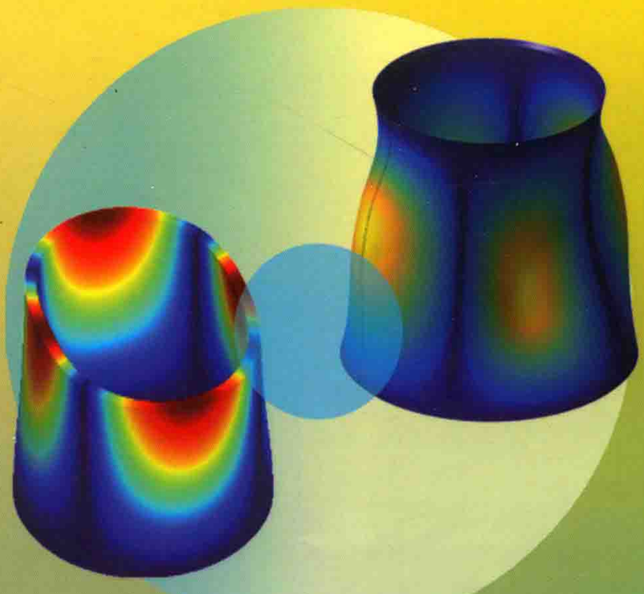
Vibration Analysis of Functionally Graded-Carbon Nanotube Reinforced Composite Structures

功能梯度碳纳米管增强复合材料结构振动特性分析（英文版）

王青山　庞福振　著



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Preface

As basic structural elements, the beams, plates, and shells are widely used in engineering structures and machines, for instance, aircraft, rockets, automobiles, turbines, architectures, vessels, and submarines. In practical applications where the range from the outer space to the deep oceans, the working environment of the above engineering structures is usually very complex such that high temperature, high pressure and the external loading also exist uncertainty due to the diversity of the working conditions. Further, the structural instability, failure and insecurity of the engineering structures may occur due to the material failure which is resulted from vibrations arising from structural loads. The destruction nature of vibration has been verified in many calamitous, such as, the main span of Tacoma Narrows Bridge also named as "Galloping Gertie" collapsed after 4 months of opening to traffic in 1940. The main cause of the disaster is mechanical resonance due to the wind providing an external periodic frequency matching one of the natural structural frequencies of the bridge. In addition, the vibration always causes noise problems to reduce the comfort of human beings. Thus, it is of particular importance to understand the structural vibrations and reduce them through proper design to ensure a reliable, safe, and lasting structural performance. To the structural vibrations, the modal information that consists of natural frequencies and mode shapes plays a key role in the design and vibration suppression of the structure when subjected to dynamics excitations. Therefore, to the designer or engineer, the vibration information is an important step in the vibration design of an engineering structure. In engineering applications, a variety of possible boundary restraining cases may be encountered for a structure. In recent decades, the ability of predicting the vibration characteristics of structures with general boundary conditions is of prime interest to engineers and designers and is the mutual concern of researchers in this field as well.

For vibration analysis of beams, plates and shells, there are many books, papers, and research reports. Among them, Prof. A. W. Leissa, J. N. Reddy, K. M. Liew and M. S. Qatu have made outstanding contributions. Based on the theoretical and experimental results of approximately 1500 research papers and reports, Prof. A. W. Leissa published the excellent monograph "Vibration of

Plates" and "Vibration of Shells" in 1969 and 1973, respectively. Prof. J. N. Reddy presented some new computational methods as well as elasticity theories and applications in the structural vibration. In 1997, he published the excellent monograph *Mechanics of laminated composite plates and shells: theory and analysis*, in which theoretical and experimental results of approximately 200 research papers and reports were presented. With the development of science and technology, the vibration of beams, plates and shells have received more and more attention. And the research papers and reports about the vibration of beams, plates and shells are in the period of explosive growth. We can prove the above points by Google Scholar search tool to retrieval the keywords from 1980 up to 2017: 681 000 items for "beams" & "vibration", 816 000 items for "plates" & "vibration" and 165 000 items for "shells" & "vibration". Among them, we also know that the classical and modern theories have also developed, such as classical structure theories (CSTs), the first-order shear deformation theories (FSDTs), and the higher order shear deformation theories (HSDTs). In addition, a large variety of accurate and efficient computational methods have been proposed by researchers, such as the Ritz method, the differential quadrature method (DQM), the Galerkin method, the wave propagation approach, the multiquadric radial basis function method (MRBFM), the meshless method, the finite element method (FEM), the discrete singular convolution approach (DSC), etc.

