, leading to increased safety for passengers.
- The biomedical industry is also exploring the use of carbon nanotube reinforced composite plates in the development of medical implants. The high strength and biocompatibility of these materials make them ideal for use in orthopedic implants, such as hip and knee replacements. The use of CNTs in these composites can also improve the wear resistance and longevity of medical implants.

Despite the numerous potential applications of carbon nanotube reinforced composite plates; there are still challenges that need to be addressed. One of the main challenges is the cost of producing these materials on a large scale. The production of high-quality CNTs is still expensive, and the process of incorporating them into composites can also be costly. Another challenge is the issue of dispersion and alignment of CNTs into composite. Along with this, the next challenge in designing CNT-reinforced composites is to understand the behavior of the composite under different loading conditions. The mechanical behavior of CNT-reinforced composites under static and dynamic loading conditions has been extensively investigated. However, the behavior of CNT-reinforced composites under complex loading conditions, such as those found in structural applications, is still not well understood.

The applications of carbon nanotube reinforced composite plates in the civil engineering:

The field of civil engineering plays a pivotal role in shaping the modern built environment, encompassing the design, construction, and maintenance of infrastructure that supports societies and economies. With the advent of nanotechnology, novel materials like carbon nanotube (CNT) reinforced composites have emerged as potential game-changers in civil engineering. These advanced materials offer unique mechanical, thermal, and electrical properties, providing opportunities to enhance structural performance, durability, and sustainability of civil infrastructure. This discussion explores the diverse applications of CNT reinforced composites within civil engineering, highlighting their potential to revolutionize the industry.

Reinforced Concrete Structures: Reinforced concrete is a cornerstone of civil engineering, used in various structures such as bridges, buildings, and dams. Incorporating CNT reinforced composites as reinforcement within concrete can lead to significant improvements in strength, ductility, and durability. CNTs can enhance the tensile strength of concrete, reducing the need for conventional steel reinforcement and potentially extending the service life of structures. Additionally, the enhanced electrical conductivity of CNTs can be utilized for structural health monitoring by detecting strain, cracks, and corrosion in real-time.

High-Performance Fiber Reinforced Polymers (FRPs): FRPs, including carbon and glass fiber composites, have gained popularity in civil engineering due to their high strength-to-weight ratio and resistance to corrosion. Introducing CNTs into FRPs can further enhance their mechanical properties, resulting in high-performance materials suitable for retrofitting and strengthening existing structures. CNT-FRP systems can effectively increase the load-carrying capacity of beams, columns, and slabs while maintaining flexibility and reducing the overall weight of the structure.

Bridge Components and Infrastructure Repair: Bridges are critical components of transportation networks, and their maintenance and repair pose significant challenges. CNT reinforced composites can be employed for the rehabilitation of aging or damaged bridge components, such as beams, decks, and cables. These materials offer rapid installation, improved load-bearing capabilities, and resistance to environmental factors, reducing downtime and ensuring the longevity of vital transportation links.

Seismic Retrofitting: Earthquakes pose substantial threats to infrastructure, necessitating strategies to enhance seismic resilience. CNT reinforced composites can be utilized for seismic retrofitting, reinforcing structures to withstand lateral forces and vibrations. By adding CNT-FRP jackets to columns and walls, engineers can improve the seismic performance of buildings and reduce the risk of collapse during earthquakes.

Smart Structures and Sensors: The unique electrical properties of CNTs enable the development of smart structures with built-in sensing capabilities. CNT-based sensors embedded within concrete or other materials can monitor strain, stress, temperature, and humidity, providing real-time data on structural health. These sensors offer early detection of potential issues, enabling proactive maintenance and extending the operational life of civil infrastructure.

Lightweight and Sustainable Construction: Civil engineering is increasingly focusing on sustainable practices and lightweight construction methods. CNT reinforced composites offer an attractive solution due to their lightweight nature and potential to reduce material consumption. Lightweight CNT-based materials can be used for façade systems, cladding, and roofing, contributing to energy-efficient and environmentally friendly building designs.

