Engineering Structures 156 (2018) 197–209

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Nonlinear harmonically excited vibration of third-order shear deformable functionally graded graphene platelet-reinforced composite rectangular plates

Raheb Gholami[a,*], Reza Ansari[b]

[a] Department of Mechanical Engineering, Lahijan Branch, Islamic Azad University, P.O. Box 1616, Lahijan, Iran
[b] Department of Mechanical Engineering, University of Guilan, P.O. Box 3756, Rasht, Iran

ARTICLE INFO

Keywords:
Third-order shear deformable FG-GPLRC plates
Graphene nanoplatelets
Nonlinear harmonically excited vibration
VDQ technique
Multistep numerical approach

ABSTRACT

The geometrically nonlinear harmonically excited vibration of third-order shear deformable functionally graded graphene platelet-reinforced composite (FG-GPLRC) rectangular plates with different edge conditions is examined. The considered plate with N_L-layers is made from a mixture of an isotropic polymer matrix and graphene platelets (GPLs) in each layer. The weight fraction of GPLs changes in a layer-wise manner. The modified Halpin-Tsai model and rule of mixture are utilized to compute the effective material properties of FG-GPLRCs. To mathematically model the vibrations of FG-GPLRC plates, the displacement field, strain tensor and constitutive relations as well as the energy functional of system including strain and kinetic energies and external work are represented in matrix forms as a function of the displacement components. Then, by simultaneous use of Hamilton's principle and an efficient numerical scheme namely, the variational differential quadrature (VDQ) technique, the weak form of discretized nonlinear equations of motion is obtained. The present model includes the influences of geometric nonlinearity, rotary inertia and transverse shear deformation. Furthermore, a multistep numerical approach based on the Galerkin method, time periodic discretization method and pseudo arc-length continuation technique in conjunction with the modified Newton-Raphson method is employed to solve the problem of nonlinear harmonically excited vibration of FG-GPLRC rectangular plates. Results are plotted in the form of frequency-response and force-response curves to indicate the effect of various parameters such as GPL distribution pattern, weight fraction, geometry of GPL nanofillers and boundary constraints of FG-GPLRC plates.

1. Introduction

Mechanical behaviors of structural elements including beams, plates and shells made of the mixture of polymer matrices and carbonaceous nanofillers such as graphene and carbon nanotubes (CNTs) have been the subject of numerous investigations in recent years, because of their extensive usages as basic elements of many devices and systems in the biology, industrial, biotechnology, engineering, and chemistry fields [1–5]. Graphene and CNTs have outstanding material properties such as low density, high Young's modulus, high fracture strength, and thermal conductivity [6–12]. Also, the excellent mechanical properties of nanocomposites reinforced by the graphene platelets and CNTs make them so promising for fabricating and manufacturing lightweight gasoline tanks, medical implants, sport equipment and strong wind turbines [13,14]. Also, because of the excellent thermal properties of graphene fillers [15], the thermal conductivity of composites reinforced by graphene nanoplatelets is considerably enhanced. This makes them suitable to be used as temperature sensors [14,16]. Since the structural elements made of new advanced materials are usually exposed to static or dynamic mechanical loadings, causing their deformation or oscillations, the investigation of their mechanical behaviors for better performance purposes as well as understanding the relationship between the structural behaviors and material properties is necessary.

Studies on the static and dynamic behaviors of structural elements reinforced with the graphene and CNTs can basically be classified into the linear and nonlinear investigations which are accomplished via the linear and nonlinear mathematical formulations as well as the analytical and numerical solution approaches. A wide range of these works was examined the linear responses of CNT- and graphene platelet-reinforced structures. On the other hand, although the studies on the mechanical behaviors of structures reinforced by the CNTs have been widely performed in the literature [17–27], the limited studies on the

* Corresponding author.
E-mail address: gholami_r@liau.ac.ir (R. Gholami).

https://doi.org/10.1016/j.engstruct.2017.11.019
Received 2 July 2017; Received in revised form 8 November 2017; Accepted 9 November 2017

behaviors of graphene platelet-reinforced structures have been performed. In the following, some performed works in the literature are reviewed.