Despite a large number of studies have been carried out based on the above theories and methods, it appears that the information available about the vibration characteristics of general boundary conditions is very limited. Furthermore, according to the review, it is observed that the existing method or technique is only suitable for a particular type of classical boundary conditions, i. e., simply-supported supports, clamped boundaries and free edges, which leads to constant modifications of the solution procedures and corresponding computation codes to adapt to the different boundary cases. Then this will lead to very boring calculations and difficulties to carry out the application in practical engineering due to the boundary conditions of the beams, plates and shells that are not always in certain classical case and contain a variety of possible boundary conditions such as elastic restraints in natural. In addition, unlike the traditional composite materials, the functionally graded carbon nanotube reinforced composites (FG-CNTRC) have wonderful mechanical properties that change continuously in a specific direction and are widely used in many fields such as space vehicles, civil constructions, and deep-sea engineering equipments. The vibration results of FG-CNTRC beams, plates, and shells are far from being completed. Thus, to establish a unified, efficient and accurate formulation which is capable of universally dealing with the FG-CNTRC shallow shells with general boundary conditions is necessary and of great significance. Besides, a systematic, comprehensive and up-to-date monograph which including vibration results of FG-CNTRC beams, plates, and shells with various material constants, boundary conditions as well as geometric parameters is very desirable and useful for senior undergraduate and graduate students, teachers, engineers, and individual researchers in this field.

Based on the above reasons, the present monograph presents an endeavor to complement the vibration Analysis of FG-CNTRC beams, plates, and shells with general boundary conditions. The main aim of this book, entitling *Vibration Analysis of Functionally Graded-Carbon Nanotube Reinforced Composite (FG-CNTRC) Structures*, is illustrated as below: (a) To develop a novel semi-analytical method which is capable of dealing with the vibrations analysis of FG-CNTRC beams, plates, and shells with arbitrarily material constants, boundary conditions as well as geometric parameters; (b) To provide a series of the results of FG-CNTRC beams, plates, and shells with various material constants, geometric parameters and boundary conditions, which may serve as the reference data for the future researches in this field; (c) To provide a summary of crucial parametric studies of FG-CNTRC beams, plates, and shells concerning the influence of the geometrical parameters, CNTs distributions, volume fraction of CNTs as well as boundary conditions, which can be served as basic parameters for the designer and enhance the work efficiency.

The book is organized into eleven chapters. Chapter. 1 performes a comprehensive summary of the current research about vibration analysis of FG-CNTRC beams, plates, and shells. Chapter. 2 introduces the micromechanical models and fundamental equations of FG-CNTRC beams, plates, and shells in the framework of classical shell theory and the first-order shear deformation shell theory without proofs. Chapter 3 expounds the theoretical of Improved Fourier Series solution, which is capable of dealing with vibration analysis of FG-CNTRC beams, plates, and shells with general boundary conditions. In despite of the external factors which consist of boundary conditions, geometric model, material constants and so on, each of the unknown displacement functions of the FG-CNTRC beams, plates, or shells is expanded as a novel Fourier series expression which has excellent convergence, accuracy and stability and a wide range of the boundary conditions including the simple classical boundary conditions, general elastic restraints and their combining cases, since the auxiliary function is introduced, it can remove any potential discontinuities of the original displacement and its derivatives at the edges. Then one can seek the solutions either in the strong form solution procedure or the weak form one. These two solution procedures are fully illustrated in this chapter. Chapters 4 ~ 11 deal with FG-CNTRC beams, rectangular plates, sectorial, annular and circular plates, cylindrical, conical, cpherical and challow shells, and coubly-curved panels and shells, respectively. In each chapter, the classical and first-order shear deformation theories are employed to establish the corresponding fundamental equations, which can be useful for potential readers. Subsequently, the fundamental equations, numerous free vibration results are presented for various configurations including different boundary conditions, and geometry and material properties.

