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Application of Advanced Composites in Engineering

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Abstract: Among the current research focus, Graphene, porous materials, carbon nanotubes (CNTs), functionally gradient materials (FGM) and other advanced composite materials have been attractive for excellent physical, chemical, and mechanical properties. These materials have vital engineering significance in aerospace, vehicle engineering, etc., which can improve the stability and performance of the structure and provide insights for the development and application of new materials. In this paper, the research progress of these materials is reviewed, and the commonly used analytical methods are introduced, including static analysis, dynamic analysis, frequency analysis and active control strategy, so as to provide a review and prospects of advanced composites for researchers in related fields.

1. Introduction

1.1. Graphene

Graphene and its derivatives are two-dimensional carbon-based materials with good physical, chemical and biological properties for its extraordinary thermal, electrical, optical and mechanical properties as a new star in the nanocomposites and materials science [1].

Namin et al. studied the free vibration of a graphene sheet with defects by means of the nonlocal elasticity theory. Based on nonlocal elasticity and first-order shear deformation theory, the natural frequency of the graphene sheet was found to be reduced by introducing defects into the atomic structure [2]. Shahsavari et al. proposed a higher-order nonlocal strain gradient model for single-layer graphene sheets (SGLS) in hygrothermal environments, which can be used in the analysis of damped vibration. It is found that the existence of the environment will reduce the natural frequency. When the damping coefficient is considered, thinner graphene sheets have greater damping capacity [3]. Ebrahimi et al. analyzed the vibration of a bilayer graphene sheet under biaxial in-plane mechanical loading, and found that increasing the longitudinal length can significantly reduce the vibration of the system when the edge-thickness ratio is constant. This is due to the increasing size of the graphene sheet and the decreasing rigidity of the system [4]. Because of its high flexibility, graphene is widely used as sensors in mechanical engineering, aerospace, medicine and other fields [5].

1.2. Porous Material

A porous material has a grid structure formed by mutually communicated or closed holes, which has low density and high porosity, large specific surface area, light weight, sound insulation, thus being widely used in many engineering fields [6].

Raturi et al. solved a stochastic framework for the dynamic behavior of a porous functionally graded cantilever plate. It is found that as the porosity index and the power law index increase, the Young's modulus decreases to reduce the natural frequency. As the thickness increases, all natural frequencies have a boost [7]. Vazic et al. used the higher-order asymptotic homogenization to study the mechanical properties of porous systems. It is found that the same porosity has almost no effect on the Young's modulus of the material, and inclusions will affect the mean value of the Young's modulus [8]. Chaabani et al. studied a method for buckling and post-buckling of porous FGM plates. Based on the asymptotic numerical method and finite element method, it is found that the deflection of the porous FG plate increases with the increase of the pore coefficient and the decrease of the power law index. In addition, its uniform porosity has a greater impact on the buckling behavior of the material than non-uniform porosity [9]. These unique structures exhibit a high degree of interconnection between pores of different sizes, a large available space, a high specific surface area, a low density, excellent adaptability to change, etc. These characteristics make porous materials widely used as functional materials in energy conversion and storage, catalysis, adsorption, biomedicine and other fields [10].

1.3. CNT (Carbon Nanotubes)

Carbon nanotubes (CNTs) have broad application prospects for their hollow tube structure and excellent mechanical, thermal and electrical properties. It has attracted great attention in many fields and become a trend in the field of new materials in the world [11].

Singh et al. analyzed the static, buckling, and free vibration behavior of a carbon nanotube reinforced composite plate on a Pasternak elastic foundation. It turns out that Pasternak foundation parameters and the carbon nanotube reinforcement have a significant effect on the static deflection, critical buckling load and natural frequency of the plate [12]. Zghal et al. studied the vibration analysis of the gradient composite shell reinforced by carbon nanotubes. A model was constructed to predict the vibration behavior of the shell structure [13]. Based on the nonlocal elasticity theory, Ho Hołubowski et al. conducted numerical simulations to conclude that the dispersion of dynamic displacements may be larger than standard deviation of the applied load due to random loading [14].

The high strength and modulus of carbon nanotubes give them significant advantages in many engineering applications. By combining carbon nanotubes with various matrix materials, the mechanical properties of the composites can be significantly improved [15].

1.4. Nanocomposite

A nanocomposite is a multiphase material in which the size of one phase is less than 100 nanometers in at least one dimension. Due to its excellent performance, it is widely used in engineering applications such as vehicle engineering and aerospace engineering [16].

