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Free vibration analysis of sandwich plate with a transversely flexible core and FG-CNTs reinforced nanocomposite face sheets subjected to magnetic field and temperature-dependent material properties using SGT

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In this research, the free vibration analysis of a sandwich plate with a transversely flexible core and functionally graded – carbon nanotubes (FG-CNTs) reinforced nanocomposite face sheets subjected to magnetic field and temperature-dependent material properties is presented based on high-order sandwich plate theory (HSAPT). The governing equations of motion are derived using Hamilton's principle. Classical plate theory (CPT) is used for modeling the face sheets and the effective properties of them are defined based on the extended mixture rule. Mechanical properties of the core such as Young's and shear moduli are assumed to be function of temperature. The influences of aspect and side ratios, temperature changes, core-to-face sheet thickness ratio, distribution types and volume fraction of carbon nanotubes are presented. The size-dependent mathematical formulation of the face sheets is developed based on the strain gradient theory (SGT). The results show that with increasing the aspect ratio, the non-dimensional natural frequency increases, however the side ratio has a reverse effect. As the temperature of the system increasing, the non-dimensional natural frequency decreases while by applying the magnetic field, the frequency parameter increases. Also it is concluded that the sandwich plate with X distribution type of carbon nanotubes in the face sheets, has higher frequency compared with the other types. Finally it is observed that by considering the size effect and introducing the material length scale parameters, the frequency of the sandwich plate increases. Employing FG-CNTs in face sheets, magnetic field, and size dependent effect leads to increase stiffness of nanostructures, thus the use of this sandwich plate has a prominent role in modern engineering applications.

1. Introduction

In recent decades, engineered materials such as composite structures have been replacing the conventional substances due to their superior mechanical properties. Sandwich structures belong to a special class of composite materials which are more popular and attractive among the various structural constructions. Sandwich structures have been successfully used for many years in the engineering applications like, transportation, aerospace industries, marine and so forth. A typical sandwich construction is generally comprised of two thin and stiff face sheets that have been separated by a thick and low density core which carries the loads from one face sheet to another. Structural efficiency of sandwich constructions depends heavily on the lightweight core which provides the particular features such as high flexural rigidity and strength to weight ratio. The materials which have been used in sandwich constructions are varied but the face sheets usually consist of metal or composite materials, whereas the core material may compose of either honeycomb structures, wood or foam [1]. According to the type of the core, sandwich structures divide into two main groups. The first is sandwich structures with traditional metallic honeycomb cores which are infinitely stiff in the thickness direction and compliant in the in-plane directions. In these cores the section plane remains linear or takes zig-zag shape under static and dynamic loads [2]. In general the analysis approaches for traditional sandwich structures are based on the equivalent single layer (ESL)

