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Dynamic buckling of functionally graded graphene nanoplatelets reinforced composite shallow arches under a step central point load

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This paper presents dynamic buckling analysis for a functionally graded graphene nanoplatelets reinforced composite (FG-GPLRC) arch subjected to a step central point load at its center. The arch is composed of multiple composite layers reinforced with graphene nanoplatelets (GPLs) which are evenly distributed in each layer while the GPL weight fraction changes from layer to layer along the thickness direction. The effective materials properties are predicted by Halpin-Tsai micromechanics model for each GPLRC layer. Analytical solutions for symmetric limit point dynamic buckling load and anti-symmetric bifurcation dynamic buckling load for fixed and pinned FG-GPLRC arches are obtained by using energy-based methods. The critical geometric parameters governing the dynamic buckling mode switching behavior are also identified and discussed. It is found that the dynamic stability of the arch can be considerably improved by adding a small amount of GPLs as reinforcing nanofillers, and both symmetric limit point dynamic buckling and anti-symmetric bifurcation dynamic buckling can happen to pinned FG-GPLRC arch while the fixed FG-GPLRC arch can buckle in a symmetric mode only. The influences of GPLs distribution, concentration, dimension of GPL as well as the arch geometrical parameters on the dynamic buckling behavior of FG-GPLRC arches are comprehensively investigated through parametric studies.

1. Introduction

The use of graphene as reinforcing nanofillers in polymer nanocomposites has been attracting considerable attention from both research and industry communities due to its exceptionally mechanical, electrical and thermal properties [1]. Previous studies have demonstrated that graphene outperforms other reinforcing materials including carbon nanotubes (CNTs) and can significantly increase the elastic stiffness and strength of polymer nanocomposites [2–5].

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Rafiee et al. [6,7] experimentally found that the Young' modulus, tensile strength and fracture toughness of epoxy nanocomposites can be remarkably improved by adding a small amount of CNTs and GPLs as reinforcing nanofillers but GPLs exhibit better reinforcing effect. Lee et al. [8] synthesized functionalized graphene sheet/epoxy nanocomposites for cryotank application in which a remarkable increase in both strength and toughness was achieved. Liu et al. [9,10] demonstrated that the mechanical properties of graphene reinforced alumina-ceramic composites are higher than those monolithic ceramic composites. In another experimental work, Tang et al. [11] reported that the graphene reinforced nanocomposite possesses higher strength and fracture toughness when the graphene is highly dispersed in the polymer matrix. To make the best use of graphene reinforcements, Yang et al. [12] introduced a novel class of multilayer functionally graded GPL reinforced composites (FG-GPLRC) where GPLs are unevenly distributed in matrix according to a layer-wise manner and the FG-GPLRC beam has the best buckling and postbuckling capacity when the outer surfaces of the beam are GPL-rich. Their study indicated that this novel nanocomposite offers huge potentials in weight-sensitive applications such as aerospace, automotive and marine structures. Song et al. [13,14] discussed the vibration and buckling of FG-GPLRC plates and found that the addition of a low content of GPLs into polymer matrix can effectively increase the critical buckling load and natural frequencies and reduce the size of unstable region when more GPLs are distributed near the top and bottom surfaces of the plate. Feng et al. [15] investigated the nonlinear free vibration of FG-GPLRC beams and observed that the performance of GPLs is directly related to its shape and size and the total number of single graphene layers. Their results revealed that GPLs with a larger surface area and fewer single graphene layers can lead to higher linear and nonlinear natural frequencies. Other notable research work in this emerging area can also be found in open literature [16–20].

It is well known that the structural behavior of a shallow arch subjected to a central point load, either static or dynamic, is nonlinear in nature and the arch will buckle in either a symmetric mode or an anti-symmetric mode [21–25]. Simitses [26] derived approximate solutions for the lower and upper dynamic buckling loads for shallow sinusoidal arches subjected to a sudden sinusoidal load. Kounadis [27] determined the exact solutions of dynamic bucking loads for an arch-like structure with one degree of freedom under an impact load. Pi and Bradford [28–32] presented theoretical solutions for dynamic buckling loads of isotropy arches with different boundary conditions through energy-based methods. They also investigated the dynamic buckling of shallow arches with fixed or pinned ends under the action of a sudden uniform radial load. Liu et al. [33] investigated the dynamic buckling of a fixed arch subjected to an arbitrary step radial point load and found that the load location has a remarkable influence on the dynamic buckling behavior of the arch. These previous studies, however, are for isotropic arches only. Most recently, Yang and Huang et al. [34–36] made the first attempts to discuss the buckling and postbuckling behaviors of statically loaded FG-GPLRC arches and found that the buckling behavior of the FG-GPLRC arch is quite sensitive to boundary conditions, geometrical parameters and temperature change. So far, no previous work has been done on the dynamic stability behavior of this novel arch under a dynamic load.

Hence, the purpose of this work is to investigate the dynamic buckling behavior of functionally graded graphene nanoplatelets reinforced composite shallow arches under a step central point load. The effective materials properties of each GPLRC layer is calculated by employing Halpin-Tsai micromechanics model. The analytical results for limit point dynamic buckling load and bifurcation dynamic buckling of FG-GPLRC arches are derived through an energy-based method. The effects of GPL distribution pattern, weight fraction, shape and size as well as arch geometry on the dynamic buckling characteristics of FG-GPLRC arches are studied comprehensively.

2. Effective materials properties

The FG-GPLRC arch consists of multilayer isotropic polymer materials reinforced by GPLs that uniformly disperses and randomly orients in each layer. Each GPLRC layer has equal thickness and perfectly bonds with each other. Three GPL distribution patterns, denoted by U-, X- and O-GPLRC respectively as shown in Fig. 1, are considered in this study where a darker color indicates a higher content of GPLs in the layer. As a special case, U-GPLRC refers to an isotropic homogeneous arch where GPL concentration is constant throughout the thickness. For symmetric and non-homogeneous arches, the GPL concentration is the highest at the outer surfaces and the lowest in the mid-plane of the X-GPLRC arch, which is reversed in the O-GPLRC arch.

According to Halpin-Tsai micromechanics based model [37], the effective Young's modulus of each GPLRC layer can be calculated by

$$E^k = \frac{3\left(1+\xi_L\eta_L V_{GPL}^k\right)}{8\left(1-\eta_L V_{GPL}^k\right)} \times E_m + \frac{5\left(1+\xi_T\eta_T V_{GPL}^k\right)}{8\left(1-\eta_T V_{GPL}^k\right)} \times E_m \tag{1}$$

with

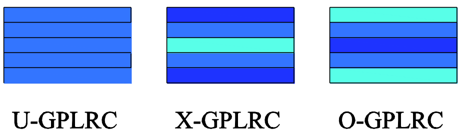

Fig. 1. GPLs distribution patterns.