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Free vibration of functionally graded-GPL reinforced composite plates with different boundary conditions

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ABSTRACT

A first order shear deformation theory based finite element approach is used in this paper to investigate the free vibration behaviour of functionally graded thin, moderately thick and thick multi-layer composite plates reinforced with graphene nanoplatelets (GPLs). The effect of four different layer-wise variations of GPL distribution along the thickness and all possible plate edge boundary condition combinations on the natural frequencies of the plate are investigated. The effective Young's modulus for each layer and distribution type is determined using the modified Halpin–Tsai model, and mass density and Poisson's ratio are calculated based on the rule of mixture. Initially, present results are verified by comparing with available reported results. Thereafter, the method is used to conduct a parametric study, focusing on the effect of length to thickness ratio, different boundary conditions, GPL distribution patterns, percentage weight fraction of GPL, and geometry and size of GPL on the natural frequencies and percentage increase in natural frequencies.

1. Introduction

Carbon based nano-filler reinforced composites have been widely used in various engineering sectors over the past two decades due to their extremely desirable electrical, mechanical and thermal properties [1]. Among all carbon nano-fillers, graphene platelets (GPLs) are gaining popularity as a reinforcement material in the past decade, mainly due to their excellent properties such as high Young's modulus (around 1000 GPa), thermal conductivity (five times that of copper), high surface area (around 2500 m^2/g), together with lower density (four times lower than copper) and higher strength (up to 50 times stronger than steel) [1]. These excellent properties in GPL have created an opportunity for engineers to develop light weight advanced composite structures [2].

Up until now, there has been a major research effort concentrating on experimental work on low weight fraction of GPL embedded in a polymer matrix in terms of its synthesis, fabrication and material properties. It has been shown that addition of 0.1% weight fraction of GPL in to a polymer matrix can produce strength and stiffness enhancement equivalent to that achieved by addition of 1% weight fraction of carbon nanotubes (CNTs) [3]. The tensile modulus was improved from 2.72 GPa to 3.36 GPa by adding 6% weight fraction of GPL [4]. The tensile strength and Young's modulus in polystyrene sheets were increased by 70% and 57%, respectively, by adding 0.9% weight fraction of graphene sheets [5]. Wang et al. [6] studied the effect of different sizes of GPL on Young's modulus and strength of GPL/epoxy nanocomposites. They observed significant improvement in tensile modulus and reduction in strength when larger GPL sizes are used.

In addition to experimental work, there are some numerical and theoretical studies reported in the literature on the mechanical performance of polymer matrix reinforced with GPL [2]. The effective stiffness of graphene sheet reinforced composite was estimated using Mori–Tanaka micromechanics model and found that it increases considerably with low content of graphene sheets [7]. Elastic constants and stress–strain response of GPL/epoxy nanocomposites were studied in terms of GPL concentration, aspect ratio and dispersion by using molecular mechanics and molecular dynamic simulation [8]. How interfacial mechanical properties between polymer matrix and reinforced graphene are affected by graphene wrinkles, matrix type, polymer chain length and pull-out velocity was studied by employing molecular dynamic simulations [9]. A more comprehensive review on theoretical and numerical investigations on the mechanical performance of GPL based composites can be found in [2].

Vibration frequency analysis of plate structures is very important for their performance assessment in engineering applications. Investigations on general plate free vibration analysis can be found

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in [10,11]. A significant amount of studies on free vibration analysis of beams, plates and shells made from functionally graded materials (FGM) are reported in the literature. FGMs are characterised by gradual tailored variation of material composition and mechanical properties over one or more dimensions to suit required performance criteria. Free vibration analysis of axially tapered Thimoshenko beams [12], curved panels [13] and cylindrical shells [14], and under various boundary conditions, have been reported.

Vibration analysis has been conducted on FGM composite plates to investigate the effect of CNT volume fraction and distribution type by using first order shear deformation theory (FSDT) based element-free method [15–17], 3D elasticity based approach [18], and exact solution method [19]. The natural frequencies have been calculated for CNT embedded FGM composite elliptical plates [20], annular sector plates [21], skew plates [22–24], square plates [25], laminated composite plates [26], sandwich plates [27–29], and porous sandwich beams [30]. Although there are many studies reported on vibration analysis of CNT reinforced FGM polymer composite plates, there is only a limited number of studies reported on its younger counterpart, GPL reinforced polymer composites. In recent studies, the natural frequencies were determined for GPL embedded FGM composite trapezoidal plate [31], square plate [2], beams [32], and porous beams [33,34].

Recently, Song et al. [2] investigated the free vibration of functionally graded multilayer GPL reinforced polymer composites plates within the framework of the first order shear deformation theory (FSDT). They used a Navier solution based technique to solve the governing differential equations for natural frequencies of simply supported functionally graded GPL reinforced polymer composites plates. In their investigation, they considered the weight fraction of GPL to have a layer-wise variation along the thickness direction with GPLs uniformly dispersed in the polymer matrix in each individual layer. For their computations, the effective Young's modulus of the plate was predicted using the modified Halpin–Tsai model while effective mass density and Poisson's ratio were determined by the rule of mixtures. However, their investigation was limited to moderately thick plates with all four sides of the plate edges simply supported.

