Investigation of hygrothermal environment effects on the static bending response of nanobeams

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ABSTRACT

Nano beams are widely utilized as fundamental structural components in microscale and nanoscale sensors, while also serving as critical elements in missile guidance and flight-control systems. This study presents an analytical solution for the static bending behavior of multilayer nanobeams accounting for the combined effects of hygrothermal environments and flexoelectricity. The considered nanobeam is composed of three material layers, in which the core layer is made of a porous material with microporosity. The theoretical formulation is established based on a novel third-order shear deformation theory, and the small-scale effect is incorporated through nonlocal elasticity theory. Several benchmark examples are provided to verify the accuracy and reliability of the proposed model. Thereafter, extensive numerical investigations are performed to elucidate the effects of key parameters on the bending behavior of multilayer nanobeams, with special attention devoted to hygrothermal environmental conditions. The results offer valuable insights for the optimal design and fabrication of multilayer nanobeam structures and contribute to improving their operational performance in practical engineering applications.

Keywords: Static bending; Nanobeams; Nonlocal elasticity; Porous; Hygrothermal environments.

1. INTRODUCTION

To exploit the advantages of different materials, multilayered structures are frequently designed and fabricated by combining multiple material layers. Such configurations not only enhance the load-carrying capacity of structures but also improve thermal and acoustic insulation performance, while enabling the utilization of unique material effects such as piezoelectricity, flexoelectricity, and other multifunctional phenomena. Consequently, the mechanical behavior of multilayered structures has attracted considerable attention from the scientific community. Tuyen and Kien [1] employed the finite element method based on a two-node beam element with three degrees of freedom per node to investigate the influence of temperature on the vibration response of functionally graded beams subjected to moving loads. A notable contribution of their study was the examination of various thermal environments, including uniform, linear, and nonlinear temperature distributions, and their effects on beam vibrations. Doan et al. [2] investigated the vibration characteristics of multilayer beams immersed in a fluid environment while accounting for thermal effects. The governing formulations were established based on an improved shear deformation theory, and the damped natural frequencies, including both real and imaginary components, were explicitly derived and discussed. In another study, Doan and co-workers [3] utilized the finite element method to analyze the forced vibration behavior of nanobeams considering the combined influences of temperature and the flexomagnetic effect, a complex multiphysical phenomenon with significant practical applications. Vuong et al. [4] developed an

analytical solution to investigate the nonlinear stability of multilayer nanobeams subjected to hygrothermal environments. Based on an improved shear deformation theory, explicit expressions for the critical buckling load were derived, facilitating parametric studies and providing valuable insights into the effects of various factors on the compressive load-bearing capacity of nanobeams.

Despite these significant contributions, the static bending behavior of nanobeams in hygrothermal environments based on a newly developed higher-order shear deformation theory has not yet been comprehensively investigated. This research gap motivates the present study, which aims to provide a deeper understanding of the effects of hygrothermal conditions on the bending deflection of nanobeams. The findings of this study provide an important scientific basis for the design and development of miniaturized sensors and control components for missile flight-control systems.

2. PROBLEM

Theoretical foundations

A three-layer nanobeam is considered, as illustrated in Figure 1. The beam has a length of L and an overall cross-sectional height of h. The core layer has a thickness of h_g, while the two surface layers each have a thickness of h_s. The core is composed of a homogeneous porous material containing micro-voids, whereas the two surface layers are made of a flexoelectric material.

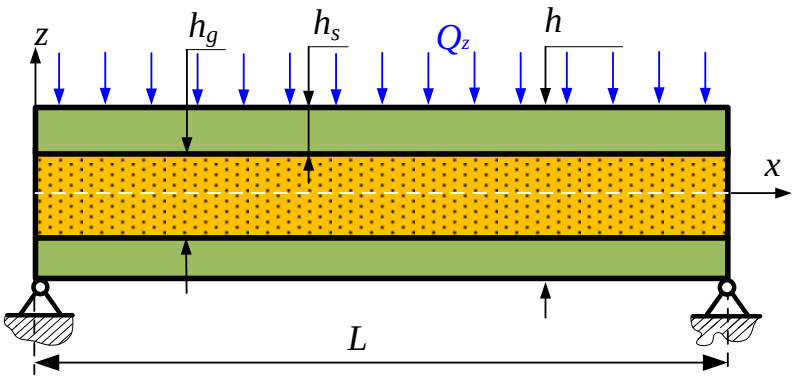


Figure 1. *Multilayer nanobeam under hygrothermal environment.*

The thickness ratio of the constituent layers can vary and is denoted in the form h_s-h_g-h_s. For example, the notation 1-0-1 indicates that the core layer has zero thickness, while the two surface layers have equal thicknesses. Similarly, the notation 1-2-1 signifies that the thickness of the core layer is twice that of each surface layer. Other thickness configurations can be interpreted in the same manner. It should also be noted that the present work only considers materials operating within the linear elastic regime.