Energy Harvesting and Storage: Civil infrastructure can also be integrated into energy harvesting and storage systems. CNTs' ability to efficiently convert mechanical vibrations into electrical energy can be harnessed in smart pavements and roadways to generate electricity from vehicular traffic. Furthermore, CNT-based supercapacitors could store and supply energy for various applications, contributing to sustainable energy management in urban environments.

Water Treatment and Filtration: Beyond structural applications, CNTs can be employed in water treatment processes. Functionalized CNTs can adsorb contaminants, heavy metals, and organic pollutants from water sources. Incorporating CNT-based filters or membranes into water treatment plants can enhance water quality and address pressing environmental challenges.

The integration of carbon nanotube reinforced composites into civil engineering practices holds immense promise for revolutionizing the industry. From enhancing the mechanical properties of traditional construction materials to enabling smart structures and sustainable solutions, CNTs offer a wide array of applications that can enhance the performance, durability, and resilience of civil infrastructure. While challenges such as cost, scalability, and regulatory considerations remain, ongoing research and development in this field are likely to pave the way for the widespread adoption of CNT reinforced composites, contributing to the advancement of civil engineering practices and the creation of a more sustainable and resilient built environment.

1.3.2. Distribution of CNTs in CNTRC plate

The distribution of CNTs in composite materials plays a significant role in determining the properties such as strength and stiffness of the composite materials. The mechanical behavior of CNT-reinforced composites has been extensively investigated both experimentally and theoretically. The stiffness and strength of CNTs have been shown to be transferred to the polymer matrix. The CNTs are arranged in such a way that it can meet the specific requirement of the strength and stiffness. The distribution of CNTs can affect the mechanical, electrical, and thermal properties of the composite materials that's why it is important to understand the distribution pattern of CNTs. There are mainly three types of distribution of CNTs in composite materials which is discussed below:

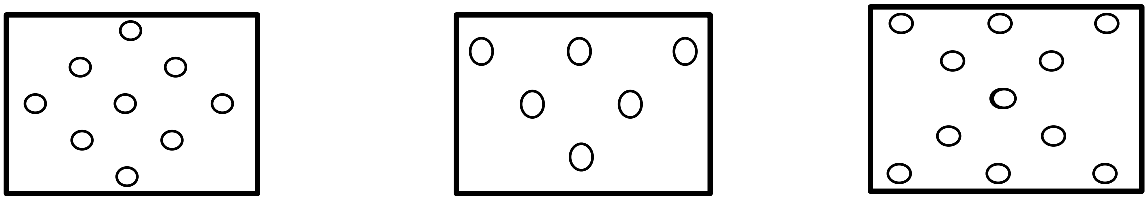
- Random distribution: In this type of distribution, the CNTs are randomly dispersed throughout the composite material. This type of distribution is easy to achieve, but it may not be optimal for improving the properties of the composite material.
- Aligned distribution: In this type of distribution, the CNTs are aligned in a specific direction within the composite material. This type of distribution can improve the mechanical properties of the composite material, but it may not be optimal for improving the thermal and electrical properties.
- Gradient distribution: In this type of distribution, the concentration of CNTs varies continuously throughout the composite material. This type of distribution can

provide improved mechanical, thermal, and electrical properties, as it allows for the combination of different concentrations of CNTs.

Incorporating carbon nanotubes in composite materials is very challenging, and several methods are used to incorporate CNTs in composite materials which are mentioned below:

- Dispersion in a liquid medium: CNTs are dispersed in a liquid medium, such as water or ethanol, and then added to the composite material during the manufacturing process.
- Dry mixing: CNTs are mixed with the composite material in dry form during the manufacturing process.
- Chemical functionalization: CNTs are chemically functionalized to improve their compatibility with the composite material.
- Electro spinning: CNTs are electrospun into a fiber form and then integrated into the composite material.
- Chemical vapor deposition: CNTs are grown directly onto the surface of the composite material using a chemical

Some of the most frequently used gradient distributions are FG-O CNTRC, FG-V CNTRC, and FG-X CNTRC which is shown in the **Figure 1.1**.



(a) (b) (c)

Figure 1.1. (a) FG-O CNTRC plate. (b) FG-V CNTRC plate. (c) FG-X CNTRC plate.

