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Exact solutions for static and dynamic analyses of carbon nanotube-reinforced composite plates with Pasternak elastic foundation

Nuttawit Wattanasakulpong [a,*], Arisara Chaikittiratana [b]

[a] Department of Mechanical Engineering, Mahanakorn University of Technology, Nongchok, Bangkok 10530, Thailand
[b] Department of Mechanical and Aerospace Engineering, Research Centre for Advanced Computational and Experimental Mechanics (RACE), King Mongkut's University of Technology North Bangkok, Bangkok 10800, Thailand

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ABSTRACT

This paper investigates static and dynamic behavior of carbon nanotube-reinforced composite plates resting on the Pasternak elastic foundation including shear layer and Winkler springs. The plates are reinforced by single-walled carbon nanotubes with four types of distributions of uni-axially aligned reinforcement material. Exact solutions obtained from closed-form formulation based on generalized shear deformation plat theory which can be adapted to various plate theories for bending, buckling and vibration analyses of such plates are presented. An accuracy of the present solutions is validated numerically by comparisons with some available results in the literature. Various significant parameters of carbon nanotube volume fraction, spring constant factors, plate thickness and aspect ratios, etc. are taken into investigation. According to the numerical results, it is revealed that the deflection of the plates is found to decrease as the increase of spring constant factors; while, the buckling load and natural frequency increase as the increment of the factors for every type of plate.

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1. Introduction

Due to the excellence in physical and chemical properties, carbon nanotubes (CNTs) have received a great attention over the last two decades since their first discovery in 1993 [1]. To produce high performance structural and multifunctional composites for various potential applications, CNTs which have high elastic modulus, tensile strength and low density can be used as reinforcing constituents instead of conventional fibers. The earliest study on carbon nanotube-reinforced composites (CNTRCs) made from polymer reinforced by aligned CNT arrays had been found in the report of Ajayan et al. [2], and since then many researchers have paid their attention on investigating material properties of the CNTRCs [3–5]. Moreover, to include thermal effect on material properties of nanocomposites produced from polymer and carbon nanotubes, it was proposed by Fidelus et al. [6]. In terms of macro scale, Hu et al. [7] provided the formulation for predicting the elastic properties of CNTRCs and the elastic deformation of a representative volume element subjected to different loading conditions was analyzed in the investigation. By using molecular dynamics (MD), the elastic properties of CNTRCs can be evaluated [8]. Zhu et al. [9] presented the stress–strain curves of CNT-reinforced Epon 862 composites which show that the mechanical,

* Corresponding author. Tel./fax: +66 29883655x3106.
E-mail address: nuttawit_mut@hotmail.com (N. Wattanasakulpong).

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electrical and thermal properties of the composite materials can be improved considerably with the addition of small amounts of CNTs to polymer matrix. In order to understand more about how to enhance dispersion and alignment of CNTs in a polymer matrix, Xie et al. [10] reported the existing techniques used for this purpose.

Based on several benefits of CNTRCs as discussed above, these can be incorporated in the structural elements such as beams, plates and shells for actual structural applications. To investigate mechanical behavior of engineering structures made from CNTRCs, there are a limited number of previous reports regarding mechanical responses of the CNTRC structures under different loadings. In general, the problem of weak interfacial bonding between CNTs and polymer can occur in CNTRC structures. However, this problem can be solved by varying the CNTs within homogenous matrix over the gradient direction [11]. For CNTRC beams, Yas and Samadi [12] used the generalized differential quadrature method (GDQM) to find buckling loads and natural frequencies of Timoshenko CNTRC beams resting on the elastic foundation. Wattanasakulpong and Ungbhakorn [13] analyzed static bending, stability and vibration of CNTRC beams based on several shear deformation beam theories. From this investigation, it is revealed that shear deformation effect has significant impact on static and dynamic behavior of such beams, especially for shear stress profile across the beam thickness. Ke at al. [14] used Timoshenko beam theory to construct energy equations for nonlinear vibration of CNTRC beams, and the Ritz method with direct iterative procedure was employed to solve such equations.

In cases of two dimensional analyses of CNTRC structures, static and vibration responses of CNTRC plates, which have thin-to-moderate thicknesses, were solved by using finite element method with the first order shear deformation theory (FSDT) [15]. Lei et al. [16] investigated buckling strength of three different types of CNTRC plates having symmetrical distribution of CNTs, using the element-free *kp*-Ritz method. Shen and Zhang [17] gave the solutions for critical buckling temperature and thermal postbuckling behavior of bi-layer CNTRC plates with symmetrically distributed CNTs. The nonlinear vibration response of CNTRC plates under thermal environments was reported by Wang and Shen [18].

Most of the previous researches have presented the mechanical behavior of CNTRC plates using approximate techniques as described above. Thus, in the present investigation, static bending, buckling and vibration problems of CNTRC plates with symmetrically and un-symmetrically distributed CNTs can be solved exactly using the closed-form formulation. The simply supported CNTRC plates resting on the Pasternak elastic foundation composing of shear layer and Winkler springs are considered. Generalized shear deformation plate theory is employed to construct the governing equations or the equations of motion. Various accurate solutions of deflections, stresses, buckling loads and natural frequencies of such plates are presented and discussed in relation to several important aspects such as plate thickness and aspect ratios, spring constant factors, volume fraction of CNTs and plate types.

2. CNTRC plates

Consider a CNTRC plate having length (a), width (b) and thickness (h) which is resting on the Pasternak elastic foundation, including shear layer and Winkler springs, as shown in Fig. 1(a). The CNTRC plates considered in this investigation are assumed to be reinforced by four different patterns of carbon nanotube distribution across the plate thickness, which can be seen in Fig. 1(b). It can be seen that UD-plate has uniform distribution of single-walled carbon nanotubes (SWCNTs); while, O- and X-plates have symmetrically distributed SWCNTs and V-plate is an un-symmetric plate reinforced by SWCNTs. Due to material properties of O-X- and V-plates varying along the thickness direction, therefore, some significant backgrounds of functionally graded (FG) structures, for example in Refs. [19–22], are useful for the validation and development in structural analysis of the plates.

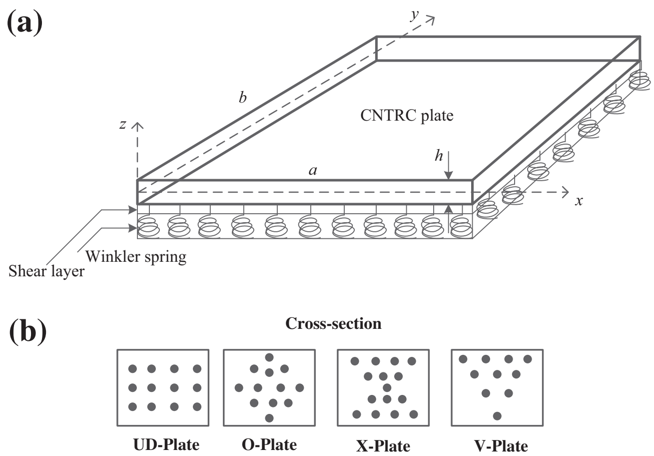

Fig. 1. Geometry of a CNTRC plate resting on the Pasternak elastic foundation (a) and cross-sections with different patterns of carbon nanotube reinforcement (b).

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