The core layer is composed of a porous material in which the porosity may be distributed according to various patterns. In the present study, a cosine-law porosity distribution is adopted and expressed as follows:

$$\begin{cases} V_V^{(1)} = 0; & \left(-h/2 \le z \le -h_g/2\right) \\ V_V^{(2)} = V_0\left\{1-k_0+\left(k_0\pi/2\right)\cos\left(\pi z/h_c\right)\right\}; & \left(-h_g/2 \le z \le h_g/2\right) \\ V_V^{(3)} = 0; & \left(h_g/2 \le z \le h/2\right) \end{cases} \tag{1}$$

where $V_V^{(i)}$ represents the volume fraction of pores in the i-th layer, V_0 is a distribution parameter controlling the porosity density throughout the material, and $V_V^{(i)}$ is a constant corresponding to

the pore volume fraction at $k_0 = 0$.

The elastic modulus of each layer varies along the thickness coordinate z according to the porosity distribution and can be expressed as follows: $E^{(i)}(z) = E_0^{(i)}\left(1 - V_0^{(i)}\right)$, where $E_0^{(i)}$ is the elastic modulus of the constituent material in the absence of porosity, while the Poisson's ratio is assumed to remain constant and is taken as 0.3.

The displacement field of the beam is described by two displacement components as follows:

$$u_x(x,y,z) = -z\left(\partial u_b / \partial x\right) - g_z\left(\partial u_s / \partial x\right);\ u_z(x,y,z) = u_b(x,y) + u_s(x,y) \tag{2}$$

where u_x and u_z represent the displacement components of an arbitrary point in the x - and z-directions, respectively. The displacement component normal to the beam axis, u_z, is decomposed into bending and shear contributions, denoted by $u_b$and u_s, respectively. The function g_z is expressed as $g_z = \left(127z^4 / 200h^3 - 77z^2 / 125h + 39h / 500\right)\sinh\left(\pi z / h\right)$. This higher-order beam theory clearly distinguishes between the bending and shear deformation components while simultaneously satisfying the zero transverse shear stress condition at the beam surfaces.

The axial and shear strain components of the beam can be expressed as follows:

$$\varepsilon_x = z\varepsilon_z + g_z\varepsilon_g;\ \gamma_{xz} = f_z\gamma_{0xz} \tag{3}$$

where the axial strain components (ε_x) and the shear strain components (γ_{xz}) are given by

$$\varepsilon_z = -\partial^2 u_b / \partial x^2;\ \varepsilon_g = -\partial^2 u_s / \partial x^2; \gamma_{xz} = \partial u_s \partial x;\ f_z = 1 - \partial g_z / \partial z; \tag{4}$$

The two surface layers of the beam are composed of a flexoelectric material, in which the flexoelectric effect accounts for strain-gradient contributions:

$$\eta_{xxz} = -\partial^2 u_b / \partial x^2 - \left(\partial g_z / \partial z\right)\partial^2 u_s / \partial x^2 = \eta_b + \left(\partial g_z / \partial z\right)\eta_s \tag{5}$$