1.4. CNT reinforced composite plates resting on a Pasternak elastic foundation

In this context, the present work investigates the mechanical behavior of a CNT-reinforced composite plate resting on a Pasternak elastic foundation. The Pasternak elastic foundation model is a mathematical model developed by Boris Pasternak in the late 1950s. The Pasternak foundation is modeled using the Winkler model. The Pasternak foundation is a two-parameter elastic foundation model that accounts for both the horizontal and vertical stiffness of the foundation. It is used to calculate the static and dynamic properties of a foundation and its support structures. The model is based on the concept of linear elasticity and accounts for the effects of shear, moment, and normal forces on a foundation. The model is particularly useful when analyzing the behavior of a foundation under various conditions, such as when constructing a building or pipeline. It is also used to assess the impact of earthquake-induced forces on a foundation and to evaluate the effect of an underground storage tank on soil structure. The basic equation of the Pasternak elastic foundation model is a simple two-dimensional equation that describes the elastic behavior of a foundation. This equation takes into account the shear and moment forces, as well as the normal forces applied to the foundation. The model is particularly useful for analyzing the behavior of a foundation under various loads and conditions. In addition to the basic equation, the Pasternak elastic foundation model also includes additional equations that take into account the effects of soil type, depth, and gravity. These equations are used to calculate the static and dynamic properties of the foundation, as well as the forces applied to it. The Pasternak elastic foundation model is a powerful tool that can be used to analyze the behavior of a foundation under various load conditions. It is particularly useful for designing structures that need to withstand earthquakes, as well as for evaluating the impact of underground storage tanks on soil structure. It also helps to identify potential weak points in a foundation, allowing engineers to design foundations that are better able to withstand extreme conditions. The CNTs are modeled as a unidirectional fiber-reinforcement, and their orientation within the composite plate is assumed to be along the longitudinal direction. The primary objective of this study is to investigate the effect of CNT reinforcement on the mechanical behavior of the composite plate resting on the Pasternak foundation. Specifically, the study aims to investigate the effect of CNT volume fraction, aspect ratio, and orientation on the mechanical behavior of the composite plate. The study also aims to investigate the effect of the Pasternak foundation parameters on the mechanical behavior of the composite plate.

1.5. Method used to analyze the behavior of CNT reinforced composite plates

In this part, we discussed the methods used to analyze the structural behavior of CNT reinforced composite plates. The analysis of plates is a critical part of engineering and research projects. The goal of this process is to understand the strength and functionality of the plate, and to assess any potential weaknesses or risks. To do this, engineers and researchers utilize a variety of solution methodology such as analytical methods, finite element analysis (FEA), strength of materials, and other computational approaches. Here, the method used to analyze the behavior CNT reinforced composite plates, including their deformation, stresses, and failure mechanisms under different loading conditions such as uniformly distributed load and sinusoidal load is discussed in detail. This section is further divided in two parts, in the first part analytical method is used to analyze the CNTRC plate and further in the second part, the numerical method i.e., FE analysis of CNTRC plate is carried out.

1.5.1. Analytical method

Deriving the governing equations in terms of partial differential equations (PDEs) or ordinary differential equations (ODEs) describing the physical phenomenon like bending, vibration, and buckling, etc. is the primary step in any analysis. The formulations can be exact or approximate. In the exact formulations, there are no assumptions involved and the responses are free from any numerical error. Strength of materials is another analytical method used to analyze plates. This is a static analysis technique, which means it determines the static mechanical properties of the plate and its components. It is used to calculate the strength and stiffness of the plate, as well as the stresses and strains it can withstand. Computational approaches are also used to analyze plates. These techniques involve using algorithms and computer models to run simulations and analyze the behavior of the plate. These techniques can be used to determine the physical properties and performance limits of the plate. By utilizing these analytical methods, engineers and researchers are able to gain a better understanding of the plate and its performance. This knowledge can then be used to create stronger, more reliable components and structures.