Yang et al. used a third-order shear theory to capture the nonlinear behavior of sandwich arches with composite facings of nanocomposites, evaluate dynamic buckling load and analyze the effect of the core material. The viscoelastic core provides vibration damping and increases the buckling load. The addition of carbon nanotubes can improve the structural strength [17]. Ebrahimi et al. proposed a higher-order beam theory, which can describe the components of the displacement field and the strain tensor of the beam. It is found that high porosity decreases the natural frequency, and the natural frequency of the beam decreases as the beam becomes thinner. Salah et al. used the finite element method to find that the graphene distribution in a laminate structure composed of reinforced nanocomposites (graphene) can significantly affect in response to its natural frequency. The composite properties can be improved by increasing the plate thickness [18].

The addition of the nano filler can obviously improve the tensile strength and the flexural modulus of the composite material with higher toughness or rigidity. Nanocomposites are widely used in aerospace, automotive, electronics, sports equipment, construction and infrastructure.

1.5. Functionally Graded Materials

Functionally graded materials (FGM) lead to the change of the overall performance through the gradual change of composition and structure. The specific properties and superior strength of these materials make it highly valuable in aerospace, automotive, biomedical, and military applications [19].

Mishra et al. provided a new method for free vibration analysis of FGM plates. The effects of different functionally graded plate parameters, such as material gradient index, aspect ratio and boundary conditions, on the frequency parameters are discussed in detail.

The frequency parameter is found to decrease with increasing material gradient index, but its value is enhanced when the loss at the edge is increased [20]. Nie et al. analyzed the dynamic behavior of multi-directional functionally graded annular plates based on three-dimensional elastic theory. It is found that different gradient directions have different effects on the dynamic behavior of functionally graded materials. The radial gradient variation helps to improve the stiffness of the plate [21]. The Akba Akbaş study considered two porosity models (homogeneous and heterogeneous) and the effects of porosity parameter, and analyzed material distribution and porosity model on the forced vibration response of functionally graded deep beams. The porosity has a significant effect on the dynamic characteristics of functionally graded deep beams. Increasing the porosity parameter significantly intensifies the difference between the homogeneous and heterogeneous porosity models [22]. FGM usually have high toughness and are suitable for high stress environments, such as aerospace, vehicle engineering, etc.

2. Multi-field Force Electrothermal Application

Advanced composites usually have excellent properties, but they are often accompanied by high cost and difficulty in analysis. These materials are widely used in extreme environments such as aerospace, nuclear energy, electronic devices, and smart structures. Under the condition of multi-physical field coupling of force, heat and electricity, these materials will be affected by a variety of external effects. Studying its behavior under multi-field coupling has important engineering significance and provides value for practical applications. Next, this paper will adopt different research methods for static analysis, dynamic analysis, frequency analysis, and active control strategies.

2.1. Static Analysis

Gupta et al.[23] studied the static response of functionally graded materials under thermal, electrical and mechanical loads. The influence of the material gradient on the buckling load and bending behavior is analyzed. They found that gradient design can effectively improve the static performance and bearing capacity of the structure under multi-physical field coupling. Lv et al. [24] modeled the static response of piezoelectric composites by the strong form method. The accuracy of the method under complex boundary conditions is verified. Zhang et al.[25] deeply analyzed the bending behavior of functionally graded piezoelectric plates under nonlinear loads under thermo-electro-mechanical loading. The effects of geometric and piezoelectric nonlinearities on the static properties of the material are revealed, and the buckling behavior under different temperatures and electric fields is explored. Jiang et al.[26] used the domain Galerkin free element method. The steady-state temperature distribution and stress response of piezoelectric structures under multi-physical field coupling are studied. Moreover, the steady state and stress distribution of the material under multi-field coupling are revealed. Alshenawy et al. [27] further analyzed the nonlinear stability of three-dimensional functionally graded piezoelectric microshells under axial, thermal and electric field loads. In these studies, the authors analyzed the static response of functionally graded materials (FGM) and piezoelectric materials under the condition of multi-physical field coupling. They mainly discussed the buckling, bending and stability of materials under thermal, mechanical and electric loading. Material gradient design, nonlinear behavior, and statics of the new numerical method in simulating complex boundary conditions and load combinations are emphasized and optimized. These studies provide a theoretical basis for load-carrying capacity assessment, buckling prevention and material design of structures in complex environments.

