**Stability analysis of a sandwich composite magnetostrictive nanoplate coupled with FG porous facesheets**

**Mehrdad Farajzadeh Ahari1,Farzad Ebrahimi2\***

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| 1MSc Student, Mechanical Engineering Department, Imam Khomeini International University | M.Farajzadehahari@edu.ikiu.ac.ir |
| 2\*Faculty of Mechanical Engineering Department, Imam Khomeini International University | febrahimy@eng.ikiu.ac.ir. |

**Abstract**

The present study focuses on the buckling behavior of the magnetostrictive material integrated with the functionally graded facesheets. The effective material properties of the functionally graded layer are gained according to the power-law model. Eringen’s nonlocal theory has been used to count the small-scale parameter. On the other hand, the proposed system rests on the Winkler and Pasternak foundation to consider the elastic medium. Higher-order sinusoidal shear deformation theory has been utilized to reach the governing equation, and the reached governing equation is solved analytically based on the Galerkin solution for different boundary conditions. To trail the accuracy and efficiency of the current investigation, results are compared with the articles available in the literature. Additionally, the effect of various parameters such as aspect ratio, velocity feedback gain, the foundation on the critical buckling load is investigated. The current study results signify that by increasing the porosity volume parameter, the buckling load of the structure increases. It is hoped that the present research can help the engineers and designers to understand and predict buckling response and be beneficial in designing nanoscale systems such as sensors and actuators as the most demanded technologies.

**Keywords:** Buckling, Hamilton’s principle, Sinusoidal shear deformation theory; Galerkin Method.

**تجزیه و تحلیل پایداری یک نانوصفحه ساندویچی کامپوزیتی ساخته شده از مواد مگنتواستراکتیو همراه با صفحات متخلخل مدرج تابعی**

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مهرداد فرج زاده اهری1، فرزاد ابراهیمی \*2

|  |  |
| --- | --- |
| 1دانشجوی کارشناسی ارشد دانشکده مهندسی مکانیک دانشگاه بین المللی امام خمینی | M.Farajzadehahari@edu.ikiu.ac.ir |
| 2\* عضو هیات علمی دانشکده مهندسی مکانیک دانشگاه بین المللی امام خمینی  | febrahimy@eng.ikiu.ac.ir. |

# چكيده

مطالعه حاضر بر رفتار کمانش نانوصفحات ساخته شده از جنس مواد مگنتواستراکتیو ادغام شده با صفحه‌هات مدرج تابعی تمرکز دارد. خواص مواد موثر لایه مدرج تابعی با توجه به مدل قانون قدرت به دست می آید. برای شمارش پارامتر مقیاس کوچک از نظریه غیرمحلی ارینگن استفاده شده است. از سوی دیگر، سیستم پیشنهادی بر پایه وینکلر و پاسترناک برای در نظر گرفتن محیط الاستیک استوار است. تئوری تغییر شکل برشی سینوسی مرتبه بالاتر برای رسیدن به معادله حاکم استفاده شده است و معادله حاکم به دست آمده به صورت تحلیلی بر اساس راه‌حل گالرکین برای شرایط مرزی مختلف حل شده است. برای ردیابی دقت و کارایی تحقیقات فعلی، نتایج با مقالات موجود در ادبیات مقایسه می‌شوند. علاوه بر این، اثر پارامترهای مختلف مانند نسبت ابعاد، بهره بازخورد سرعت، بستر بر روی بار کمانش بحرانی بررسی شده است. نتایج مطالعه حاضر نشان می دهد که با افزایش پارامتر حجم تخلخل، بار کمانش سازه افزایش می یابد. امید است که پژوهش حاضر بتواند به مهندسان و طراحان در درک و پیش‌بینی پاسخ کمانش کمک کند و در طراحی سیستم‌های نانومقیاس مانند حسگرها و محرک‌ها کمک کند.