Finally, the authors would like to record their appreciation to the National Natural Science Foundation of China (Grant Nos. 51705537 U1604255 and 51535012), National Key Research and Development Program of China (2016YFC0303406), Assembly Advanced Research Fund of China (6140210020105), High Technology Ship Funds of Ministry of Industry and Information Technology of China and Fundamental Research Funds for the Central University (HEUCFD1515、HEUCFM170113) for partially funding this work.

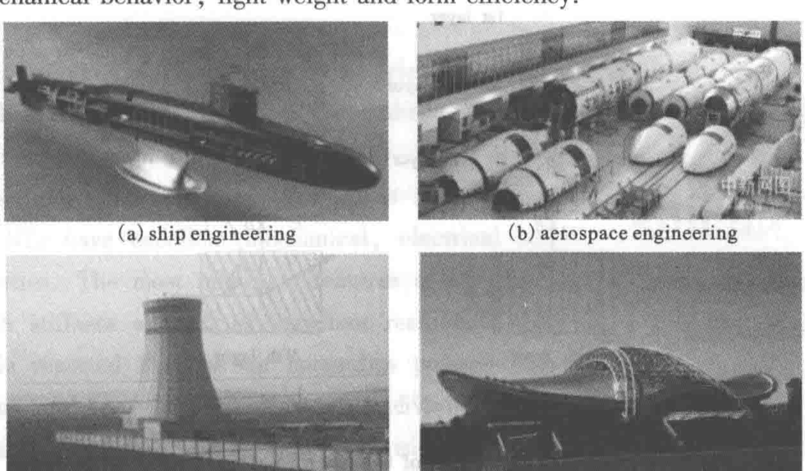
Contents

Chapter 1 Introduction

This chapter firstly describes structural beams, plates and shells in the engineering application, and then a brief discussion on existing composite materials is given. Next, the concept of the functionally graded carbon nanotube reinforced composite (FG-CNTRC) is presented. Finally, the vibration analysis of functionally graded carbon nanotube reinforced composite beams, plates and shells with various boundary conditions are reviewed.

1.1 Structural Beams, Plates and Shells

As fundamental components, the structure members, such as the straight beams, curved beams, rectangular plates, sectorial plates, annular plates, circular plates, cylindrical shells, conical shells, spherical shells, shallow shells, and doubly-curved shells, are widely applied in practical engineering. For instance, in the ship engineering, the submarine consists of curved beams, sectorial plates, annular plates, circular plates cylindrical shells, conical shells and spherical shells, which is shown in Fig. 1.1 (a). For the aerospace engineering, the main body of a rocket is composed of cylindrical shells, conical shells, spherical shells and annular plates, as shown in Fig. 1.1 (b). In some special projects, such as the petrochemical container engineering and civil engineering [as shown in Fig. 1.1 (c) and Fig. 1.1 (d) respectinely], the doubly-curved shells elements have received extensive attention due to the excellent performance of the smooth and continuous mechanical behavior, light weight and form efficiency.



(a) ship engineering (b) aerospace engineering

(c) petrochemical container engineering (d) civil engineering

Fig. 1.1 Engineering application examples for structural beams, plates and shells

Under the practical circumstances, these structural elements are commonly subjected to various forms of dynamic loadings in their service life. Therefore, the knowledge of vibration characteristics of them is of crucial importance from the standpoint of the practical design. Thus, it's of great significance to have a good understanding of the vibration behaviors of structural beams, plates and shells, which can provide some useful results to the designers and engineers to avoid the unpleasant, inefficient and structurally damaging resonant in the design process.