According to [5], flexoelectric materials differ fundamentally from conventional piezoelectric materials, and their stress–strain constitutive relations can be expressed as follows:

$$\left(1 - l^2\partial^2\sigma_x^{(i)} / \partial x^2\right) = E^{(i)}\varepsilon_x - e_{31}E_z^{(i)};\qquad \left(1 - l^2\partial^2\tau_{xz}^{(i)} / \partial x^2\right) = G^{(i)}\varepsilon_{xz} \tag{6}$$

$$\Psi_{xxz}^{(i)} = -k_{14}E_z^{(i)};\quad P_z^{(i)} = e_{31}\varepsilon_{xx} + \kappa_{33}E_z^{(i)} + k_{14}\eta_{xxz} \tag{7}$$

where $\sigma_x^{(i)}$ and $\tau_{xz}^{(i)}$ are the normal and shear stresses, respectively; l denotes the nonlocal elastic parameter that characterizes the influence of size effects; $V_z^{(i)}$ represents the electric field, $G^{(i)} = E^{(i)} / 2\left(1 + \nu^{(i)}\right)$, and k_{14} is the flexoelectric coefficient. Gauss's law is applied to the two surface layers and can be expressed as follows: $\partial P_z^{(i)} / \partial z = 0$. In the absence of an externally applied electric potential, the electric displacement is taken to be zero at the external surfaces of the outer layers. This work gets:

$$E_z^{(i)} = \left(e_{31}z / \kappa_{33} + k_{14} / \kappa_{33}\right)\left(\partial^2 u_b / \partial x^2\right) + \left(e_{31}g_z / \kappa_{33} + \left(k_{14} / \kappa_{33}\right)\partial g_z / \partial z\right)\left(\partial^2 u_s / \partial x^2\right) \tag{8}$$

For the porous core layer, the normal and shear stresses are related to the axial and shear strains through the framework of nonlocal elasticity theory: $\left(1 - l^2\partial^2 / \partial x^2\right)\left\{\sigma_x^{(2)}, \tau_{xz}^{(2)}\right\} = \left\{E^{(2)}\varepsilon_x^{(2)}, G^{(2)}\gamma_{xz}^{(2)}\right\}$

The equilibrium equations governing the behavior of the nanobeam are established using the

principle of virtual work: $\delta C_B = \delta C_{Tai} + \delta C_{NA}$, where δC_B, δC_{Tai}, and δC_{NA} denote the virtual work contributions arising from the internal forces, the external transverse loading, and the hygrothermal environment, respectively. Their mathematical expressions are given below: $\delta C_{Tai} = \int_S Q_z \delta u_z dS$, where Q_z denotes the external load acting perpendicular to the beam axis. The virtual work associated with the hygrothermal environment is expressed as:

$$\delta C_{NA} = \int_S \left(N_T + N_A\right)\left(\partial u_z / \partial x\right)\delta\left(\partial u_z / \partial x\right) dS \tag{9}$$

where $N_T = \sum_{i=1}^{3} \int_{h_i}^{h_{i+1}} E^{(i)} \alpha_T^{(i)} \Delta T dz, N_A = \sum_{i=1}^{3} \int_{h_i}^{h_{i+1}} E^{(i)} \beta_T^{(i)} \Delta M dz$ denotes the hygrothermal force resultant induced by temperature and moisture variations, while ΔT and ΔM represent the temperature and moisture differences, respectively, relative to the stress-free reference temperature and moisture conditions.

The virtual work contribution arising from the deformation-induced internal forces of the nanobeam can be written as:

$$\delta C_B = \int_S \begin{pmatrix} -\left(\partial^2 M_x / \partial x^2\right)\delta u_b - \left(\partial^2 S_x / \partial x^2\right)\delta u_s \\ -\left(\partial^2 T_{xxz} / \partial x^2\right)\delta u_b - \left(\partial^2 Y_{zzx} / \partial x^2\right)\delta u_s + \left(\partial Q_{xz} / \partial x\right)\delta u_s \end{pmatrix} dS \tag{10}$$

Unlike the method presented in [6], this work employs an analytical approach, for a nanobeam with simply supported boundary conditions at both ends, the general solutions for the displacement components u_b and u_s, together with the expression of the external load, are assumed in the following form: $\{u_b, u_s, Q_z\} = \sum_{n=1}^{\infty} \{U_{0b}, U_{0s}, Q_{0v}\} \sin\left(\alpha_n x\right)$, where U_{0b} and U_{0s} denote the amplitudes of the displacement components u_b and u_s, respectively, while Q_{0v} represents the amplitude of the transverse external load Q_z, $\alpha_n = n\pi / L$. After performing the necessary transformations, the following relations can be obtained:

$$\begin{aligned} &\left\{\left[A_{Yb} - A_{Tb} + A_{gz} - \frac{e_{31}^2}{\kappa_{33}} A_{Mzg} - A_{zz} + \frac{e_{31}^2}{\kappa_{33}}\left(\frac{h^3}{12} - \frac{h_g^3}{12}\right)\right] - l^2\left(A_{Tb} - A_{Yb}\right)\left(\alpha_n\right)^2\right\} U_{0b}\left(\alpha_n\right)^2 \\ &+\left\{\left(A_{Ys} - A_{Ts} + A_{gg} - \frac{e_{31}^2}{\kappa_{33}} A_{Sgg} - A_{gz} + \frac{e_{31}^2}{\kappa_{33}} A_{Mzg}\right)\left(\alpha_n\right)^2 - l^2\left(A_{Ts} - A_{Ys}\right)\left(\alpha_n\right)^4 - A_s\right\} U_{0s} = 0 \end{aligned} \tag{11}$$

If U_0 denotes the amplitude of the displacement component perpendicular to the beam axis, then

$$U_{0b} + U_{0s} = U_0 \tag{12}$$

This work derives the following relationship: $U_{0b} = Y_b U_0;\ U_{0s} = Y_s U_0$, where Y_b and Y_s denote coefficients determined by the geometric characteristics and material properties of the nanobeam.

By performing the necessary algebraic manipulations, the governing equation of the nanobeam under static bending is reduced to the following compact form: $R_1 U_0 = R_Q Q_{0v}$, where:

$$R_1 = \begin{Bmatrix} \left(A_{Yb} + A_{gz} - A_{Mzg}e_{31}^2/\kappa_{33}\right)Y_b\alpha_n^2 - \left(1+l^2\alpha_n^2\right)\left(N_T + N_M\right) \\ +\left(A_{Ys} + A_{gg} - A_{Sgg}e_{31}^2/\kappa_{33}\right)Y_s\alpha_n^2 + l^2\left(A_{Yb}Y_b + A_{Ys}Y_s\right)\alpha_n^4 - A_sY_s \end{Bmatrix}\alpha_n^2; \quad (13)$$

$$R_Q = \left(1+l^2\alpha_n^2\right)$$

When the nanobeam is subjected to a uniformly distributed load $Q_{0v} = 4P_{0v}/n\pi$, the static deflection takes the following form: $U_0 = \sum_{n=1}^{\infty}\left(4P_{0v}/n\pi\right)\left(R_Q/R_1\right)\sin\left(n\pi x/L\right)$.

3. RESULTS AND DISCUSSION

3.1. Verification example

This section is devoted to validating the accuracy of the proposed solution for the static bending analysis of nanobeams while accounting for small-scale effects. The nanobeam has a length of $L =$ 10nm, and the height and width of its cross-section are denoted by $h$and b, respectively, with the aspect ratio L/h = 10. The material properties are $E = 30$GPa and $\nu = 0.3$, and the beam is subjected to a uniformly distributed load with an intensity of $Q_0 = 1$ N/m. The maximum deflection at the beam midpoint is selected as the comparison parameter and is defined as $u_{zmax}^* = 100\left(EI/Q_0L^4\right)u_z\left(L/2\right)$.

The calculated maximum deflections are compared with the exact solution of Ref. [6] and the numerical results of Ref. [7], as presented in Table 1. Good agreement is observed among the three sets of results, with only minor discrepancies. Such differences are expected since the formulations employed in Refs. [6] and [7] are based on the Classical Beam Theory (CT) and Timoshenko's First-Order Shear Deformation Theory (FT), respectively, whereas the present study adopts a different beam theory.