**کليدواژه­ها:** کمانش، اصل همیلتون، نظریه تغییر شکل برشی سینوسی؛ روش گالرکین

1. **Introduction**

As a result of the modern structural revolution, analyzing innovative structures is undeniable. To this mean, buckling analysis of these structures is necessary for engineering fields. Some researchers did so. For instance, buckling of symmetrically laminated plates using the element-free Galerkin method investigated by Liu and Chen (1) Liew et al. (2) studied the buckling behavior of corrugated plates using a mesh-free Galerkin method based on the first-order shear deformation theory. The buckling behavior of isotropic and orthotropic plates using two variable refined plate theory analyzed by Kim et al. (3) used the Navier method for a simply-supported rectangular plate. The virtual displacement principle is used to obtain the governing equation of the plate. Different parameters such as thickness ratio, shear correction factor were studied in detail in their research. Lei et al. (4) studied the buckling behavior of functionally graded carbon nanotube-reinforced composite plates using the element-free KP-Ritz method in 2013. The outcomes of their research showed that the distribution type of CNT significantly affects the buckling strength of CNTRC plates. In another study, Karimi and Shahidi (5) studied the buckling behavior of skew magneto-electro-elastic nanoplates considering surface energy layers using Galerkin’s method and, according to their research, increasing the skew angle results in decreasing the influence of the surface layer on the buckling of the METE nanoplate. Buckling analysis of a functionally graded anisotropic nanoplate for different boundary conditions using Galerkin’s method studied by Karimi et al. (6). They used nonlocal strain gradient theory to consider the small-scale affect behavior of the nanoplate. In order to reach the governing equation, a higher-order shear deformation theory is used. Their investigation illustrated that the CCFF boundary condition results in a more significant critical buckling load among different boundary conditions. Zenkour and Radwan (7) studied hygrothermal-mechanical buckling of FGM plates resting on elastic foundations. In another study, Zenkour and Radwan (8) analyzed the bending and buckling of FGM plates in the hygrothermal environment using the four-variable exponential shear deformation theory. The buckling behavior of a single-layered graphene sheet studied by Rouabhia et al. (9) using nonlocal integral first shear deformation theory.

Ebrahimi and Barati (10) analyzed hygrothermal buckling of magnetically actuated embedded higher-order functionally graded nanoscale beams considering the neutral surface position. Shafiei and Setoodeh (11) analyzed free vibration and post-buckling of FG-CNTRC beams on a nonlinear foundation based on the Euler- Bernoulli beam theory. Malikan and Dastjerdi (12) analyzed the buckling behavior of FG nanobeams on the basis of a new one variable first-order shear deformation beam theory. Taati (13) analyzed buckling and post-buckling behavior of functionally graded micro-beams in the thermal environment using Fourier series for doubly-simply supported boundary conditions. Post-buckling behavior of continuously graded functionally graded (FG) nanobeams with geometrical imperfections investigated by Ahmad et al. (14). Interactive thermal and inertial buckling of rotating temperature-dependent FG-CNT reinforced composite beams analyzed by Khosravi et al. (15). Abo-Bakr et al. (16) used optimal weight for buckling of FG beam under variable axial load using Pareto optimality. Carrera and Demirbas (17) employed the Newton-Raphson linearization scheme to analyze bending and post-buckling behavior of thin-walled beams in a geometrical nonlinear regime with CUF. The influence of porosity on thermal buckling behavior of functionally graded beams is investigated by Belifa et al. (18) in 2021.

On the other hand, the buckling behavior of carbon nanotube reinforced FG shells were analyzed using an efficient solid-shell element based on a modified first-order shear deformation theory by Hajlaoui et al. (19). The buckling behavior of functionally graded porous nanocomposite cylindrical shells reinforced with graphene platelets under uniform external lateral pressure analyzed by Shahgholian-Ghahfarokhi et al. (20). Sofiyev et al. (21) analyzed the buckling behavior of functionally graded carbon nanotube-reinforced composite conical shells by employing first-order shear deformation theory. Hieu and Tung (22) investigated thermal and thermomechanical buckling of shear deformable FG-CNTRC cylindrical shells and toroidal shell segments with tangentially restrained edges. Post-buckling behavior of functionally graded multilayer graphene platelet reinforced composite cylindrical shells analyzed by Sun et al. (23). Static stability of carbon nanotube reinforced polymeric composite doubly curved micro-shell panels studied by Huang et al. (24) by using Hamilton’s principle.

As the features of magnetostrictive materials, the buckling behavior of these intelligent materials is necessary. In recent years some researchers did so. For instance, the numerical simulation of magnetoelastic buckling based on the magnetostrictive material model studied by Ren et al. (25). In 2017, Arani et al. (26) used nonlocal piezomagnetoelasticity theory to study the buckling behavior of piezoelectric/magnetostrictive nanobeams (PMNB), including surface effects based on Timoshenko beam theory. The results of their investigation delineate the significance of surface layers on the critical buckling loads of PMNBs. Buckling analysis of nanocomposite plates coated with magnetostrictive layer based on the first-order shear deformation theory studied by Tabbakh and Nasihatgozar (27) in 2018. They used the Mori-Tanaka model to consider the agglomeration effect and the governing equation solved using the Navier method. Their research investigates the effect of various parameters such as volume percent and agglomeration of CNTs and magnetic fields on buckling loads. Dynamic stability of truncated conical microshells made of functionally graded material integrated with magnetostrictive facesheets studied by Yuan et al. (28) based on the nonlocal strain gradient theory. In another study, Fan et al. (29) studied a couple stress-based dynamic stability of functionally graded composite truncated conical microshells with magnetostrictive facesheets embedded within nonlinear viscoelastic foundations.