1.2 Background of Functionally Graded-Carbon Nanotube Reinforced Composite (FG-CNTRC)

The most general definition of a composite material is very closely related to the dictionary definition of the wordcomposite that it means"made up of different parts or material". The composite material is constructed of two or more than two independent physical phases which contain bonding materials and reinforced materials. Depending on the manner in which the independent physical phases are put together, the composite materials have the outstanding material characteristics including high specific strength and stiffness, good corrosion resistance, long fatigue life and excellent structural performance of light weight and form efficiency. Thus, it is widely used in modern structural design, such as aviation, aerospace, transportation, electronics, energy, etc.

As shown in Fig. 1.2, the laminated composite material is two or more than two thin layers of material fully bonded together, which may assumes a number of different forms, depending on the arrangement of the fiber constituent. The layers may be composed of short fibers embedded in a matrix. The short fibers may be distributed in random orientations, or aligned in some manner forming oriented short-fiber composites. Thus, laminated composite structures such as the beams, plates or shells, have the advantage of low specific density, high stiffness, high specific strength, high design ability and strong fatigue resistance.

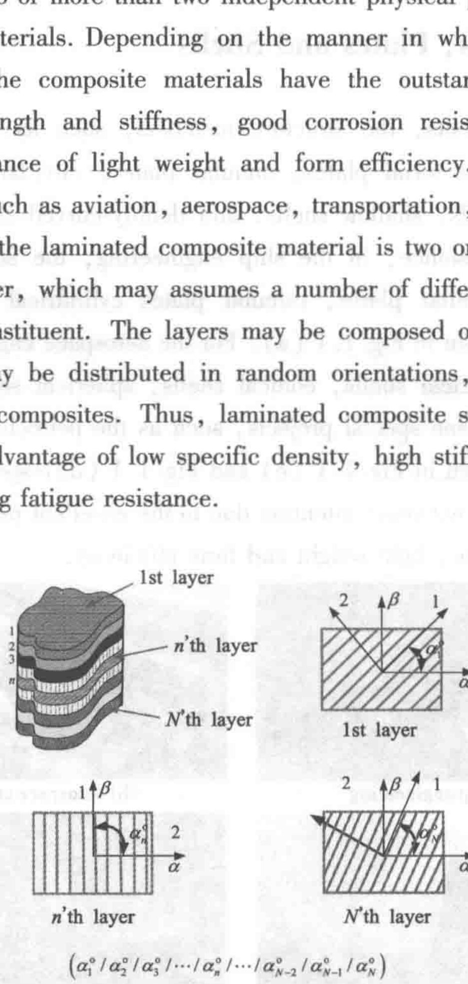


Fig. 1.2 Schematic diagram of the fiber reinforced composites

Fiber reinforced composite materials (laminated composite structure) have been widely used in many industrial fields. However, when the engineering structure encounters the high load or overheating, the delamination failure or crack phenomena is emerged due to the inter layer stress problem of the internal structure. To overcome this problem, MasyuhiNINO ToshioHIRA, RyuzoWATANBE of Japan and other materials scientists firstly proposed the concept of "functionally graded materials" (FGM) in 1984[1]. The basic idea of FGM design is eliminating the internal structure of the interface and then adapting to the special environment. Thus, in the material preparation process, both sides in one direction with different mechanical properties of materials, but not directly bonded together, can lead to a transition zone which exhibits a continuous gradient in composition, organization, and performance. In this way, the elastic modulus and thermal expansion coefficient of the functionally graded materials show continuous gradient changes in the material direction, which weaken and even eliminate the uncoordinated phenomenon and finally improve the bearing capacity of the structure and the environment, as shown in Fig. 1.3.