Table 1. *Comparison of the static deflection* u_{zmax}^* *of the nanobeam.*

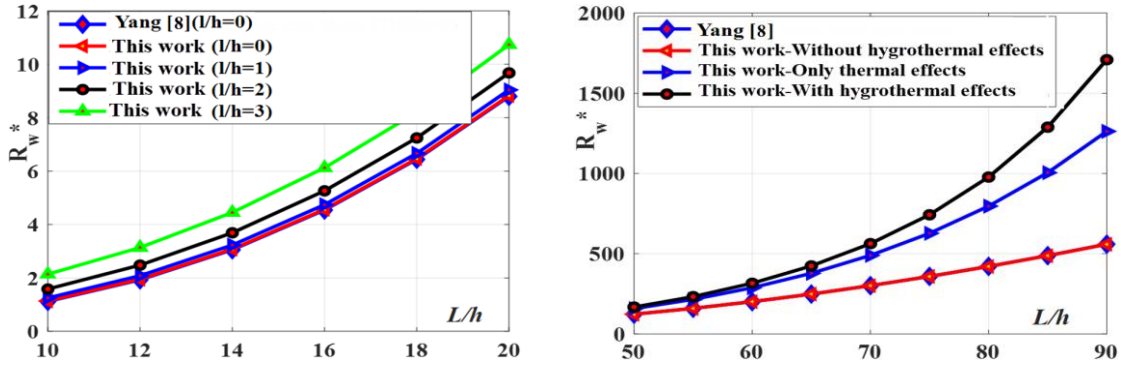
L/h	l^2 (nm^2)	Ref. [6] (CT)	Ref. [7] (CT)	Ref. [6] (FT)	Ref. [7] (FT)	This work
10	0	1.3130	1.3021	1.3483	1.3346	1.3237
	0.5	1.3809	1.3646	1.4210	1.3971	1.3891
	1.0	1.4487	1.4271	1.4937	1.4596	1.4544

3.2. Parametric study on the bending deflection of the nanobeam

This section investigates the effects of several geometric, material, and hygrothermal parameters on the nonlinear bending response of the nanobeam. The beam has a length of $L =$ 1000 nm and a thickness ranging from $L/10$ to $L/40$. The surface layers are made of a flexoelectric material characterized by the following properties: $c_{11} = 102$GPa, $e_{31} = -17.05$ C/m^2, $k_{33} = 1.76 \times 10^{-8}$C/(V·m), $k_{14} = f_{14}^* \times 10^{-7}$C/m, where f_{14}^* is a coefficient, $\alpha^{(1)} = 9.6384 \times 10^{-6}$ K^{-1}, and $\beta^{(2)} = 0.44$ (%H$_2$O)$^{-1}$. The core layer is composed of aluminum with the following material properties: $E^{(2)} = 70$ GPa, $\nu^{(2)} = 0.3$, $\alpha^{(2)} = 23.10^{-6}$ 1/K, $\beta^{(2)} = 0.44$ (%H$_2$O)$^{-1}$. The beam is subjected to a uniformly distributed load of intensity Q_{0v}. The output parameter considered in the present study is the maximum deflection of the nanobeam, which is normalized according to $R_w^* = 100\left(c_{11}h_0^3/Q_0L^4\right)u_{zmax}$, where $h_0 = L/10$.

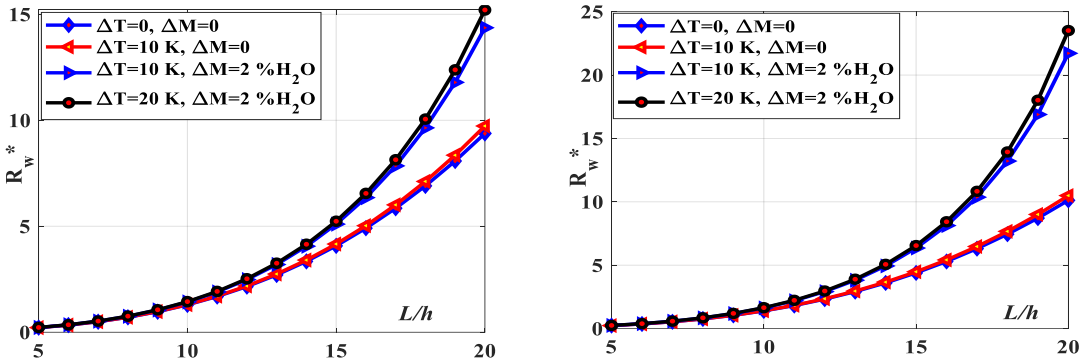
Figures 2 and 3 present the effects of various parameters on the maximum deflection of the nanobeam in the absence and presence of hygrothermal conditions, respectively. The obtained

results lead to the following observations: When the size effect and hygrothermal effects are neglected, excellent agreement is observed between the present results and those calculated using the analytical formula developed by Yang [8], thereby further validating the accuracy of the proposed formulation. It is observed that the maximum bending deflection of the nanobeam occurs when both temperature and moisture effects are considered. This trend is more evident for thinner beams. The reason is that a decrease in thickness results in reduced structural stiffness, making the beam more sensitive to hygrothermal effects. As the thickness of the core layer increases, the deflection of the nanobeam also increases. This is because the elastic modulus of the core layer is higher than that of the surface layers; therefore, an increase in the core thickness leads to a reduction in the overall stiffness of the nanobeam.



