Composite Structures 204 (2018) 114–130

Contents lists available at ScienceDirect

Composite Structures

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

Isogeometric Analysis of functionally graded porous plates reinforced by graphene platelets

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ARTICLE INFO

Keywords:
Functionally graded porous materials
Graphene platelet
First- and third order shear deformation plate theory
Nanocomposite reinforcement
Isogeometric Analysis

ABSTRACT

This paper investigates the static linear elasticity, natural frequency, and buckling behaviour of functionally graded porous plates reinforced by graphene platelets (GPLs). Both first- and third-order shear deformation plate theories are incorporated within the Isogeometric Analysis (IGA) framework. The pores and the GPLs within the plates are distributed in the metal matrix either uniformly or non-uniformly according to different patterns. The graded distributions of porosity and nanocomposite are achieved by material parameters varying across the thickness direction of plate. The Halpin-Tsai micromechanics model is implemented to establish the relationship between porosity coefficient and Young's modulus, as well as to obtain the mass density of the nanocomposite. The variation of Poisson's ratio is determined by the mechanical properties of closed-cell cellular solids under Gaussian Random Field scheme. A comprehensive parametric study is accomplished to investigate the effects of weight fraction, distribution pattern, geometry, and size of the GPLs reinforcement on the static linear elasticity, natural frequency, and buckling behaviour of the nanocomposite plates with diverse metal matrices and porosity coefficients. The outcome of numerical investigation shows that the inclusion of the GPLs can effectively improve the stiffness of functionally graded porous plate.

1. Introduction

Artificial porous material is one of the modern engineered composite materials, which possesses combinations of stimulating physical and mechanical properties [1]. Particularly, metal foams, as one of the highly porous materials with cellular structures, have shown tremendous potential to achieve significantly improved structural stiffness, electrical conductivity, thermal management and energy absorption [2–4]. The advanced design and manufacturing of metal foams have been extensively commercialized, which have been implemented in general society including the examples of the design of high-strength-but-light-weight materials for new space shuttle in aerospace engineering, as well as the biocompatibility design of artificial tissues and bone implants in biomedical engineering etc. [1,5–9].

The porosity distribution pattern of the metal foam significantly influences the associated properties. Most current researches on metal foams are primarily focusing on the uniform or random distribution of porosity. However, it has been shown that these primary porosity distribution patterns would lead to problems such as the mismatch of the Young's modulus of biomaterials and the surrounding natural bones, which has been identified as a major cause for implant loosening following stress shielding of bone [13]. In order to overcome the issues associated with the primary metal foams, the idea of functionally graded (FG) porosity has been introduced such that more controllable, and consequently, more specific problem targeting mechanical properties can be accomplished by meticulously modifying the size and density of the internal pores in multi-dimensions of the metal foams [14–17]. Consequently, the FG porous materials with demand-customized properties can be accomplished [18–19]. For example, the FG porosity has already been utilized in biological adaption of living tissues. As several examples illustrated in Fig. 1, based on the successful development of the functionally graded porous material technology, more biocompatible bone implants with smooth transition from a dense stiff external cortical bone (or the compact bone), to a porous cancellous bone (or the sponge bone) can be achieved and implemented [7–8]. Although FG porosity has provided opportunities for the possible manipulation of material properties of the metal foam, the material strength of such FG porous material could be significantly compromised

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https://doi.org/10.1016/j.compstruct.2018.07.059
Received 15 January 2018; Received in revised form 2 June 2018; Accepted 16 July 2018
Available online 20 July 2018
0263-8223/

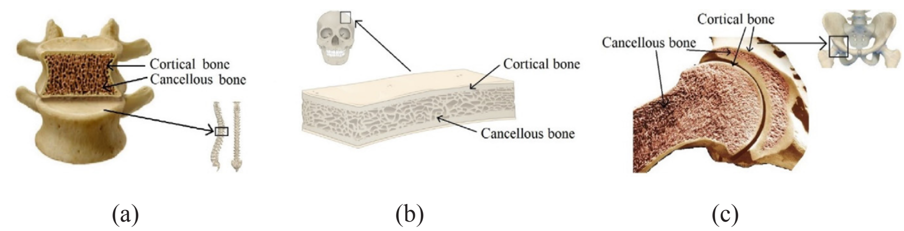

Fig. 1. Functionally graded porous bone structure on (a) vertebrae [10]; (b) skull [11]; (c) pelvis [12].

[20].

One practical and prevalent approach to compensate the strength reduction of the FG metal foam is to reinforce such advanced composite material with diverse nanofillers. Consequently, the desirable material strength can be achieved without significantly increasing the material weight and disturbing any particular porosity distribution. Carbonaceous nanofillers, such as carbon nanotubes (CNTs) [21] and Graphene platelets (GPLs) [22,23], are ideal ultra-lightweight reinforcement candidates with extremely high mechanical strength and exceptional chemical stability [24–26]. There are numbers of research that have been conducted to investigate the advanced performance of nanocomposite structures reinforced by CNTs [27–48]. Also, it has been experimentally demonstrated that GPLs can provide better mechanical property enhancement than the CNTs [22,39,40]. However, research work on the computational modelling of the mechanical behaviour of nanofillers reinforced FG metal foams is still at the early stage.