Concerning the linear studies on the functionally graded carbon nanotube-reinforced composite (FG-CNTRC) structures, Yas and Samadi [28] numerically examined the free vibration and buckling of FG-CNTRC beams embedded on the elastic foundation using the Timoshenko beam model and generalized differential quadrature (GDQ) method introduced by Shu [29] employing the element-free kp-Ritz method and first-order shear deformation plate theory, Lei et al. [30] contributed to the filed by studying the buckling of FG-CNTRC plates. Based on a micromechanical model based on the agglomeration of nanoparticles, using the first-order shear deformation theory and a numerical solution approach, the free vibration of several arbitrarily shaped FG-CNTRC plates was studied by Fantuzzi et al. [31]. Moreover, Tornabene et al. [32] investigated the static response of plates and shells reinforced by agglomerated nanoparticles composed of CNTs using different higher-order equivalent single layer models and GDQ method. Ansari and Torabi [33] used a variational approach in order to investigate the free vibration and buckling of FG-CNTRC conical shells with various boundary conditions. Furthermore, regarding to the linear mechanical behaviors of structures reinforced by graphene platelets (GPLs), Kitipornchai et al. [34] used the Ritz method to study the influences of various porosity distributions on the buckling and free vibration characteristics of FG porous beams reinforced by GPLs. Using the GDQ method, the stability of FG-GPLRC Timoshenko beams in thermal environments under the periodic axial force was studied by Wu et al. [35]. By proposing a linear model based upon the first-order shear deformation plate theory as well as using Navier solution technique, Song et al. [36] examined the free and forced vibrations of FG-GPLRC rectangular plates with fully simply-supported edges.

Regarding to the nonlinear investigations, the nonlinear bending of FG-CNTRC rectangular plates in the thermal environments was examined by Shen [37]. Using the Ritz approach and a direct iterative method, Ke et al. [38] analyzed the nonlinear free vibration of FG-CNTRC Timoshenko beams with symmetric and unsymmetrical CNTs' distributions through the thickness direction. Ansari and Gholami [39] examined the large amplitude resonant dynamics of FG-CNTRC rectangular plates by employing the nonlinear third-order shear deformable plate model and a numerical solution strategy. Recently, Gholami et al. [40] investigated the imperfection sensitivity on the nonlinear resonance of FG-CNTRC beams by proposing a unified nonlinear higher-order shear deformable beam model. Thermal postbuckling od temperature-dependent sandwich beams with CNT-reinforced face sheets was analyzed by Kiani [41]. An improved moving least-squares approximation was utilized by Zhang and Liew [42] to investigate geometrically nonlinear large deflection of FG-CNTRC straight-sided quadrilateral plates. The pre- and post-buckling behaviors of FG-GPLRC beams with different end constraints were studied by Yang et al. [43]. Chen et al. [44] contributed the field by investigating the nonlinear postbuckling equilibrium and free vibration of FG-GPLRC porous beams. Moreover, Feng et al. [45] discussed the large deflection of FG-GPLRC beams. Using the higher-order shear deformation plate theory and perturbation method, Shen et al. [46,47] analyzed the nonlinear free vibration and postbuckling of FG-GPLRC laminated plates in thermal environments. Also, the thermal buckling and postbuckling of embedded FG-GPLRC laminated plates were analyzed by Shen et al. [48]. Feng et al. [49] examined the nonlinear free vibration of multilayer FG-GPLRC beams. On the basis of the sinusoidal shear deformation plate theory, the large deflection of FG-GPLRC plates was examined by Gholami and Ansari [50]. Furthermore, Shen et al. [51] proposed a multiscale approach to study the nonlinear bending and thermal postbuckling of FG-GPLRC laminated beams embedded in the elastic foundation. Recently, by proposing a higher-order shear deformable model and employing a two-step perturbation technique, Shen et al. [52]. Investigated the nonlinear bending of FG-GPLRC laminated rectangular plates under the transverse uniform/sinusoidal loading combined with initial compressive in-plane force. Also, on the basis of the first-order shear deformation plate theory, Wu et al. [53] utilized a differential quadrature-based iteration technique to analyze the nonlinear thermal buckling and postbuckling of FG-GPLRC plates. It should be remarked that from material fabrication perspective, due to the poor dispersion of nanofillers in the polymer matrix, only a low percentage of CNT, graphene and GPL nanofillers can be added into the polymer [54,55]. Adding a high mass fraction of nanofilers results in deteriorating the mechanical properties of nanocomposites [56,57]. That is why a low content of GPLs is utilized in aforementioned studies.