2.2. Dynamic Analysis

Dynamic analysis aims to evaluate the response of a structure to transient loads, vibration, and impact. Wu et al. [28] analyzed the post-buckling dynamic behavior of a piezoelectric functionally graded carbon nanotube reinforced composite beam under thermo-electro-mechanical loading. The effects of geometric imperfection, temperature variation and electric field on the dynamic buckling path and stability of the beam are revealed. Subsequently, Jiang et al. [26] studied the transient heat conduction and dynamic behavior of piezoelectric structures under multi-field coupling. The effects of various temperature and electric field conditions on dynamic features of the structure are analyzed.

Zhang et al. [29] used the nonlocal Kirchhoff plate theory to analyze the dynamic vibration of piezoelectric nanoplates under thermo-electro-mechanical loading, with the influence of viscoelastic foundation on vibration mode and stability discussed. Zhang et al. [25] further studied the nonlinear dynamic response of functionally graded piezoelectric plates under thermo-electro-mechanical loading. The manifestations of geometric and piezoelectric nonlinearities in the vibration are also emphatically analyzed. In the dynamic influence of frequency doubling effect under high temperature and strong electric field, these studies reveal the complex dynamic characteristics of piezoelectric and functionally graded materials under multi-physical field coupling from different perspectives.

2.3. Frequency

Frequency analysis is a key method to understand the vibration behavior of structures under different external excitation and loading conditions. The natural frequencies and resonance characteristics of structures may be significantly affected by multi-physical fields. Liu et al.[30] studied the natural frequency behavior of piezoelectric nanoplates by nonlocal theory. They revealed the influence of nonlocal effects on the natural frequency, with the effects of temperature, biaxial force and applied voltage on the frequency discussed. Gupta et al.[23] discussed in detail the natural frequency characteristics of functionally graded materials (FGM) under thermal, electrical and mechanical conditions. The effects of material gradient and boundary conditions on the frequency are revealed, and the frequency calculation and optimization for various cases are provided. Zhang et al.[29] used the nonlocal Kirchhoff plate theory to analyze the natural frequency of piezoelectric nanoplates on the basis of viscoelasticity. They further discussed the influence of different environmental parameters (such as thermal, mechanical and electric fields) on the frequency characteristics. The contribution of nonlinear coupling to the SHG effect is also revealed. These studies show the frequency response characteristics of different materials and structures under multi-physical fields, which is helpful to understand the vibration of structures under different excitation and loading conditions.

2.4. Active Control

In recent years, active vibration control of functionally graded materials (FGM), piezoelectric structures and membrane structures is being the optimization of structural performance under multi-physical conditions as a key issue. By exploring different control strategies and techniques, significant progress has been made in structural stability and vibration suppression. Alshenawy et al. [27] performed active vibration control on the microshell by applying voltage. The effectiveness of different control strategies under multi-physical field coupling is verified. Then, Zhang et al. [31] analyzed the active vibration and shape control of functionally graded piezoelectric plates under various excitation conditions. The optimal control strategy and its efficiency under strong electric field are discussed. Wu et al. [32] proposed a control strategy based on velocity feedback, and studied the active control effect under different cable vibration conditions, especially in a strong electric field environment. Zhang et al. [31] discussed the force control and moment control strategies for membrane structures. The optimal control effects of these strategies under different excitation conditions are analyzed. They not only demonstrate the diverse active vibration control of functionally graded materials, piezoelectric structures and membrane structures under multi-physical field conditions, but also provides valuable theoretical basis and practical reference for the design and optimization of new engineering structures.

3. Conclusion

According to the static, dynamic and frequency analysis of these studies and the exploration of active control, there is the complex behavior of FGM and piezoelectric structures under multi-physical field conditions. These analyses reveal the unique response characteristics of the material under thermal, mechanical and electric field loading. In addition, the critical role of nonlinear effects, material gradients, applied voltage, and control strategies in improving structural performance is also emphasized. The static analysis provides an assessment of the structural stability and bearing capacity of the foundation. Dynamic analysis reveals the response characteristics under vibration and transient loads. Frequency analysis helps to understand the influence of different parameters on natural frequency and frequency doubling effect. Active control further verifies the application effect of various control strategies in complex environment.

These studies provide theoretical support and practical methods for material design, vibration suppression, buckling prevention and dynamic optimization in engineering applications, especially in the fields of aeronautics and astronautics, civil engineering, electronic equipment and intelligent structure. With a deep understanding of the properties of these materials under multi-field coupling, novice researchers can build more robust and efficient engineering systems.

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