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Effect of Porosity on the Nonlinear Thermal Stability of Functionally Graded Material Beams under Various Boundary Conditions

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Abstract: In this project work, the impact of porosity on the nonlinear thermal buckling response of power law functionally graded beam with various boundary conditions is investigated; the derivation of equations is based on the Euler–Bernoulli beam theory where the distribution of material properties is imitated polynomial function. Using the nonlinear strain–displacement relations, equilibrium equations and stability equations of beam are derived. The beam is assumed under thermal loading, namely: Nonlinear temperature distribution through the thickness. Various types of boundary conditions are assumed for the beam with combination of roller, clamped and simply-supported edges equations for these types of structures. The effects of the porosity parameter, slenderness ratio and power law index on the thermal buckling of P-FG beam are discussed.

Keywords: Euler beam theory, Functionally graded material, Porosity parameter, Thermal buckling

Introduction

During last two decades, the need to design the high per Functionally graded materials (FGMs) are composite materials composed of two or more constituent phases with a continuously variable variation by gradually changing the volume fraction. These materials type have been proposed, developed and successfully employed in industrial application since 1980s (Koizumi, 1993). FGMs were designed as a thermal barrier coating in aerospace application, such as ceramic-metal composite structure.

Nowadays, FGMs are alternative materials widely employed in aerospace, civil, mechanical, nuclear, optical, electronic, chemical, shipbuilding, and biomechanical industries (Akavci, 2016; Kar & Panda, 2015, 2016;Eltaher et al., 2014; Belkorissat et al., 2015; Ait Atmane et al.,.2015; Akbas, 2015; Arefi 2015a,2015b;Arefi & Allam, 2015b; Celebi et al.,2016; Darabi & Vosoughi, 2016; Turan et al., 2016; Ebrahimi & Shafiei, 2016; Mouaici al.2016, Mouffoki et al.,2017; Zidi et al., 2017, Bellifa et al.,2017; Karami et al., 2018a, 2019a; Bennai et al., 2019; Bouamoud et al., 2019; Bellifa et al., 2017, 2021; Batou et al., 2019; Chaabane et al., 2019; Alwabli et al., 2021; Benbakhti et al., 2023 , 2024; Benfrid et al., 2023; Maachou et al., 2024; Semmah et al., 2024).

The problem of buckling of the porous materials with varying properties has been discussed by many authors. The buckling analysis of thin functionally graded (FG) rectangular plates based on the classical or first order shear deformation theory (FSDT) under various loads were discussed by Mohammadi et al. (2010). Jabbari et al. (2013, 2014) examined porosity distribution influence on buckling characteristics of plates. Buckling of metal foam porous beams using a shear deformation beam model was studied by Chen et al. (2015). In a recent study,

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Bellifa et al. (2016) analyzed the wave propagation of an infinite FG plate having porosities by using various simple higher-order shear deformation theories. Ebrahimi et al. (2016) considered the thermal effects on linear free vibration of functionally graded Euler-Bernoulli beams with porosities for pinned-pinned and clamped pinned edges.

To conclude, we have noticed through our reading in the literature that studies on the effect of porosity across the thickness of the FG beam are rare. For this, the aim of this paper first is to extend the Euler–Bernoulli beam theory proposed by Eslami and Kiani (2010) and Bellifa et al. (2017) to porous functionally graded (FG) beams, then to study the critical buckling temperature for FG beams with porosity for different types of boundary conditions and thermal loadings which are assumed to be non-linear distribution through the thickness. Material properties were assumed to be temperature dependent, and graded in the thickness direction according to a simple power law distribution. Finally, the results based on the Euler-Bernoulli beam theory and the effects of thermal loading, porosity, and other parameters on FG beam buckling thermo mechanical behaviour are investigated.