The literature review shows that the mechanical behaviors of polymer nanocomposite elements reinforced by GPLs have been analyzed in a few works. Moreover, studies on their nonlinear vibration characteristics using numerical or analytical solution approaches are limited. Also, there is no work in the literature concerning the nonlinear harmonically excited vibrations of FG-GPLRC rectangular plates. The present work aims to fill this gap and examine the geometrically nonlinear harmonically excited vibration of third-order shear deformable multilayer FG-GPLRC rectangular plates with different edge conditions. The considered multilayer plate is composed of the mixture of an isotropic polymer matrix and GPLs in each layer. The weight fraction of GPLs changes from layer to layer. The modified Halpin-Tsai model and rule of mixture are utilized to compute the effective material properties of FG-GPLRCs. Since the nonlinear coupled governing equations for the nonlinear harmonically excited vibration can be hardly solved analytically, an efficient numerical technique is introduced to attain the solution of the problem. In this regard, first, the matrix forms of the displacement field, non-zero strain elements, constitutive relations and energy functional of systems including the strain and kinetic energies and external work are obtained as a function of the displacement components. Then, by simultaneous using Hamilton's principle and an efficient numerical scheme namely, the variational differential quadrature (VDQ) technique proposed by Faghih Shojaei and Ansari [58], the weak form of discretized nonlinear equations of motion is obtained. In this article, an efficient multistep numerical method based on the Galerkin method, time periodic discretization and pseudo arc-length continuation technique in conjunction with the modified Newton-Raphson method is employed to solve the discretized nonlinear governing equations of motion for obtaining the frequency-response and force-response curves of harmonically-excited FG-GPLRC rectangular plates. The effects of contributing design parameters such as the GPL distribution pattern, weight fraction, geometry of GPL nanofillers and boundary conditions are discussed in detail.

2. Mathematical formulation

A multilayer FG-GPLRC rectangular plate made of N_L perfectly bonded GPLRC layers of the same thickness $h_L = h/N_L$ is illustrated in Fig. 1. Each layer of plate is composed of a mixture of isotropic polymer matrix and GPLs. It is assumed that the graphene nanofillers uniformly dispersed and randomly oriented in the polymer matrix. The material points of plate are labeled by selecting the Cartesian coordinate system ($0 \leqslant x_1 \leqslant a, 0 \leqslant x_2 \leqslant b, -h/2 \leqslant x_3 \leqslant h/2$). The geometries of FG-GPLRC rectangular plate are signified by length a, width b and total thickness .

In the following, first, the effective material properties of FG-GPLRCs are calculated using the modified Halpin-Tsai model and rule of mixture. Then, a variational approach will be employed to derive the weak form of discretized nonlinear governing equations of FG-GPLRC rectangular plates on the basis of the Reddy's third-order shear deformation plate theory.

2.1. Micromechanics of the FG-GPLRCs

The main aim of this subsection is to calculate the effective mechanical properties of a GPL-reinforced medium, which can be utilized