a. Without hygrothermal effects *b. ΔT = 10 K, ΔM = 1%H_2O, l/h=0*

Figure 2. *Maximum deflection of the nanobeam under hygrothermal and non-hygrothermal conditions, 1-0-1.*

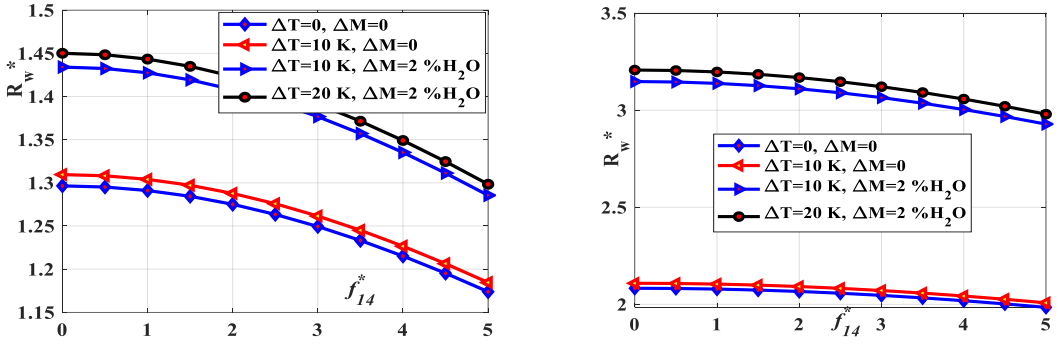


a. 1-1-1 b. 1-2-1

Figure 3. *The maximum deflection of the nanobeam depends on the hygrothermal environment, l/h=1.*

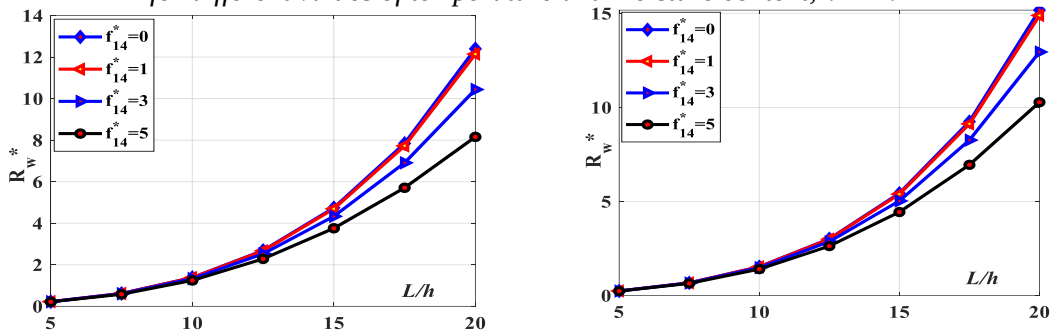
The dependence of the maximum deflection on the flexoelectric characteristic parameter is presented in Figures 4 and 5. The obtained results lead to the following observations: As the value of f_{14}^* increases, the maximum deflection of the sandwich nanobeam decreases, indicating that the parameter f_{14}^* contributes to an increase in the stiffness of the beam. As the flexoelectric coefficient increases, the coupling between the bending strain gradient and the induced electric polarization becomes stronger. The resulting polarization and associated electric field enhance the electromechanical contribution to the strain energy of the system, thereby increasing the effective bending stiffness. As the thickness of the core layer increases, the effect of flexoelectricity becomes less significant. As the beam thickness decreases, the influence of the flexoelectric effect

becomes more pronounced. This also indicates that the flexoelectric effect is strongly dependent on the beam thickness.