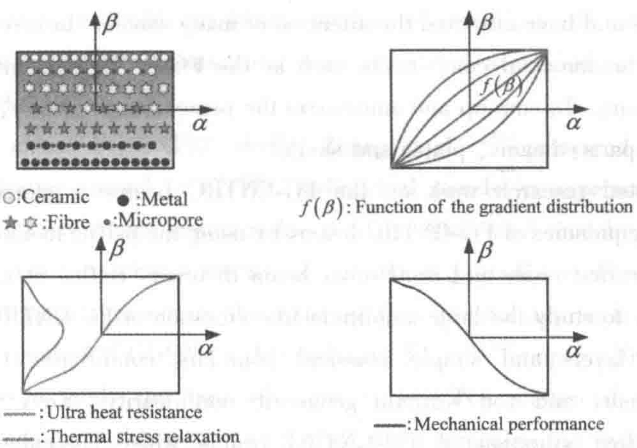


Fig. 1.3 Schematic diagram of the functionally graded materials

In 1991, Iijima[2] and other materials scientists firstly found the carbon nanotubes (CNTs) in the cathode sediment formed by the discharge of the graphite rod by means of the High-resolution electron microscopy. Numerous studies have shown that CNTs have excellent mechanical, electrical and thermal properties. The most important features of CNTs are extremely high stiffness as well as excellent resilience. For example, it is reported that carbon nanotubes possess high elastic modulus and large elastic strain up to 5% [3]. With these remarkable properties, CNTs can be considered as an excellent reinforcement for polymer composites which may significantly improve the mechanical, electrical and thermal properties of the resulting Nano composites. Thus, as a new type of composite materials, the concept of the functionally graded

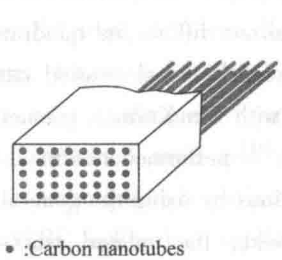


Fig. 1.4 Schematic diagram of the functionally graded carbon nanotube reinforced composites

carbon nanotube reinforced composites (FG-CNTRC) is firstly presented and the effect of the CNTs along the isotropic matrix on the mechanical properties of CNTRCs wasverified by the Chinese researcher Shen[4] in 2009 who studied the nonlinear bending of FG-CNTRC plates, as shown in Fig. 1. 4. Compared with laminated composite materials and functionally graded materials, the functionally graded carbon nanotube reinforced composites does not only own the mechanical properties of the functionally graded materials (their properties change continuously in a specific direction), but also possess the characteristics of carbon nanotubes (CNTs).

1.3 Overview of vibration analysis of the FG-CNTRC Beams, Plates and Shells

Since the FG-CNTRC structures have the excellent mechanical, thermal and electrical properties, the FG-CNTRC structures have gradually formed a new research hot spot in the actual industrial applications and have attracted the attention of many scholars to investigate the mechanical characteristics of the fundamental components such as the FG-CNTRC beams, plates, panels and shells in recent ten years. To sum up and summarize the present work clearly, the review works will be divided into three parts: beams, plates and shells.

Firstly, the related research work on the FG-CNTRC beams is stated. Lin and Xiang[5] obtained the nature frequencies of FG-CNTRC beams by using the p-Ritz method and investigated the difference between the first order and third order beam theories. Rafiee et al. [6] used the Euler-Bernoulli beam theory to study the large amplitude free vibration of FG-CNTRC beams with surface-bonded piezoelectric layers and simple classical boundary conditions. On the basis of the Timoshenko beam theory and von Kármán geometric nonlinearity, Ke et al. [7] surveyed the geometric nonlinear free vibration of FG-CNTRC beams with classical boundary conditions. Afterwards, Ke and his co-authors [8] considered the size effect and investigated the bending, buckling and vibration behavior of functionally graded micro plates. Ansari et al. [9-10] used the generalized differential quadrature to deal with the forced vibration behavior of nanocomposite beams reinforced by single-walled carbon nanotubes (SWCNTs) based on the Timoshenko beam theory along with von Kármán geometric nonlinearity. Based on the surface stress elasticity theory, Ansari et al. [11] performed nonlinear vibration analysis of nanobeams with various classical end boundary conditions by using the generalized differential quadrature method and Galerkin-based method.