Theoretical Formulations

Kinematics

The classic beam theory is applied throughout the work. Based on the Euler-Bernoulli assumption, the following displacement field can be obtained, (Kiani & Eslami 2010; Belbachir et al., 2024).

$$\begin{aligned} u(x,z) &= u_0(x) - z\frac{\partial w_0}{\partial x} \\ v(x,z) &= 0 \\ w(x,z) &= w_0(x) \end{aligned} \tag{1}$$

Where $u_0(x,y)$, $w_0(x,y)$ are the two unknown displacement functions of middle surface of the beam in the *x* and *z* directions. The Von-Karman-type of geometric non-linearity is taken into consideration in the strain–displacement relations which are as follows

$$\varepsilon_x = \varepsilon_x^0 + z\,k_x \tag{2}$$

Where ε_x^0 and k_x are, respectively, the nonlinear longitudinal strain and curvature defined as (Bellifa and al. 2017)

$$\varepsilon_x^0 = \frac{du_0}{dx} + \frac{1}{2}\left(\frac{d\,w_0}{dx}\right)^2 \text{ and } k_x = -\frac{d^2 w_0}{dx^2} \tag{3}$$

Constitutive Relations

Consider a FG rectangular beam with thickness h, length a and width b The Cartesian coordinate system is established so that $0 \le \mathrm{x} \le 1$, and $-\frac{h}{2} \le \mathrm{z} \le +\frac{h}{2}$.

Functionally graded materials (FGMs) are composed of two kinds of materials: one is a metal and the other is ceramic. Here, Young’s modulus E (z) varies continuously through the beams thickness by a polynomial material law. We will consider a non-homogeneity material with a porosity volume function, $\xi \;\; (0 \le \xi \le 1)$. In such a way, the efficient material properties, as Young’s modulus E, the coefficient of thermal expansion α and thermal conductivity K at a point are usually assumed to be given by the rule of mixture (Ait Atmane and al. 2017)

$$\mathrm{E(z)} = \mathrm{E_m} + (E_c - E_m)\left(\frac{h+2z}{2h}\right)^p - (E_c + E_m)\frac{\xi}{2}$$
$$\alpha(\mathrm{z}) = \alpha_{\mathrm{m}} + (\alpha_c - \alpha_m)\left(\frac{h+2z}{2h}\right)^p - (\alpha_c + \alpha_m)\frac{\xi}{2} \quad (4) \tag{4}$$
$$K(\mathrm{z}) = K_{\mathrm{m}} + (K_c - K_m)\left(\frac{h+2z}{2h}\right)^p - (K_c + K_m)\frac{\xi}{2}$$

Where p is the volume fraction exponent. The value of p equal to zero represents a fully ceramic beam, whereas infinite p indicates a fully metallic beam. The distribution of the combination of ceramic and metal is linear for $p=1$.

The constitutive relation of a FG beam under thermal and mechanical conditions using thermo-elasticity can be expressed as

$$\sigma_x = E(\varepsilon_x - \alpha(T - T_r)) \tag{5}$$

Where σ_x, T and T_r are, respectively, the axial stress, the temperature distribution through the thickness and the reference temperature. The axial force N , the bending moment M caused by thermal stress, respectively are written as

$$(\mathrm{N}, M) = \int_{-\frac{h}{2}}^{\frac{h}{2}} \sigma_x(1, z)dz \tag{6}$$

By substituting Eq. (4) and Eq. (5) into Eq. (6) we obtain

$$N = \overline{A}\left(\frac{du_0}{dx} + \frac{1}{2}\left(\frac{d\,w_0}{dx}\right)^2\right) - \overline{B}\frac{d^2w_0}{dx^2} - N_T$$
$$M = \overline{B}\left(\frac{du_0}{dx} + \frac{1}{2}\left(\frac{d\,w_0}{dx}\right)^2\right) - \overline{C}\frac{d^2w_0}{dx^2} - M_T \tag{7}$$

Total potential energy of the FGM beam may be expressed as follows

$$\delta U = \int_0^l \int_A \left(\sigma_x\left(\varepsilon_x - \alpha(T - T_r)\right)\right) dA dx \tag{8}$$

Substituting Eq.(3) and Eq.(5) into Eq.(8) and integrating with respect to z and y, The total potential energy of the beam is given by

$$\delta U = \frac{b}{2}\left[\int_0^l \begin{pmatrix} \overline{A}\left(\frac{du_0}{dx} + \frac{1}{2}\left(\frac{d\,w_0}{dx}\right)^2\right)^2 - 2\overline{B}\frac{d^2w_0}{dx^2}\left(\frac{du_0}{dx} + \frac{1}{2}\left(\frac{d\,w_0}{dx}\right)^2\right) \\ + \overline{C}\left(\frac{d^2w_0}{dx^2}\right)^2 - 2N_T\left(\frac{du_0}{dx} + \frac{1}{2}\left(\frac{d\,w_0}{dx}\right)^2\right) + 2M_T\left(\frac{d^2w_0}{dx^2}\right) \end{pmatrix} dx + \int_0^l \int_{-\frac{h}{2}}^{\frac{h}{2}} \left[E(z)\alpha(z)(T - T_r)\right] dx\right] \tag{9}$$

