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Post-buckling analysis of imperfect multi-phase nanocrystalline nanobeams considering nanograins and nanopores surface effects

Mohammad Reza Barati[a,*], Ashraf M. Zenkour[b,c]

[a] Aerospace Engineering Department & Center of Excellence in Computational Aerospace, AmirKabir University of Technology, Tehran, Iran
[b] Department of Mathematics, Faculty of Science, King Abdulaziz University, P.O. Box 80203, Jeddah 21589, Saudi Arabia
[c] Department of Mathematics, Faculty of Science, Kafrelsheikh University, Kafr El-Sheikh 33516, Egypt

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ABSTRACT

In this paper, a size-dependent nonlinear higher order refined beam model is developed based on modified couple stress theory. Then, it is applied to investigate post-buckling behavior of multi-phase nanocrystalline silicon nanobeams with geometrical imperfection. Nanocrystalline materials (NcMs) are multi-phase composites with the contribution of nanopores, nanograins and interface phase. Because of experimental observation of strain gradients near interface phase, the nanobeam is modeled via strain gradient based couple stress theory. A micromechanical model based on Mori-Tanaka scheme is employed to incorporate the size of nanograins/nanopores and their surface energies. The post-buckling load-deflection relation is obtained by solving the governing equations having cubic nonlinearity applying Galerkin's method needless of any iteration process. New results show the importance of porosity percentage, nanograins size, geometrical imperfection, couple stress parameter, foundation parameters and surface phase of nanograins/nanopores on nonlinear buckling behavior of NcM nanoscale beams.

1. Introduction

Nanosize structural components made of silicon are important part of small scale sensors and actuators because of their great mechanical performances [1]. Nanocrystalline silicon materials exhibit mechanical behaviors different from traditional silicon material due to the reason that their material properties rely on the size of nanograins/nanopores. Actually, nanocrystalline materials are multi-phase composites with nanograins separated by interface phase. Effect of interface phase on elastic constants of nanocrystalline materials is studied by Wang et al. [2]. They stated that magnitude of elastic moduli of nanocrystalline materials are lower than that of their traditional counterparts because of the softening impact of interface region. A comprehensive study on the mechanical characteristics and synthesis approaches of nanocrystalline materials has been performed by Meyers et al. [3]. Analysis of the growth of nanopores inside a nanocrystalline material based on a micromechanical model is carried out by Zhou et al. [4].

Moreover, considerable progression in the utilization of structural elements such as beams and plates with micro and nano scales in micro/nano electro-mechanical systems (MEMS/ NEMS), due to providing outstanding mechanical, chemical, and electronic characteristics, led to a sudden momentum in modeling of micro and nano scale structures. In these applications, size effects become prominent. The problem in using the classical theory is that the classical continuum mechanics theory does not take into account the size influence in nanosize structures. So new forms of continuum mechanics capturing small scale effect are required, such as nonlocal elasticity theory [5] and modified couple stress theory [6]. Nonlocal elasticity theory accounts for the wide range interaction between atoms, while modified couple stress theory considers the material micro rotation. Several studies have been conducted extending nonlocal and couple stress beams/plates to predict the mechanical responses of the nanobeams and nanoplates [7–20].

Analysis of post-buckling of nanoscale beams has been a topic of investigation in recent years [21–24]. Searching the literature reveals that there is no published paper on post-buckling of NcM nanobeams with the effect of geometrical imperfection. However, there are some published papers on analysis of linear mechanical behaviors of NcM nanostructures. Shaat [25] performed bending analysis of nanocrystalline beams accounting for the size of nanograins and their rigid rotation based on modified couple stress theory. In another work, Shaat et al. [26] explored vibrational behavior of cracked nanocrystalline nanobeams using modified couple stress theory to capture the nanograins micro rotation. Ebrahimi and Barati [27] examined vibrational

* Corresponding author.
E-mail addresses: mrb.barati@ymail.com, mrb.barati@aut.ac.ir (M.R. Barati).