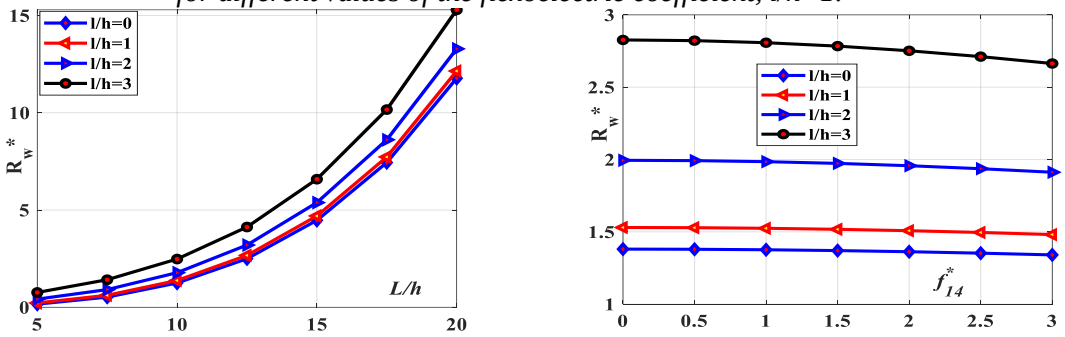
a. 1-1-1 b. 1-8-1

Figure 4. *The maximum deflection of the nanobeam depends on the flexoelectric coefficient for different values of temperature and moisture content, l/h=1.*



a. 1-1-1 b. 1-2-1

Figure 5. *The maximum deflection of the nanobeam depends on the beam thickness for different values of the flexoelectric coefficient, l/h=1.*



a. 1-1-1 b. 1-2-1, *L*/*h*=10

Figure 6. *The maximum deflection of the nanobeam depends on the size effect for different values of the beam thickness and the parameter f_{14}.*

Figure 6 presents the variation of the maximum deflection of the nanobeam with respect to the size effect. It is observed that the deflection increases as the nonlocal elastic parameter increases. This is because a larger nonlocal parameter corresponds to a greater effective interatomic distance within the beam material, which in turn leads to a reduction in the stiffness of the nanobeam.

In addition, the size effect is also influenced by the flexoelectric effect. An increase in the flexoelectric coefficient f_{14} enhances the stiffness of the nanobeam, thereby reducing the influence of the size effect on the structural response.

4. CONCLUSIONS

By employing an analytical approach, this study investigates the static bending response of a multilayer nanobeam in a hygrothermal environment. The main conclusions drawn from this work are summarized as follows: The hygrothermal environment leads to an increase in the static bending deflection of the nanobeam, and the extent of this increase depends on both the beam thickness and the core-layer thickness ratio. Specifically, the influence of the hygrothermal environment becomes more pronounced for thinner beams and for larger core-layer thicknesses.

An increase in the core-layer thickness weakens the contribution of the flexoelectric effect, resulting in a higher maximum deflection of the nanobeam. Furthermore, it is observed that the maximum deflection increases with increasing nonlocal elastic parameter, indicating that this parameter reduces the stiffness of the beam and consequently its load-carrying capacity.

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TÓM TẮT

Nghiên cứu ảnh hưởng của môi trường nhiệt ẩm đến uốn tĩnh của dầm kích thước nano

Dầm nano là một kết cấu thường được sử dụng trong các cảm biến cỡ nhỏ, đây cũng là một thành phần quan trọng trong các thiết bị điều khiển thiết bị bay. Nghiên cứu này sử dụng phương pháp giải tích để tìm lời giải đối với bài toán uốn tĩnh của dầm nano nhiều lớp có kể đến ảnh hưởng của môi trường nhiệt ẩm và hiệu ứng flexoelectric, dầm gồm ba lớp vật liệu, trong đó, lớp giữa làm bằng vật liệu có lỗ rỗng vi mô. Các công thức tính toán được xuất phát từ lý thuyết biến dạng cắt bậc ba kiểu mới, ảnh hưởng của hiệu ứng kích thước nhỏ cũng được tính đến thông qua lý thuyết đàn hồi phi cục bộ. Bài báo cũng đưa ra ví dụ để kiểm tra độ tin cậy của lời giải, từ đó thực hiện tính toán số nhằm làm rõ một số yếu tố ảnh hưởng đến đáp ứng uốn của dầm nano nhiều lớp, đặc biệt là ảnh hưởng của môi trường nhiệt ẩm. Các kết quả của nghiên cứu này có ý nghĩa định hướng thiết kế và chế tạo các dầm nano nhiều lớp trong thực tế để đạt hiệu quả cao trong quá trình làm việc.

Từ khoá: Uốn tĩnh; Dầm nano; Phi cục bộ; Lỗ rỗng; Nhiệt ẩm.