The stability equations of the beam may be derived by the adjacent equilibrium criterion. Assume that the equilibrium state of the FGM beam under thermal loads is defined in terms of the displacement components $(u_0^0, u_0^1, w_0^0, w_0^1)$. The displacement components of a neighboring stable state differ by (u_1, u_2, w_1, w_2) with respect to the equilibrium position. Thus, the total displacements of a neighboring state are

$$\begin{aligned} u_0 &= u_0^0 + u_0^1 \\ w_0 &= w_0^0 + w_0^1 \end{aligned} \quad (10)$$

The stability equation of an FGM beam under thermal loading is assumed to be given by eliminating (u_0^1) as

$$\frac{d^4 w_0^1}{dx^4} + \lambda^2 \frac{d^2 w_0^1}{dx^2} = 0 \quad (11)$$

Where

$$\lambda^2 = \frac{\overline{A} N_T}{\overline{A}\,\overline{C} - \overline{B}^2} \quad (12)$$

The parameter λ is a constant and the Eq. (11) is a linear homogeneous equation whose general solution is

$$w_0^1(x) = D_1 \sin(\lambda x) + D_2 \cos(\lambda x) + D_3 x + D_4 \quad (13)$$

Where D_1, D_2, D_3 and D_4 are undetermined constants calculated via the boundary conditions.

$$\begin{aligned} w_0^1(x) &= D_1 \sin(\lambda x) + D_2 \cos(\lambda x) + D_3 x + D_4 \\ u_0^1(x) &= \frac{\overline{B}}{\overline{A}} \lambda D_1 \cos(\lambda x) - \frac{\overline{B}}{\overline{A}} \lambda D_2 \sin(\lambda x) + D_5 x + D_6 \\ M_0^1(x) &= \frac{\overline{A}\,\overline{C} - \overline{B}^2}{\overline{A}} \lambda^2 D_1 \sin(\lambda x) + \frac{\overline{A}\,\overline{C} - \overline{B}^2}{\overline{A}} \lambda^2 D_2 \cos(\lambda x) + \overline{B} D_5 \\ N_0^1(x) &= \overline{A} D_5 \end{aligned} \quad (14)$$

(13)

The following boundary conditions are imposed at the edges for FGM beam

$$u_0^1(0) = w_0^1(0) = \frac{dw_0^1}{dx}(0) = u_0^1(l) = w_0^1(l) = \frac{dw_0^1}{dx}(l) = 0 \quad (15)$$

(14)

Finally, the critical thermal force of the beam, N_{Tcr} for all cases of boundary conditions, can be expressed as follows

$$N_{Tcr} = D \frac{\overline{A}\,\overline{C} - \overline{B}^2}{\overline{A}(l)^2} \quad (16)$$

Where D is a constant and depends on the type of boundary conditions (clamped-clamped, simply supported-simply supported, clamped-roller edges, simply supported-roller edges, clamped-simply supported).

Thermal Buckling Solution

Buckling of FGM Beams Under Non-Linear Temperature Across the Thickness

The FGM beams are subjected to transversely non-linear temperature rise, and the increments of temperature on top surface and bottom surface are T_t and T_b, respectively. Four sides of the beam are adiabatic with environment. Due to the increments of transversely temperature inside FGM beams are assumed to be the function of thickness coordinate z, the increments $T = T(z)$ satisfy the following one-dimensional thermal conduction equation

$$\frac{d}{dz}\left[\left(K(z)\frac{dT}{dz}\right)\right] = 0 \tag{17}$$

This model ignores the time of heat conduction, and the change of temperature due to work produced by the deformations is also neglected. However, the non-linear temperature fields can be obtained easily by using the boundary conditions as

$$T(z) = T_t + \left(\frac{\Delta T}{\Omega}\right)\left[\sum_{i=0}^{5}\frac{(-1)^i}{(ip+1)}\left(\frac{(K_c - K_m)}{K_m}\right)^i\left(\frac{h+2z}{2h}\right)^{(ip+1)}\right] \tag{18}$$

with

$$\Omega = \sum_{i=0}^{5}\frac{(-1)^i}{(ip+1)}\left(\frac{(K_c - K_m)}{K_m}\right)^i \tag{19}$$