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theory in which the sandwich structure is replaced by a similar panel with equivalent mechanical properties. For instance Thai et al. [3] analyzed static, dynamic and buckling behavior of functionally graded material (FGM) made of isotropic and sandwich plates. They presented a theory that is derived from the classical plate theory (CPT) whereas has the same number of degree of freedom as the first order theory (FSDT), but it does not require shear correction factor. They also presented a higher order displacement fields in which the in-plane displacement expressed as inverse trigonometric functions of the thickness coordinate with constant transverse displacement across the thickness. They showed that the distribution function along the thickness of sandwich plate can be easily used to obtain the best optimum solution for the problem. Jin et al. [4] carried out vibration and damping analysis of sandwich beams comprised of laminated composite face sheets and a viscoelastic core. They presented a unified formulation based on higher order shear deformation theory and employed a modified Fourier-Ritz method for solving the problem. They studied the effects of various parameters such as layer number, ply configuration, moduli and thickness ratios on the natural frequencies and loss factor. They also expressed that the applied solution method yields accurate results at a low computational cost. Also Thai et al. [5] studied bending, buckling and free vibration of functionally graded (FG) sandwich plates by using a new FSDT in which the number of unknowns and governing equations are reduced. They employed the analytical solutions to examine the effects of the parameters like various boundary conditions, shear deformation and power law index on the behavior of a sandwich plate with FG face sheets and isotropic homogeneous core. Sofiyev [6] also used FSDT to examine the vibration and buckling of the sandwich cylindrical shells covered by various types of coatings, like FG, metal and ceramic coatings. He considered four types of sandwich cylindrical shells which were subjected to the hydrostatic pressure, and assumed the effective mechanical properties of the FG coatings to be graded along the thickness direction according to an exponential law distribution. The closed form solutions were employed to obtain non-dimensional frequencies and critical hydrostatic pressures. The effects of various parameters such as the shear stresses, the radius-to-thickness ratio and the compositional profiles of coatings on the vibration and buckling behaviors of the sandwich cylindrical shells were discussed by him. Free vibration analysis of FG sandwich shells is presented by Pandey and Pradyumna [7]. They considered two configurations of FGM sandwich shells. The first was composed of a homogenous core and FGM face sheets whereas in the second one core layer was FGM and face sheets were homogenous. They developed a layer-wise finite element formulation based on FSDT and investigated the effects of volume fraction index, core thickness and temperature gradient on natural frequencies of sandwich structures. Arvin [8] modeled a composite sandwich beam with viscoelastic core based on the higher order theory with linear variations along the thickness of the core and examined the effect of the face sheet fiber angle and layer thickness on the frequency response. He showed that the core Young's modulus and the beam rotary inertia have the significant role on the frequency response of the sandwich beam. Kahya [9] investigated the buckling of laminated composite and sandwich beams via finite element method (FEM). He considered the effect of shear deformation according to FSDT and studied the buckling behavior of the laminated and sandwich beams with different boundary conditions and lamina stacking. The flexural behavior of the thin skew sandwich plates is investigated by Upadhyay and Shukla [10]. They studied the effect of skew angle, core thickness, lamination scheme and material properties on the static and dynamic behavior of skew sandwich plates by using the high order shear deformation theory. They observed that with decreasing of core thickness and increasing in shear rigidity of the core significantly affects the static and dynamic responses of the skew sandwich plates. The numerical approaches which have been used in the aforementioned articles are based on the assumptions that the height of the core remains unchanged and boundary conditions for upper and lower face sheets are identical at the same cross-section. So utilizing these approaches are correct about traditional sandwich panels that have incompressible cores. But in the second group of sandwich structures that are known by modern sandwich panels, the core is made of foam or low strength honeycomb structure that are flexible in all directions. So the behaviors of modern sandwich panels are associated with local effects. Frosting and Thomsen [11] presented the vibration analysis of sandwich panels with a flexible core based on the high-order sandwich plate theory approach (HSAPT). They proposed the non-linear patterns of the in-plane and the vertical displacements of the core through its thickness. They applied the classical thin plate theory for modeling the face sheets and a three-dimensional elasticity theory for the core. They proposed two types of computational models. The first model uses the vertical shear stresses in the core in addition to the displacement of the top and bottom face sheets as its unknown while the second model assumes a polynomial description of the displacement fields in the core that is based on the displacement fields of the first model and the unknowns are the coefficients of these polynomials in addition to the displacements of the face sheets. This theory has been successfully used for the various applications in the analysis of modern sandwich structures, e.g. static analysis, see Khalili et al. [12], biaxial buckling, see Kheirikhah et al. [13], damped vibration of sandwich plates, see Malekzadeh et al. [14] and also biaxial wrinkling analysis, see Khalili et al. [15]. Liu et al. [16] analyzed high-order free vibration behavior of sandwich plates with both FG face sheets and FG flexible core. They applied FSDT and 3D-elasticity theory for modeling the face sheets and core, respectively. They employed the Navier's solution method and examined the effects of distribution of FG materials and thickness to side ratio on the natural frequencies. Also Sadeghpour et al. [17] developed a high-order theory to study the free vibration response of a debonded curved sandwich beam. They employed the Lagrange's principle to derive the governing equations and solved them by applying the Rayleigh-Ritz method. They observed that curvature angle and boundary conditions play prominent roles in the vibration response of a curved sandwich beam. In the most of the modern sandwich structures, the core is made of polymer foam material so its mechanical properties depend on the temperature and degrade considerably as the temperature increases. The effects of this phenomenon on the free vibration of the sandwich plates are studied by many researchers, such as Khalili and Mohammadi [18], Frostig and Thomsen [19] and Fazzolari and Carrera [20]. Also the buckling response of the sandwich panels with temperature-dependent materials is proposed by some researchers, for example see Zenkour and Sobhy [21] and Frostig and Thomsen [22]. In a sandwich structure generally the bending loads as tensile and compressive stresses are carried by the face sheets, so the researchers are interested in improving the stiffness of them by using the laminated composites, FGM, and polymer matrix with reinforcement. For example Zhang et al. [23] performed vibration analysis of a sandwich structure composed of fiber-reinforced mullite composite face sheets and ceramic foam core. They assumed that the sandwich structure is subjected to high temperature. They researched the vibration characteristics of the sandwich structure by both experimental and FEM. They showed that the structural stiffness and damping characteristics of such sandwich constructions remain excellent in thermal environment. The nanomaterials can also be used as a protective coating layers against the harmful