Kitipornchai et al. [49] studied the free vibration and elastic buckling of FG porous nanocomposite beams where the internal pores and graphene platelets were layer-wise distributed in the matrix either uniformly or non-uniformly according to three different patterns. Chen et al. [50] investigated the nonlinear free vibration and post-buckling behaviours of multilayer FG porous nanocomposite beams that were made of metal foams reinforced by GPLs. Feng et al. [51] studied the nonlinear free vibration of a multi-layer polymer nanocomposite beam reinforced by graphene platelets non-uniformly distributed along the thickness direction. Also, Feng et al. [52] studied the nonlinear bending behaviour of a class of multi-layer polymer nanocomposite beams reinforced with graphene platelets that were non-uniformly distributed along the thickness direction. Yang et al. [53] investigated the thermoelastic bending behaviour of functionally graded polymer nanocomposite rectangular plates reinforced with graphene nanoplatelets whose weight fraction varied continuously and smoothly along the thickness direction. Yang et al. [54] investigated the axisymmetric bending of functionally graded polymer nanocomposite circular and annular plates reinforced with graphene nanoplatelets within the framework of three-dimensional elasticity theory. Moreover, Yang and Feng [55] presented an analytical study on the flexural vibration of polymer beams reinforced with uniformly distributed graphene nanoplatelets. Zhao et al. [56] investigated the bending and vibration behaviours of a novel class of functionally graded trapezoidal plates reinforced with graphene nanoplatelets.

Stronger material with light weight can be adequately manufactured for various purposes, meanwhile, new challenges are also emerging in real-life engineering applications. One frequently encountered challenge is how to accurately use higher-order operator to model the physical object with very complex, yet unique, topology geometries. One prevalent approach for computational mechanics modelling is the Finite Element Method (FEA). Due to the remarkable advantages associated with this approach, it has been widely implemented in a wide range of engineering application. However, this masterpiece is also confronting difficulties when the geometry of the physical object is irregularly intricate, i.e. 1) The design-to-analysis bottleneck inherent in the traditional Computer Aided Design (CAD) through FEA paradigm significantly influences the computational modelling efficiency; 2) The widely applied lower-order polynomials within FEA framework cannot deal with mathematical models involving higher-order operator and complicated topology geometry.

To conquer such challenges, a superior numerical analysis framework, the Isogeometric Analysis (IGA), is proposed by Hughes et al. [57]. By meticulously utilizing the Non-Uniform Rational B-Splines (NURBS), IGA can handle mathematical problem modelled by the higher-order operator properly and represent the complicated topology geometry in the CAD model exactly. By seamlessly integrating the analysis and modelling processes, IGA can effectively improve industrial manufacturing efficiency. Grounding on the superior competence of such novel computational approach, IGA has been applied to a wide range of engineering disciplines with very promising results [58–61].

This paper presents a novel IGA analysis framework which has been specifically targeted to investigate static linear elasticity, natural frequency, and buckling analyses of the GPLs reinforced FG metal foam plates. Two non-uniform porosity distributions are considered in this paper. First-order shear deformation theory (FSDT) and third-order shear deformation theory (TSDT) under IGA analysis framework are employed for establishing a thorough theoretical formulation of the nanocomposite plate with different functionally graded porosity coefficients and different GPLs content. The effects of GPLs and the porosity distribution are freshly studied through comprehensive parametric studies. Moreover, in order to achieve the highest stiffness reinforcement, the most effective GPLs contents and porosity distribution pattern are explored. Such information is very beneficial for engineering practice, and the proposed method can certainly be implemented for real-life structural design.

To achieve a self-contained paper with enhanced readability, this paper is organized as follows. The material property considering different porosity distributions and GPLs patterns is presented in Section 2. The concept of IGA is briefly introduced in Section 3. Subsequently, the basic concept and IGA formulation of FSDT and TSDT are presented in Section 4. To rigorously verify the proposed computational methods, and illustrate the reinforcement effect of GPLs, several numerical examples are thoroughly explored in Section 5. Finally, conclusions are drawn in Section 6.

2. Material models of the graphene platelets reinforced functionally graded porous plates

The plate considered in this paper is defined in a Cartesian coordinate system with bases $\{\mathbf{e}_i, \quad i = 1,\ 2,\ 3\}$, where a point $\mathbf{x}$ is denoted as $\mathbf{x} = x\mathbf{e}_1 + y\mathbf{e}_2 + z\mathbf{e}_3$, simply, (x, y, z). The plate has thickness h, length a, and width b. The plate is defined on its mid-plane with each point denoted as $\mathbf{x}_0 = (x_0, y_0)$, then, any point on the plate can be represented as $\mathbf{x} = \mathbf{x}_0 + z\,\mathbf{n}$, where $\mathbf{n}$ is a unit vector normal to the mid-plane of the plate, usually, $\mathbf{n} = \mathbf{e}_3$, the thickness direction, and z denotes the coordinate in $\mathbf{n}$ direction, $-0.5\ \text{h} \leqslant z \leqslant 0.5\,\text{h}$.

In this paper, two types of porosity distribution and three distinctive GPLs dispersion patterns are considered. The porosity varies non-uniformly along the thickness direction. The nonuniformity is reflected on Young's modulus along the thickness direction, where E_1', E_2' denote the maximum and minimum Young's modulus of the non-uniform porous plates without GPLs along the thickness direction as shown in Fig. 2. Three GPLs dispersion patterns are denoted as A, B, and C. The volume fraction V_{GPL} of GPLs varies smoothly along the thickness