According to the best knowledge of the author, the buckling behavior of the sandwich composite magnetostrictive nanoplate coupled with FG porous materials cannot be addressed. Motivated by the available lack in the literature, the buckling behavior of a three-layered composite containing magnetostrictive core and two FGM facesheets is investigated herein.

1. **Theory and Formulation**

Consider a rectangular plate of Length a width, b, and total thickness h in the x, y, and z-direction, respectively, containing the Aluminum () as the nano-face sheets of the top and Aluminum oxide () as the bottom surface.

**2-1-** **Material properties of functionally graded material**

According to the power-law equation, the properties of the top and bottom layers can be determined utilizing the volume fraction of the constitutive materials. When k equals zero, it represents a fully Aluminum () nano-surface, and k represents a fully Aluminum oxide () material. Based on the power-law method, in-homogenous Young’s modulus and mass density of the facesheets are given as (30-32):

For z

|  |  |  |
| --- | --- | --- |
|  |  | (1) |

 For z

|  |  |  |
| --- | --- | --- |
|  |  | (2) |

Parameter is the symbol of Young's modulus and mass density, which changes through the thickness. Also, it is supposed that Poisson's ratio is constant throughout the thickness.

In the present research, the Cartesian system, as shown in [Figure 1](#Figure1), is used and, the origin is at one plate corner. Winkler and Pasternak's medium have been utilized to consider the foundation effect.



**Figure 1**: Configuration of sandwich composite

* 1. **Geometrical configuration**

In the present article, the higher-order sinusoidal shear deformation plate theory was firstly introduced by Touratier (33-35) has been used. According to the higher-order sinusoidal shear deformation, plate theory, normal to the midline (neutral surface) remains normal before and after deformation.

**2-2-1- Displacement field**

Based on the assumptions of the higher-order sinusoidal shear deformation plate theory, the displacement field can be displayed as follows (33):

|  |  |  |
| --- | --- | --- |
|  |  | (3) |
|  |  | (4) |
|  |  | (5) |

It should be noted that, unlike first-order shear deformation plate theory, the shear correction factor does not require in higher-order shear deformation theory.

Also, is a function that describes the displacement field along the thickness direction and is defined as: , .

* 1. **Eringen’s Nonlocal Theory**

According to Eringen’s nonlocal theory (36), which generally can be used in cases on the micro and nanoscale, the stress at the reference point (x) in an elastic continuum is not only dependent on the strain of the point x but also on the strain of all the bystander points and can be exposed as:

|  |  |  |
| --- | --- | --- |
|  |  | (6) |

In which and are symbols of the nonlocal stress tensor and classical stress tensor, respectively. Also, is the Laplacian operator. Besides, is the nonlocal parameter.

* 1. **Equation of motion**

Using Eringen's nonlocal theory, the presented nanoplate's constitutive relations can be stated below.

**2-4-1- Stress-strain relation for the magnetostrictive materials**

In engineering applications, magnetostrictive material has gained lots of interest due to its unique properties, such as converting one sort of energy (magnetic, electric, or mechanic) to another type of energy. The relationship for stress, strain, magnetic of the core layer can be revealed as (37):

|  |  |  |
| --- | --- | --- |
|  |  | (7) |

where are stress and strain constant, respectively. Moreover, signifies a magnetic field. Besides, it should be noted that means for elastic stiffness coefficient. If the thickness stretching () supposed to be zero (), then the plane stress elastic constants can be defined as (38):

|  |  |  |
| --- | --- | --- |
|  |  | (8) |

where and  denote for modulus of the elasticity and Poisson's ratio of the core layer and are the transformed magnetostrictive moduli that can be reached as (39):

|  |  |  |
| --- | --- | --- |
|  |  | (9) |
|  |  |  |

**2-4-2- Velocity feedback gain**

The magnetic field () can be obtained from the following relation (39):

|  |  |  |
| --- | --- | --- |
|  |  | (10) |

Symbol signifies the coil constant that depends on a coil’s properties, such as its width, radius, and the number of turns of the coil. Besides, and symbolize coil current and coil gain, respectively. It should be pointed out that the control gain is considered to be constant. Additionally, is the velocity feedback gain. The connection between coil constant and coil features can be expressed as:

|  |  |  |
| --- | --- | --- |
|  |  | (11) |

in the above equation, , , and typify turns of the coil, coil width, and coil radius, respectively.

The nonzero strains of the core layer can be defined as (40):

|  |  |  |
| --- | --- | --- |
|  |  | (12) |

where,

|  |  |  |
| --- | --- | --- |
|  | ,, | (13) |

* 1. **Stress-strain relation of the facesheets**

The relation between stress and strain for the facesheets can be expressed as (41):

|  |  |
| --- | --- |
|  | (14) |

in which elastic functions can be defined as:

|  |  |  |
| --- | --- | --- |
|  |   | (15) |

in which and are defined as elastic modulus and poison’s constant of the facesheets, respectively. Material properties of consecutive layers are presented in [Table 1](#Table1).