1.5.2. Numerical method

The approximate formulations are derived based on some approximations made in the variation of the displacements and stresses of the structures. Though the solutions from the approximate formulation are not exact, yet, the formulations are often useful because of the mathematical complexities involved in deriving the exact governing equations and also solving them to get the responses. Finite element analysis (FEA) is a numerical method used to analyze the behavior of structures under different loading conditions. FEA is a powerful technique for the analysis of plates. It is a numerical simulation method used to analyze the behavior of complex structures and materials, such as plates and other components. The process involves creating a computer model of the plate and then running simulations to determine the stress, strain, and other physical properties of the plate. The method involves dividing the structure into a finite number of elements, each with its own material properties, and solving a system of equations to determine the deformation and stresses of each element. FEA has been widely used to analyze the behavior of CNT reinforced composite plates under different loading conditions. The use of FEA allows researchers to predict the deformation, stresses, and failure mechanisms of composite plates with a high degree of accuracy. This information can be used to optimize the design of composite plates, ensuring that they meet the requirements of various structural applications. The method involves dividing the structure into a finite number of elements, each with its own material properties, and solving a system of equations to determine the deformation and stresses of each element.

1.6. Solution Schemes for governing differential equation of CNTRC plate

In this section, various solution techniques are discussed which are frequently used for finding the solutions of the governing equations. The Navier-based analytical method is very popular in the research community as it produces exact solutions of the governing equations of beams/plates and shell structures with diaphragm supported boundary conditions. There are many popular numerical approaches adopted in the literature for solving the governing equations of beams, plates, and shell structures. The main principle of any numerical approach is to reduce the governing PDEs and ODEs to a system of algebraic equations by making some approximations. This reduction helps to replace a continuous differential equation having a solution space that is infinite-dimensional with a finite system of algebraic equations whose solution space is now finite-dimensional. To begin with, the very popular and commonly used method in almost all disciplines of science and engineering, the finite element method (FEM). In the FEM, the field variables are assumed over an element as a linear combination of the polynomial shape functions and the nodal coordinates. The strong form of the governing equations is converted to an equivalent weak form and the assumed solutions are plugged in the weak form to get the elemental level equations.

1.7. Organization of the thesis

The complete work presented in the thesis has been organized into five chapters- Chapter 1 contains a brief introduction to the development of carbon nanotube, structural use of carbon nanotube reinforced composite and sandwich plates in conjunction with Pasternak's elastic foundation. The development and applications of carbon nanotube is discussed in detail. The method of the structural analysis of the carbon nanotube reinforced composite plates in conjunction with Pasternak's elastic foundation is presented. Next, in chapter 2, a detailed discussion on the modeling of plate structures using plate theories, development of the plate theories and the underlying assumptions, various approaches used to extend the single-layered plate theories for multi-layered plate structures, literature review on the development of carbon nanotube, structural use of carbon nanotube reinforced composite and sandwich plates in conjunction with Pasternak's elastic foundation, modelling of functionally graded carbon nanotube reinforced composite and sandwich plates resting on Pasternak's elastic foundation using different modelling approach and the various solution techniques used for solving the governing equations are presented in detail. Chapter 3 is devoted to the detailed mathematical formulations of the problem. The fundamentals of functionally graded carbon nanotube reinforced composite and sandwich plates resting on Pasternak's elastic foundation are discussed in this chapter. This chapter contains two major sections: the first section contains the analytical formulation and the closed-form solution scheme used to solve the governing equations. The second section is devoted to the finite element (FE) formulation and solution of the problem. Chapter 4 presents the discussions on the results obtained from the developed mathematical formulations for the bending, free vibration and buckling analysis of functionally graded carbon nanotube reinforced composite and sandwich plate’s structure resting on Pasternak’s elastic foundation, validation of the solutions, and new results. This chapter contains five major sections: the first section contains the modelling of the mechanical properties of different functionally graded carbon nanotube reinforced composite and sandwich plates, the second section contains the analytical modelling for the structural analysis of the functionally graded carbon nanotube reinforced composite and sandwich plates, the third section contains the analytical modelling for the structural analysis of the functionally graded carbon nanotube reinforced composite and sandwich plates resting on Pasternak’s elastic foundation, the fourth section contains the FE modelling for the structural analysis of the functionally graded carbon nanotube reinforced composite and sandwich plates, the fifth section contains the FE modelling for the structural analysis of the functionally graded carbon nanotube reinforced composite and sandwich plates resting on Pasternak’s elastic foundation. In Chapter 5, important findings have been summarized, major contributions of the present research are stated and the recommendations for the future scopes of the work are identified.