Next, the related works of FG-CNTRC plate are examined. Liew et al. [12] wrote a comprehensive literature to review FG-CNTRC plates. Shen and his co-authors [7-8][13-15] applied the two-step perturbation technique to the study of linear and nonlinear vibration characteristics of FG-CNT reinforced composite plates and sandwich plates with stiff core as well as FG-CNT reinforced composite face sheets based on the von-Karman formulation and higher-order shear deformation theory. Based on the first-order shear deformation theory and element-free improved moving least-squares (IMLS)-Ritz method, Liew and his co-authors [16-33] examined the bending, vibration, buckling and buckling of FG-CNTRC plates including the rectangular, skew and triangular plate. Ansari et al. [34] employed the mapping-differential quadrature (DQ) methodology to perform the free vibration of carbon nanotube-reinforced composite quadrilateral plates under thermal environments with various classical boundary conditions. Malekzadeh and Zarei [35] examined the free vibration characteristics of laminated plates containing FG-CNT reinforced composite layers in an arbitrary straight-sided quadrilateral shape and with arbitrary classical boundary conditions via the differential quadrature method. Then, Malekzadeh and Heydarpour [36] applied the mixed Navier-layerwise differential quadrature method to investigate the free vibration and static response of simply supported laminated plates with FG-CNTRC layers. By employing the higher order shear and normal deformable plate formulation, Natarajan et al. [37] studied the static and free vibrations of single layer FG-CNT reinforced composite plates and sandwich plates with FG-CNT reinforced composite face sheets. Phung-Van et al. [38] studied the static and dynamic behavior of functionally graded carbon nanotube-reinforced composite plates by using the isogeometric analysis (IGA) method and higher-order shear deformation theory. Alibeigloo and Emtehani [39] adopted the differential quadrature method to investigate the free vibration and the bending behavior of an FG-CNTRC rectangular plate subjected to uniform pressure with different classical boundary conditions.

For the open and closed FG-CNTRC shells, Zhang et al. [40] presented an aerothermoelastic properties and active flutter control of CNTRC cylindrical panels in supersonic airflow. Reddy's third-order shear deformation theory was introduced in the structural modeling. Aragh et al. [41] examined the natural frequency characteristics of continuously graded carbon nanotube-reinforced (CGCNTR) cylindrical panels based on the Eshelby-Mori-Tanaka approach and 2-D generalized differential quadrature method (GDQM). Mirzaei and Kiani [42] employedthe Ritz method with Chebyshev polynomials to study the free vibration of FG-CNT reinforced composite reinforced composite cylindrical panels. In this research, the boundary condition was restricted to the classical boundary cases, i. e. CCCC, SCSF and so on. Thomas and Roy [43] presented vibration analysis of functionally graded carbon nanotube-reinforced composite shell structures. Hosseini [44] used the hybrid mesh-free method based on the generalized finite difference (GFD) method to examine the natural frequencies of FG-CNTRC cylindrical shells with shock loading. Bagherizadeh and Eslami [45] asserted closed-form solutions to examine the mechanical buckling of functionally graded material cylindrical shell embedded with elastic foundation and subjected to combined axial and radial compressive loads. Shen and his groups [46-50] extended the perturbation technique to investigate the thermal, nonlinear vibration and mechanical postbuckling of FG-CNTRC cylindrical shells and panels with classical boundary conditions on the basis of the higher-order shear deformation theory and nonlinear Von Kaarmaan-type theory. Ansari et al. [51] presented an analytical solution procedure for the nonlinear postbuckling analysis of piezoelectric functionally graded carbon nanotubes reinforced composite (FG-CNTRC) cylindrical shells subjected to combined electro-thermal loadings, axial compression and lateral loads. Also, Moradi-Dastjerdi et al. [52] examined the free vibration and stress wave propagation analysis of nanocomposite cylindrical shells reinforced by CNTs by means of the mesh-free method. It should be noted that the effective material properties were determined by the micro mechanical model. Heydarpour et al. [53] presented the free vibration analysis of rotating functionally graded carbon nanotube-reinforced composite truncated conical shells with classical boundary conditions by using the differential quadrature method. Wang et al. [54] performed the free vibration analysis of the functionally graded carbon nanotubereinforced composite (FG-CNTRC) spherical panels and shells with general boundary conditions. Ansari and Torabi [55] presented an efficient numerical method within the framework of variational formulation to study the buckling and vibration of axially-compressed functionally graded carbon nanotube-reinforced composite (FG-CNTRC) conical shells with classical boundary conditions. The linear buckling analysis of the nanocomposite conical shells reinforced by single walled carbon nanotubes (SWCNTs) was examined by Jam and Kiani [56] using the generalized differential quadrature method. Ansari et al. [57] applied the variational differential quadrature (VDQ) method to study the free vibration characteristics of embedded functionally graded carbon nanotubereinforced composite (FG-CNTRC) spherical shells with classical boundary conditions and resting on the elastic foundation. Tornabene et al. [58] applied the generalized differential quadrature method and Carrera unified formulation to study the effect of Carbon Nanotube (CNT) agglomeration on the free vibration of laminated composite doubly-curved shells and panels reinforced by CNTs. In this work, the boundary conditions were limited to the classical boundary cases. Wang et al. [59] claimed a semi-analytical method to conduct the linear vibration analyses of functionally graded carbon nanotube reinforced composite (FG-CNTRC) doubly-curved panels and shells of revolution with arbitrary boundary conditions, in which the carbon nanotubes through the thickness of the structures might be uniform or functionally graded and four types of the CNTs distribution were considered.