**Table 1**: Material properties of FG facesheets and magnetostrictive core layer (10, 42)

|  |  |  |  |
| --- | --- | --- | --- |
| Symbol | Aluminum | Aluminum oxide | Magnetostrictive |
| E(GPa) | 70 | 380 | 30 |
|  | 0.3 | 0.3 | 0.25 |
|  | 2702 | 3800 | 9250 |
|  | - | - | 442.55 |
|  | - | - | 442.55 |
|  | - | - | -212 |

The nonzero strains of upper and lower layers can be defined as (40):

|  |  |  |
| --- | --- | --- |
|  |   | (16) |

in which

|  |  |  |
| --- | --- | --- |
|  |   | (17) |

* 1. **Governing Equation**

The first variation of Hamilton’s principle can be expressed as (43):

|  |  |  |
| --- | --- | --- |
|  |   | (18) |

which, , and symbolize the strain energy, kinetic energy, and external work, respectively.

**2-6-1- Strain energy**

The first variation of the strain energy of the core layer and facesheets can be express as (44):

|  |  |  |
| --- | --- | --- |
|  |   | (19) |
|  |   | (20) |

where,

|  |  |  |
| --- | --- | --- |
|  |    | (21) |

In the above equations, superscripts ‘c’ and ‘f’ designate core layer and facesheets, respectively. The nonlocal relations of forces and moments with strains are given as:

|  |  |  |
| --- | --- | --- |
|  |  | (22) |

where,

|  |  |  |
| --- | --- | --- |
|  | , , , ,  | (23) |

where,

|  |  |  |
| --- | --- | --- |
|  |   | (24) |

**2-6-2- External work**

There are many valuable relationships to define work as a precise physical quantity. Work is a type of energy that enters or leaves the nanoplate by an external force. In the studied system, which is a sandwich nanoplate consisting of magnetostrictive and functionally graded material, work is defined as energy applied by external forces along the axes of the nanoplate and causes displacement and deformation in the nanoplate.

The first variation of the external work can be expressed as (45):

|  |  |  |
| --- | --- | --- |
|  |  | (25) |
|  |  |  |

where and are the Winkler stiffness and shear layer stiffness, respectively. Also, the dimensionless form of the Winkler and Pasternak foundation is defined as:

The pre-buckling resultant forces are supposed as below:

|  |  |  |
| --- | --- | --- |
|  |  ,  | (26) |

**2-6-3- Kinetic energy**

 The first variation of the kinetic energy can be written as:

|  |  |  |
| --- | --- | --- |
|  |   | (27) |

in which, the mass moment of inertias is defined as:

|  |  |  |
| --- | --- | --- |
|  | ,,  | (28) |

* 1. **Equation of Motion**

Now, to have the five equilibrium equations, the first variation of strain energy, work done by applied forces, and kinetic energy are substituted into the Euler-Lagrange equation for the sinusoidal shear deformation by substituting equations (19)- (28) into equation (18) yields to:

|  |  |  |
| --- | --- | --- |
|  |   | (29) |
|  |  |  |
|  |   | (30) |
|  |   | (31) |
|  |   | (32) |
|  |  |  |
|  |   | (33) |
|  |  |  |

1. **Exact solution for buckling of nanoplate**

In Galerkin’s method, the boundary conditions of the problem must be satisfied by the proposed responses. To continue, the critical buckling loads will obtain, by substituting the recommended response (equation 34) in the governing equation. Galerkin’s technique has been successfully manipulated to determine various problems in buckling analysis and is a conclusive technique that can solve partial differential equations with high accuracy, convergence, and performance.

The suggested series of displacement components for satisfying the above boundary conditions are defined in these formats:

|  |  |  |
| --- | --- | --- |
|  |   | (34) |

in which , , , and are the

 amplitude of the vibration. Also, and are admissible functions which defiend according different types of boundary conditions.

By interchanging the equation (34) into the equations (29)- (33) and separating the variations of the natural frequencies will be obtained by solving the equation. In order to capture the natural frequencies determinant of the bellow equation will be equal to zero.

|  |  |  |
| --- | --- | --- |
|  |  | (35) |

where, matrix of ,  ,and  are stiffness, mass and damping matrixes which are specified in Appendix 1. In order to reach the critical buckling load natural frequency () must be set zero (=0).

**3-1- Numerical results and discussion**

In this section, the selected results of the present research will discuss the effect of various parameters on the non-dimensional critical buckling load in detail. For illustration, the thickness of the magnetostrictive layer (core layer) is represented by , and represents the thickness of facesheets.

* 1. **Model verification**

In this section, to examine the accuracy and efficiency of the proposed system, there are comparisons between the results of the mentioned system and the articles available in the literature in [Table 2](#Table3). As the first comparison, results are compared with an article by Refs (48), (49), (50). In order to compare the results, the magnetostrictive core and hygro-thermal condition are neglected.