In most of the studies in the literature [20–29], vibration analysis was conducted on CNT embedded FGM composite plates and shells. In recent studies, the natural frequencies were determined for GPL embedded FGM composite plates with different shape of plates with moderately thick and one boundary condition only [2,31]. There are no reported studies investigating different thicknesses, sixteen possible plate edge boundary condition combinations and importance of each distribution type for the vibration problem of GPL embedded FGM composite plates. This paper attempts to fill this research gap by using a finite element based approach to solve the governing differential equations for natural frequencies.

In most of the reported literature, vibration analysis was conducted based on first order shear deformation theory (FSDT) which accounts for the additional deflections due to shear effects as opposed to the thin plate theory wherein only bending deflections are accounted for. Researchers have also used Higher Order Shear Deformation Theories (HSDT) to account for effects of shear deformations, changes in thickness and rotary inertia. However, for length to thickness ratios up to 5, the difference in frequency results between FSDT and HSDT has been insignificant [2,25,35]. Therefore, in the present work, FSDT is employed.

In summary, a detailed parametric study focusing on the effect of length to thickness ratio, different boundary conditions, GPL distribution patterns, percentage weight fraction of GPL, and geometry and size of GPL on the natural frequencies and percentage increase in natural frequencies is presented in this paper.

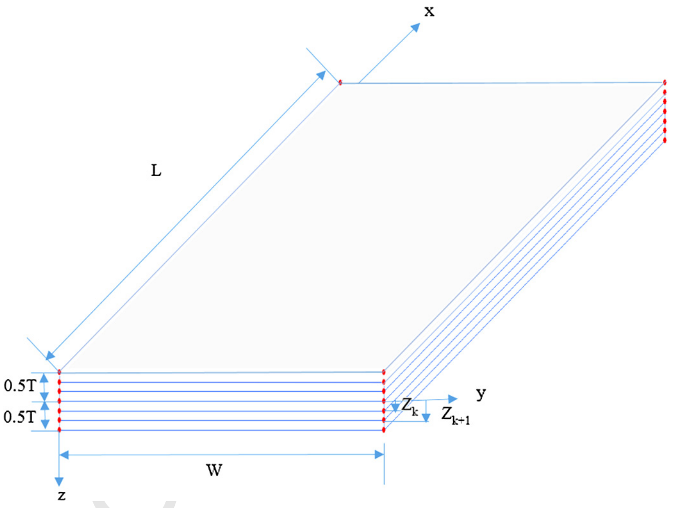

Fig. 1. Multi-layer FG composite plate.

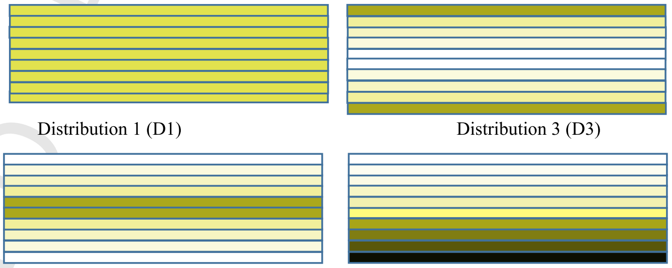
Distribution 1 (D1)
Distribution 3 (D3)
Distribution 2 (D2)
Distribution 4 (D4)

Fig. 2. GPLs distributed into epoxy polymer matrix in different types of distributions.

2. Formulation

A functionally graded GPL reinforced composite multi-layer plate with length L, width W and thickness T as shown in Fig. 1 is considered in this study. The number of layers is N_L and the thickness of each layer is the same. Each layer of the composite plate is assumed to have a uniform dispersion of GPLs in polymer matrix in xy plane. The weight fraction of GPLs is distributed in each layer along thickness direction in four different patterns as shown in Fig. 2. The distribution 1 (D1) is the special case of isotropic and homogeneous composite plate in which GPLs are distributed uniformly along plate thickness. The GPL weight fraction is distributed linearly along plate thickness in the symmetric way in distributions 2 (D2) and 3 (D3) and the unsymmetrical way in distribution 4 (D4). The GPL weight fraction increases linearly from the top layer to middle layer in D2 and vice versa in D3 as shown in Fig. 3.

The mathematical equation form of Fig. 3 for distribution type 1–4 is given below.

$$p_{total} = \sum_{k=1}^{N_L} p_{L,k} = N_L p \tag{1}$$

where p_{total} is total pseudo weight fraction of GPL in equivalent multi-layer plate, $p_{L,k}$ is the weight fraction in the kth layer, and p is weight fraction of GPLs in a single layer corresponding to uniform distribution pattern. The weight fraction distribution of GPLs in epoxy matrix is expressed as

$$\Delta p_L = \frac{2(\frac{p_{total}/2}{N_L/2})}{(N_L/2)-1} \tag{2}$$