Through the above literature review of the related research, we can know that most of methods or technique in those papers dealing with the FG-CNTRCstructures, such as beam, plate or shells, are generally suitable for a particular type of classical boundary conditions, i. e., simply-supported supports, clamped boundaries and free edges. However, the boundary conditions of the FG-CNTRC structures are not only limited to clamped, simply-support, free and their combination, but also the unknown elastic constraints. In addition, when the boundary conditions change, the solution procedures and corresponding computation codes will need revising, which makes the design jobs gradually transformed into a tedious work and wastes a lot of effective time in the process. Thus, establishing a unified, efficient and accurate formulation to deal with the related FG-CNTRC structures on this book is necessary and of vital importance.

Chapter 2 Micromechanical models and Fundamental Equations

This chapter presents the development of the micromechanical models and fundamental equations of FG-CNTRC beams, plates and shells. Two typical micromechanical models which are the extended rule of mixture and the Eshelby-Mori-Tanaka scheme are introduced to predict the effective material properties of carbon nanotube reinforced composites. A comparison study of these two micromechanical models is also developed. The fundamental equations of FG-CNTRC shells in the framework of the classical shell theory (CST) and the shear deformation shell theory (SDST) are presented in the following section. The corresponding equations of FG-CNTRC beams and plates are specialized from the equations of shells.

2.1 Micromechanical models

It goes without saying that the scale effect plays a significant role in the effective material properties of CNT-reinforced nanocomposites. Thanks to the efforts of numerous researchers, several micromechanical models have been successfully developed to predict the effective material properties of carbon nanotube reinforced composites. Two methods, the extended rule of mixture and the Eshelby-Mori-Tanaka scheme, are employed in the present study. With regard to the extended rule of mixture, CNT efficiency parameters are introduced to indicate the size-dependent material properties. Five kinds of CNT distributions of CNTRC beams, plates and shells are presented.

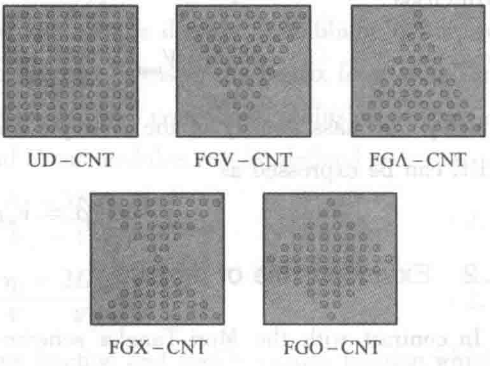


Fig. 2.1 Cross-section of a UD, FG-V, FG-Λ, FG-X and FG-O CNTRC structures

2.1.1 CNTRC material properties

The carbon nanotube reinforced composite material which is analogous to fiber reinforced polymers is regarded as the mixture of an isotropic polymer matrix and carbon nanotube reinforcements. The carbon nanotubes are distributed along the length direction and change smoothly and continuously in the cross section. As depicted in Figures 2.1, five kinds of distribution forms