**Table 2:** Comparison of the non-dimensional critical buckling load () of Al/ SiC for different boundary conditions (a= b= 10hc)

|  |  |  |  |
| --- | --- | --- | --- |
| Gradient index | k=0 | k=1 | k=2 |
| () | Method | CCSS | SSSS | CCSS | SSSS | CCSS | SSSS |
| (-1,0) | Reference [[43](#Ref43)]FSDT | 63.0039 | 37.3708 | 64.8195 | 37.7132 | 64.7963 | 37.7089 |
|  | Reference [[44](#Ref44)]HSDT | 63.1628 | 37.3714 | 64.9643 | 37.7172 | 64.3779 | 37.5765 |
|  | Reference [[45](#Ref45)] | 64.8257 | 37.3721 | 66.4778 | 37.7143 | 65.9443 | 37.6042 |
|  | **Present** | **63.0668** | **37.3729** | **63.6358** | **37.7101** | **63.5664** | **37.669** |
| (-1, -1) | Reference [[43](#Ref43)]FSDT | 33.3206 | 18.6854 | 33.9966 | 18.8566 | 33.9881 | 18.8545 |
|  | Reference [[44](#Ref44)]HSDT | 33.3392 | 18.6860 | 34.0121 | 18.8571 | 33.7942 | 18.8020 |
|  | Reference [[45](#Ref45)] | 34.1195 | 18.6861 | 34.6939 | 18.8572 | 34.5084 | 18.8021 |
|  | **Present** | **36.0382** | **18.6865** | **36.3633** | **18.8551** | **36.3237** | **18.8345** |

**Material properties of Al/ SiC** (48)**:**

, ,

As can be seen, results are in a good convergence, and error is trivial. It should be noted that in the above table, critical buckling load is reached according to:

|  |  |  |
| --- | --- | --- |
|  |  | (36) |

* 1. **Results and Discussion**

In [Table 3](#Table5), non-dimensional buckling load is obtained for different values of aspect ratio ( ) and side-to-thickness ratio ( ) ratios for different values of porosity volume. As shown in Table 5, increasing the aspect ratio () increases the non-dimensional buckling load. Additionally, the non-dimensional buckling load increases due to increasing the side-to-thickness ratio (). Due to the effect of velocity feedback gain, the amount of buckling load decreases by increasing the value to the .

**Table 3:** Non-dimensional buckling load for different aspect ratios for SSCC boundary conditions and even porosity distribution. (, , k=0, a=40nm, hf=0.2nm**,** )

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | Porosity |  |  |  |  |
|  |  | 5 | 10 | 20 | 30 |
| 0.5 | **0.1** | 49.8101 | 85.9312 | 168.643 | 266.355 |
| 1 |  | 36.9724 | 63.784 | 125.178 | 197.707 |
| 0.5 | **0.2** | 47.7433 | 81.591 | 159.097 | 250.659 |
| 1 |  | 35.4383 | 60.5624 | 118.093 | 186.056 |
| 0.5 | **0.3** | 45.6764 | 77.2508 | 149.551 | 234.964 |
| 1 |  | 33.9041 | 57.3408 | 111.007 | 174.406 |
| 0.5 | **0.4** | 43.6096 | 72.9106 | 140.005 | 219.268 |
| 1 |  | 32.37 | 54.1192 | 103.921 | 162.756 |
| 0.5 | **0.5** | 41.5427 | 68.5704 | 130.459 | 203.573 |
| 1 |  | 30.8359 | 50.8977 | 96.8359 | 151.105 |
| 0.5 | **0.6** | 39.4759 | 64.2303 | 120.914 | 187.877 |
| 1 |  | 29.3017 | 47.6761 | 89.75.3 | 139.455 |

[Table 4](#Table6) elucidated a computation of the non-dimensional buckling load for simply-simply and simply-clamped boundary conditions. This table shows that the buckling load in SSCC boundary conditions is greater than that of the SSSS boundary conditions. This is due to the fact that stronger support in boundary conditions tends to make the nanoplate more rigid due to the enhancement of the nanoplate structure. Also, in this table, the values ​​of dimensionless buckling load are expressed for different values ​​of the non-local Eringen parameter. As previously explained, as the non-local parameter increases, the dimensionless buckling load decreases. This phenomenon happens mainly due to the fact that as the non-local parameter increases, the nanoplate becomes softer. It can be said that increasing the small-scale parameter reduces the system's energy, and the system becomes weaker. Therefore, it can be said that the dimensionless buckling loads of the local system are higher than the non-local system. In other words, the stiffness owing to the couple stress effect is added to the classical stiffness; thus, the total stiffness is larger than that of its classical counterpart. On the other hand, in Table 4, the dimensionless buckling load for uniaxial and biaxial compressive loading is investigated.