Numerical Results and Discussion

In this study, various numerical examples are presented and discussed for verifying the accuracy and efficiency of the present theory in predicting buckling stability of FG beams with various boundary conditions under mechanical nonlinear thermal loadings through the thickness. For the verification purpose, the results obtained by the present theory are compared with the existing data in the literature. It is assumed that the functionally graded beam is made of a mixture of aluminum and alumina. The Young modulus and coefficient of thermal expansion for aluminum are $E_m = 70$ GPa, $\alpha_m = 23\times10^{-6}$ /°C and $K_m = 204$ W/m°K and for alumina are $E_c = 380$ GPa, $\alpha_c = 7{,}4\times10^{-6}$ /°C and $K_c = 10{,}4$ W/m°K, respectively. It is assumed that the temperature difference between the metal-rich surface of the FGM and reference temperature is $T_m - T_r = 5°C$.

Table 1 present the comparisons of the critical buckling temperature for a CR FG beam under non-linear temperature rise with results of Kiani and Eslami (2015) for different values power law index *p*. It can be concluded that the results obtained by the present model and those obtained by Kiani and Eslami (2015) are identical for all considered values of power law index *p*. As we can see, our results are in excellent agreement with those published. It can be concluded that the present theory is efficient for the prediction of critical thermal buckling loads.

Table 1. Critical buckling temperature for a CR FG beam non-linear temperature rise for different values of power law index *p* with porosity coefficient $\xi = 0$, $(l/h = 8)$

Temperature load	Theory	p p=0.2	p=1	p=2	p=4	p=5	p=6	p=10
Non linaire	Kiani(2010)	1542.24	965.23	745.45	541.15	325.70	245.12	141.52
	Present	1542.24	965.23	745.45	541.15	325.70	245.12	141.52

Critical buckling temperature of FG beam under linear and non-linear temperature rise for different values of power law index *p*, porosity coefficient ξ and thickness ratio l/h is illustrated in table 2. For nonlinear temperature distribution across the thickness, the buckling temperature decreases with the increase of the power law index *p*. It can be conclude that the critical buckling temperature difference decreases as the thickness ratio and power law index increases and that the maximum critical buckling temperature is obtained with a porosity coefficient equal to $\xi = 0.2$.

Table 2 Critical buckling temperature for a SS FG beam under non-linear temperature rise for different values of power law index *p*, porosity coefficient ξ and thickness ratio l/h

l/h	$\xi = 0$				$\xi = 0.15$				$\xi = 0.2$			
	p=0.2	p=1	p=3	p=8	p=0.2	p=1	p=3	p=8	p=0.2	p=1	p=3	p=8
5	7882.6064	5363.8274	4153.6144	4010.3236	9245.1247	5843.2816	4199.4816	605.1055	11961.7043	6386.9652	3764.3410	3859.2009
15	864.9335	584.4105	451.3542	436.3786	956.2357	637.7606	458.3493	309.4740	1317.6582	698.2690	409.1272	420.8147
25	303.5197	202.0572	155.17341	150.4630	302.4521	221.3189	159.0587	151.2763	466.1345	243.1733	140.7101	145.7438
35	148.8445	96.7149	73.5726	71.6903	120.2457	106.5850	76.6011	151.2763	231.5311	117.7898	66.7585	69.9590
45	85.1921	53.3642	39.9920	39.2736	94.3254	59.3694	42.6679	37.8191	134.9864	66.1916	36.3257	38.7718

Conclusion

This article deals with thermo-mechanical analysis of nonlinear thermal buckling behaviour of porous FG beams with various combinations of boundary conditions under non-linear thermal loadings distribution through the thickness based on Euler–Bernoulli beam theory. Comparison studies are presented out for a large number of beams with different values of thickness ratio, power law index and various combinations of boundary conditions. It can be conclude that the critical buckling temperature difference decreases as the thickness ratio and power law index increases. From the results and the comparisons between the different porosity distributions, it was found that the different distributions give values that are more at least close with the exception of . Finally, some new results critical thermal buckling loads of FG beams with porosity are reported in tabular form for a wide range of thickness ratio and power law index. This new results can be used for comparison with other beam models developed in the future.

Scientific Ethics Declaration

The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

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