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behavior of viscoelastic nanocrystalline nanobeams considering the size and percentage of porosities inside the material structure. Barati and Shahverdi [28] performed vibration analysis of multi-phase nanocrystalline silicon nanoplates considering the size and surface energies of nanograins/nanovoids. Also, Barati and Shahverdi [29] carried out frequency analysis of porous nano-mechanical mass sensors made of multi-phase nanocrystalline silicon materials.

In this research, post-buckling analysis of nanocrystalline silicon nanobeams is carried out applying a refined beam model considering porosity dispersion. Nanograins and nanopores are randomly distributed in the material structure and they are separated by the interface (matrix) phase. Since beam structures are not ideal or straight after fabrication, they have an initial configuration called geometrical imperfection. Therefore, the geometrical imperfection as an important parameter is considered in this study. Size-dependency of nanobeam is described via modified couple stress theory to capture nanograins rigid rotation. The present non-polynomial shear deformation theory possesses three field variables and doesn't require a correction factor. The post-buckling load-deflection relation is obtained by solving the governing equations having cubic nonlinearity applying Galerkin's method. It is shown that the post-buckling loads of NcM nanobeams are significantly affected by nanopore percentage, nanograin size, geometrical imperfection, couple stress parameter, elastic foundation constants and nanograins/nanopore surface energies.

2. Modeling of nanocrystalline nanobeam

A nanocrystalline beam containing nanograins, nanopores and interface phase has been shown in Fig. 1. Surface layers of nanograins and nanopores are also observable in this figure which have a great influence on the material properties. Considering this surface layer is important for accurate modeling of nanostructured materials, as reported in previous investigations [28]. Generally, Young's modulus and Poisson's ratio of NcM have the following forms:

$$E_{NcM} = \frac{9K_{NcM}\mu_{NcM}}{3K_{NcM} + \mu_{NcM}} \tag{1}$$

$$v_{NcM} = \frac{3K_{NcM} - 2\mu_{NcM}}{2(3K_{NcM} + \mu_{NcM})} \tag{2}$$

in which, the bulk K_{NcM} and shear μ_{NcM} modules of NcMs should be defined by:

$$K_{NcM} \cong k_{H_1} \times k_{H_2} \times \frac{1}{\eta k_g} \tag{3}$$

$$\mu_{NcM} \cong \mu_{H_1} \times \mu_{H_2} \times \frac{1}{\eta \mu_g} \tag{4}$$

where $\eta = E_{in}/E_g$ and

$$k_{H_1} = k_{eff}(k_{in} = \eta k_g, \mu_{in} = \eta\mu_g, k_g, \mu_g, f_g, k_g^s, \mu_g^s, v_{in} = v_g, R_g) \tag{5a}$$

$$\mu_{H_1} = \mu_{eff}(k_{in} = \eta k_g, \mu_{in} = \eta\mu_g, k_g, \mu_g, f_g, k_g^s, \mu_g^s, v_{in} = v_g, R_g) \tag{5b}$$

$$k_{H_2} = k_{eff}(k_{in} = \eta k_g, \mu_{in} = \eta\mu_g, k_g = 0, \mu_g = 0, f_v, k_v^s, \mu_v^s, v_v, R_v) \tag{5c}$$

$$\mu_{H_2} = \mu_{eff}(k_{in} = \eta k_g, \mu_{in} = \eta\mu_g, k_g = 0, \mu_g = 0, f_v, k_v^s, \mu_v^s, v_v, R_v) \tag{5d}$$

It should be noted that the indices *g, v* and *in* are related to the nanograins, nanopores and interface, respectively. Also, the relation between the nanograins volume fraction f_g and porosity percent f_v can be expressed by:

$$f_g = r(1 - f_v), \quad r = \frac{R_g^3}{(R_g + T_{in})^3} \tag{6}$$

Here, R_g,R_v and T_{in} are the average radius of nanograins, nanopores and interface thickness, respectively.