**Table 4:** Non-dimensional buckling load for different values of the nonlocal parameter and SSSS and SSCC boundary conditions

|  |  |  |  |
| --- | --- | --- | --- |
| Nonlocal parameter | () | SSCC | SSSS |
|  | (-1, 0) | 74.1982 | 43.9693 |
|  |  | 73.2939 | 43.4334 |
|  |  | 72.4115 | 42.9105 |
|  |  | 71.5500 | 42.4 |
|  |  | 70.7088 | 41.9015 |
|  | (-1, -1) | 37.0991 | 21.9846 |
|  |  | 36.647 | 21.7167 |
|  |  | 36.2057 | 21.4533 |
|  |  | 35.775 | 21.02 |
|  |  | 35.3544 | 20.9508 |

[Table 5](#Table7) has been rendered to compare the non-dimensional buckling load for different external loads and for even and uneven porosity distribution. As can be seen from Table 5, non-dimensional buckling loads are greater in uneven distribution. This is principally owing to the fact that for the uneven distribution, the cavities are less, and therefore the nanoplate’s stiffness is higher. Withal, in Table 5, the value of the Winkler and Pasternak foundation is supposed to be constant as Kw=0, Kg=0.

**Table 5**: Comparison of the non-dimensional buckling load for SSSS and SSCC boundary conditions (, , , k=0, hc=3nm, hf=0.2nm, )

|  |  |  |  |
| --- | --- | --- | --- |
| SSCC | SSSS | () | Porosity |
| 74.1982 | 43.9693 | (-1, 0) | **Even Porosity** |
| 37.0991 | 21.9846 | (-1, -1) |  |
| 99.3098 | 58.8503 | (-1, 0) | **Uneven porosity** |
| 49.6549 | 29.4251 | (-1, -1) |  |

To examine the effect of the thickness of the magnetostrictive layer on the non-dimensional buckling load, [Figure 2a](#Figure3a) and [Figure 2b](#Figure3b) have been rendered. In these figures, Winkler and Pasternak foundation values are supposed to be zero (Kw=Kg=0). Also, the gradient index is supposed to be zero. In these figures, non-dimensional buckling load rendered for the even and uneven distribution for six different values of the nonlocal parameter. As can be seen from these figures, increasing the thickness of the magnetostrictive layer decreases the non-dimensional buckling load due to the effect of mass and inertia. Also, by increasing the nonlocal parameter, the non-dimensional buckling load decreases.





1. **Even distribution**





1. **Uneven distribution**

**Figure 2**: Effect of the thickness of the magnetostrictive layer on the non-dimensional buckling loads for (**a**): Even porosity (**b**): Uneven porosity

1. **Conclusion**

For the first time, buckling behavior of the composite magnetostrictive nano-plate integrated with the functionally graded facesheets using the higher-order sinusoidal shear deformation plate theory. Also, Hamilton’s principle is utilized to obtain governing equations, and equations are solved by utilizing Galerkin’s analytical solution. It is seen that dimensional buckling load for boundary conditions is more trapped than dimensionless buckling load for simple boundary conditions. Additionally, increasing the thickness of the magnetostrictive layer reduces the dimensionless buckling load. Further, it is indicated that the dimensional buckling loads for Simply-clamped boundary conditions are greater than dimensionless buckling loads for simply-supported boundary conditions.

**References**

1. Liu G, Chen X, Reddy J. Buckling of symmetrically laminated composite plates using the element-free Galerkin method. International Journal of Structural Stability and Dynamics. 2002;2(03):281-94.

2. Liew K, Peng L, Kitipornchai S. Buckling analysis of corrugated plates using a mesh-free Galerkin method based on the first-order shear deformation theory. Computational Mechanics. 2006;38(1):61-75.

3. Kim S-E, Thai H-T, Lee J. Buckling analysis of plates using the two variable refined plate theory. Thin-Walled Structures. 2009;47(4):455-62.

4. Lei Z, Liew K, Yu J. Buckling analysis of functionally graded carbon nanotube-reinforced composite plates using the element-free kp-Ritz method. Composite Structures. 2013;98:160-8.

5. Karimi M, Shahidi AR. Buckling analysis of skew magneto-electro-thermo-elastic nanoplates considering surface energy layers and utilizing the Galerkin method. Applied Physics A. 2018;124(10):1-15.

6. Karami B, Janghorban M, Tounsi A. Galerkin’s approach for buckling analysis of functionally graded anisotropic nanoplates/different boundary conditions. Engineering with Computers. 2019;35(4):1297-316.

7. Zenkour A, Radwan A. Hygrothermo-mechanical buckling of FGM plates resting on elastic foundations using a quasi-3D model. International Journal for Computational Methods in Engineering Science and Mechanics. 2019;20(2):85-98.

8. Zenkour A, Radwan A. Bending and buckling analysis of FGM plates resting on elastic foundations in hygrothermal environment. Archives of Civil and Mechanical Engineering. 2020;20(4):1-23.

9. Rouabhia A, Chikh A, Bousahla AA, Bourada F, Heireche H, Tounsi A, et al. Physical stability response of a SLGS resting on viscoelastic medium using nonlocal integral first-order theory. Steel and Composite Structures. 2020;37(6):695-709.

10. Ebrahimi F, Barati MR. Hygrothermal buckling analysis of magnetically actuated embedded higher order functionally graded nanoscale beams considering the neutral surface position. Journal of Thermal Stresses. 2016;39(10):1210-29.

11. Shafiei H, Setoodeh AR. Nonlinear free vibration and post-buckling of FG-CNTRC beams on nonlinear foundation. Steel and Composite Structures. 2017;24(1):65-77.

12. Malikan M, Dastjerdi S. Analytical buckling of FG nanobeams on the basis of a new one variable first-order shear deformation beam theory. International Journal of Engineering and Applied Sciences. 2018;10(1):21-34.

13. Taati E. On buckling and post-buckling behavior of functionally graded micro-beams in thermal environment. International Journal of Engineering Science. 2018;128:63-78.

14. Ahmed RA, Fenjan RM, Faleh NM. Analyzing post-buckling behavior of continuously graded FG nanobeams with geometrical imperfections. Geomechanics and Engineering. 2019;17(2):175-80.

15. Khosravi S, Arvin H, Kiani Y. Interactive thermal and inertial buckling of rotating temperature-dependent FG-CNT reinforced composite beams. Composites Part B: Engineering. 2019;175:107178.

16. Abo-Bakr R, Abo-Bakr H, Mohamed S, Eltaher M. Optimal weight for buckling of FG beam under variable axial load using Pareto optimality. Composite Structures. 2021;258:113193.

17. Carrera E, Demirbas MD. Evaluation of bending and post-buckling behavior of thin-walled FG beams in geometrical nonlinear regime with CUF. Composite Structures. 2021;275:114408.

18. Bellifa H, Selim MM, Chikh A, Bousahla AA, Bourada F, Tounsi A, et al. Influence of porosity on thermal buckling behavior of functionally graded beams. Smart Structures and Systems. 2021;27(4):719-28.

19. Hajlaoui A, Chebbi E, Dammak F. Buckling analysis of carbon nanotube reinforced FG shells using an efficient solid-shell element based on a modified FSDT. Thin-Walled Structures. 2019;144:106254.

20. Shahgholian-Ghahfarokhi D, Rahimi G, Khodadadi A, Salehipour H, Afrand M. Buckling analyses of FG porous nanocomposite cylindrical shells with graphene platelet reinforcement subjected to uniform external lateral pressure. Mechanics Based Design of Structures and Machines. 2019:1-21.

21. Sofiyev AH, Tornabene F, Dimitri R, Kuruoglu N. Buckling behavior of FG-CNT reinforced composite conical shells subjected to a combined loading. Nanomaterials. 2020;10(3):419.

22. Hieu PT, Van Tung H. Thermal and thermomechanical buckling of shear deformable FG-CNTRC cylindrical shells and toroidal shell segments with tangentially restrained edges. Archive of Applied Mechanics. 2020;90(7):1529-46.

23. Sun J, Zhu S, Tong Z, Zhou Z, Xu X. Post-buckling analysis of functionally graded multilayer graphene platelet reinforced composite cylindrical shells under axial compression. Proceedings of the Royal Society A. 2020;476(2243):20200506.

24. Huang Y, Karami B, Shahsavari D, Tounsi A. Static stability analysis of carbon nanotube reinforced polymeric composite doubly curved micro-shell panels. Archives of Civil and Mechanical Engineering. 2021;21(4):1-15.

25. Ren H-y, Li Z-g, Shu X-f. The Numerical Simulation of Magnetoelastic Buckling Based on Magnetostrictive Material Model. JOURNAL-TAIYUAN UNIVERSITY OF TECHNOLOGY. 2005;36(5):561.

26. Ghorbanpour Arani A, Abdollahian M, Rahmati A. Nonlocal Piezomagnetoelasticity Theory for Buckling Analysis of Piezoelectric/Magnetostrictive Nanobeams Including Surface Effects. Journal of Solid Mechanics. 2017;9(4):707-29.

27. Tabbakh M, Nasihatgozar M. Buckling analysis of nanocomposite plates coated by magnetostrictive layer. Smart Structures and Systems. 2018;22(6):743-51.

28. Yuan Y, Zhao X, Zhao Y, Sahmani S, Safaei B. Dynamic stability of nonlocal strain gradient FGM truncated conical microshells integrated with magnetostrictive facesheets resting on a nonlinear viscoelastic foundation. Thin-Walled Structures. 2021;159:107249.