Eq. (5) is used to incorporate the effect of nanopores into a two-phase composite containing nanograins and interface. In Eq. (5), the effective bulk modulus k_{eff} and shear modulus μ_{eff} of two-phase composites by discarding nanopores effect should be defined by [27]:

$$k_{eff} = \frac{3k_g(4f_g\mu_{in} + 3k_{in}) + 2\mu_{in}(4f_g\mu_{in}k_s^* + 3k_{in}(2 - 2f_g + k_s^*))}{3(3(1 - f_g)k_g + 3f_g k_{in} + 2\mu_{in}(2 + k_s^* - f_g k_s^*))} \tag{7}$$

$$\mu_{eff} = \frac{\mu_{in}(5 - 8f_g\xi_3(7 - 5v_{in}))}{5 - f_g(5 - 84\xi_1 - 20\xi_2)} \tag{8}$$

where

$$\xi_1 = \frac{15(1 - v_{in})(k_s^* + 2\mu_s^*)}{4H} \tag{9a}$$

$$\xi_2 = \frac{-15(1 - v_{in})\left(\left(\frac{\mu_g}{\mu_{in}}\right)(7 + 5v_g) - 8v_g(5 + 3k_s^* + \mu_s^*) + 7(4 + 3k_s^* + 2\mu_s^*)\right)}{4H} \tag{9b}$$

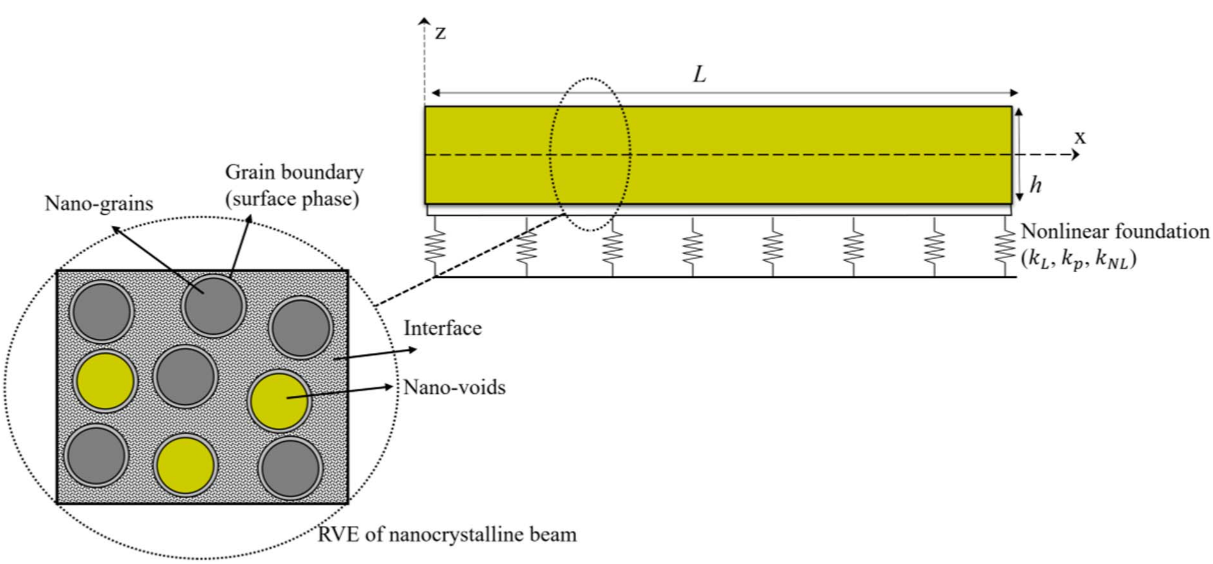

Fig. 1. Configuration and coordinates of NcM nanobeam.