29. Fan L, Sahmani S, Safaei B. Couple stress-based dynamic stability analysis of functionally graded composite truncated conical microshells with magnetostrictive facesheets embedded within nonlinear viscoelastic foundations. Engineering with Computers. 2021;37(2):1635-55.

30. Reddy J, Wang C, Kitipornchai S. Axisymmetric bending of functionally graded circular and annular plates. European Journal of Mechanics-A/Solids. 1999;18(2):185-99.

31. Ebrahimi F, Barati MR. Electro-magnetic effects on nonlocal dynamic behavior of embedded piezoelectric nanoscale beams. Journal of Intelligent Material Systems and Structures. 2017;28(15):2007-22.

32. Ebrahimi F, Farazmandnia N, Kokaba MR, Mahesh V. Vibration analysis of porous magneto-electro-elastically actuated carbon nanotube-reinforced composite sandwich plate based on a refined plate theory. Engineering with Computers. 2021;37(2):921-36.

33. Touratier M. An efficient standard plate theory. International journal of engineering science. 1991;29(8):901-16.

34. Touratier M. A generalization of shear deformation theories for axisymmetric multilayered shells. International Journal of Solids and Structures. 1992;29(11):1379-99.

35. Touratier M. A refined theory of laminated shallow shells. International Journal of Solids and Structures. 1992;29(11):1401-15.

36. Eringen AC, Edelen D. On nonlocal elasticity. International journal of engineering science. 1972;10(3):233-48.

37. Ebrahimi F, Dabbagh A, Rabczuk T. On wave dispersion characteristics of magnetostrictive sandwich nanoplates in thermal environments. European Journal of Mechanics-A/Solids. 2021;85:104130.

38. Ghorbani K, Rajabpour A, Ghadiri M, Keshtkar Z. Investigation of surface effects on the natural frequency of a functionally graded cylindrical nanoshell based on nonlocal strain gradient theory. The European Physical Journal Plus. 2020;135(9):1-23.

39. Ebrahimi F, Dabbagh A, Tornabene F, Civalek O. Hygro-thermal effects on wave dispersion responses of magnetostrictive sandwich nanoplates. Advances in nano research. 2019;7(3):157.

40. Thai H-T, Kim S-E. A simple quasi-3D sinusoidal shear deformation theory for functionally graded plates. Composite Structures. 2013;99:172-80.

41. Mahinzare M, Akhavan H, Ghadiri M. A nonlocal strain gradient theory for rotating thermo-mechanical characteristics on magnetically actuated viscoelastic functionally graded nanoshell. Journal of Intelligent Material Systems and Structures. 2020;31(12):1511-23.

42. Hebali H, Tounsi A, Houari MSA, Bessaim A, Bedia EAA. New quasi-3D hyperbolic shear deformation theory for the static and free vibration analysis of functionally graded plates. Journal of Engineering Mechanics. 2014;140(2):374-83.

43. Rao SS. Vibration of continuous systems: John Wiley & Sons; 2019.

44. Ebrahimi F, Dabbagh A. Vibration analysis of multi-scale hybrid nanocomposite plates based on a Halpin-Tsai homogenization model. Composites Part B: Engineering. 2019;173:106955.

45. Ebrahimi F, Barati MR. Temperature distribution effects on buckling behavior of smart heterogeneous nanosize plates based on nonlocal four-variable refined plate theory. International Journal of Smart and Nano Materials. 2016;7(3):119-43.

46. Ebrahimi F, Jafari A, Barati MR. Vibration analysis of magneto-electro-elastic heterogeneous porous material plates resting on elastic foundations. Thin-Walled Structures. 2017;119:33-46.

47. Barati MR. A general nonlocal stress-strain gradient theory for forced vibration analysis of heterogeneous porous nanoplates. European Journal of Mechanics-A/Solids. 2018;67:215-30.

48. Mohammadi M, Saidi A, Jomehzadeh E. A novel analytical approach for the buckling analysis of moderately thick functionally graded rectangular plates with two simply-supported opposite edges. Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science. 2010;224(9):1831-41.

49. Bodaghi M, Saidi A. Levy-type solution for buckling analysis of thick functionally graded rectangular plates based on the higher-order shear deformation plate theory. Applied Mathematical Modelling. 2010;34(11):3659-73.

50. Thai H-T, Choi D-H. An efficient and simple refined theory for buckling analysis of functionally graded plates. Applied Mathematical Modelling. 2012;36(3):1008-22.

51. Sobhy M. A comprehensive study on FGM nanoplates embedded in an elastic medium. Composite Structures. 2015;134:966-80.

52. Barati MR, Zenkour AM, Shahverdi H. Thermo-mechanical buckling analysis of embedded nanosize FG plates in thermal environments via an inverse cotangential theory. Composite Structures. 2016;141:203-12.