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Intelligent simulation of the thermal buckling characteristics of a tapered functionally graded porosity-dependent rectangular small-scale beam

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Abstract. In the current research, the thermal buckling characteristics of the bi-directional functionally graded nano-scale tapered beam on the basis of a couple of nonlocal Eringen and classical beam theories are scrutinized. The nonlocal governing equation and associated nonlocal boundary conditions are constructed using the conservation energy principle, and the resulting equations are solved using the generalized differential quadrature method (GDQM). The mechanical characteristics of the produced material are altered along both the beam length and thickness direction, indicating that it is a two-dimensional functionally graded material (2D-FGM). It is thought that the nanostructures are defective because to the presence of porosity voids. Finally, the obtained results are used to design small-scale sensors and make an excellent panorama of developing the production of nanostructures.

Keywords: bi-directional functionally graded material; non-uniform nanobeam; porosity dependent material; static analysis

1. Introduction

In recent years the application of functionally graded material in novel researches has been developed. Due to this fact, the main part of available material in the environment are graded material, and they are not isotropic type; the researchers have focused on their studies by assuming the functionally graded material as their supposed structures. The functionally graded materials were made of one or more phases that the material properties are varied in a particular direction. Several phases' composition leads to different applications and properties in unique structures; for example, ceramics are brittle and do not bend until near-melting temperatures are reached. Metals are malleable and bendable. Ceramics have a higher melting point than metals and can contain molten metal. While metals conduct electricity, ceramics do not. Pure ceramics are electrical insulators and semi-conductors. The specific gravity of metals is greater than that of ceramics. Metals carry heat, whereas ceramics act as thermal insulators, etc., So, the composition of both ceramic and metal in functionally graded structures leads to having all the properties in unique structures (Fazaeli *et al*. 2016, Habibi *et al*. 2016, Hosseini *et al*. 2018, Alipour *et al*. 2020, Cheshmeh *et al*. 2020, Ghabussi *et al*. 2020, Ghazanfari *et al*. 2020, Liu *et al*. 2020a, b, Moayedi *et al*. 2020b, Shariati *et al*. 2020b, Shi *et al*. 2020, Wang *et al*. 2020).

The small-scale structures, especially in the nano-sized, are among the more popular subjects for research that their investigation moves toward them (Zhang *et al*. 2016, Oyedotun 2018, Hu *et al*. 2021, Long *et al*. 2021, Sun *et al*. 2021). However, the investigation on the small-scale structures are attractive, but the investigation of nanostructures because of timely and costly procedure in the experimental analysis, the actual tests on them are complicated, so in order to respond to this deficiency, the nonclassical theories were created because the classical theories could not answer the small-scale behavior, i.e., classic continuum theories are inadequate for investigating systems at nanoscales because they do not account for the effects of strain on the whole body and the effect of small distances between atoms in a mass. In nanoscales, the small distance between atoms is much higher than in macroscales compared to the nanostructure's scale. Eringen and Edelen (1972) introduced the nonlocal theory to address this flaw of the traditional theory, and experimental research validates the accuracy of the nonlocal findings. According to the Eringen and Edelen (1972) theory, many investigators applied this nonclassical theory in their research to examine the nanoscale structures (Dai *et al*. 2021a, Ebrahimi *et al*. 2021, Hashemi *et al*. 2021, Hou *et al*. 2021, Huang *et al*. 2021b, c, Jiao *et al*. 2021, Liu *et al*. 2021a, c, Najaafi *et al*. 2021, Shariati *et al*. 2021, Wu and Habibi 2021, Xu *et al*. 2021, Zhao *et al*. 2021, Yu *et al*. 2022).

Among the different structures, beam structures are more attractive than others for the investigators because of their simple geometry and formulation. One of the important analyses to examine the behavior of beams and tubes is the buckling analysis. The buckling can happen from mechanical or thermal stresses. This analysis has been more attractive for researchers to investigate the statical characteristics of the various structures such as beam, tube, plate, shell, etc. In the eigenvalue problem, including the dynamical and statical behavior if the material properties or the geometry are varied along the x-axis, the governing

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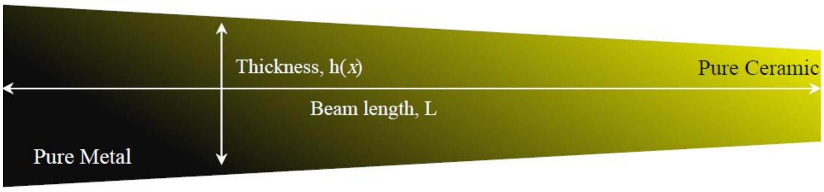

Fig. 1 Geometry and material distribution of the 2D-FG nonuniform beam

Table 1 Temperature-dependent coefficients for Nickel and Si_3N_4 (Reddy and Chin 1998)

Materials	Proprieties	P_0	P_{-1}	P_1	P_2	P_3
Si_3N_4	E(Pa)	348.43e9	0	-3.070e-4	2.160e-7	-8.964e-11
	α (1/K)	5.8723e-6	0	9.095e-4	0	0
	ν	0.24	0	0	0	0
Nickel	E(Pa)	223.95e9	0	-2.794e-4	3.998e-9	0
	α (1/K)	9.9209e-6	0	8.705e-4	0	0
	ν	0.31	0	0	0	0

ordinary differential equations (ODE) changes to the partial differential equation (PDE) that are more complicated in deriving and solving. Because of simple equations, the buckling analysis of functionally graded (FG) uniform beam has been enticed by many experimenters, while this analysis for the nonuniform nanobeams or axially functionally graded (AFG) uniform nanobeam still needs to develop. In the current study, the buckling analysis of nonuniform and two-dimensional functionally graded nanobeam is presented that includes both nonuniformities and changes the material in the length direction of the beam that making the equation more complicated (Ebrahimi and Shafiei 2017, Ebrahimi *et al.* 2017, Ehyaei *et al.* 2017, Ghadiri *et al.* 2017a, b, c, d, e, Mirjavadi *et al.* 2017a, b, c, d, Shafiei *et al.* 2017a, b, c, 2019, 2020, Shafiei and Kazemi 2017, Shivanian *et al.* 2017, Azimi *et al.* 2018, Shafiei and She 2018).

Based on the provided description in this paper, the thermal buckling behavior of the two-dimensional functionally graded (2D-FG) nonuniform and the porosity-dependent nanoscaled rectangular beam is investigated. The material properties are combined from metal and ceramic phases in axial and thickness directions, including the porosity voids. According to the Euler-Bernoulli beam theory and utilizing the conservation energy principle, the PD governing equations are derived, and on the basis of nonlocal Eringen theory, the impact of small-scale have applied. Finally, the extended differential quadrature technique is used to solve the temperature-dependent PD equations (GDQM). The obtained findings are addressed in-depth to study the influence of different factors on the thermal buckling of a 2D-FG tapered nanobeam, such as length-scale, rate of thickness to length, porosity parameter, etc.

2. The issue and its articulation

Fig. 1 shows the geometry and material distribution of a rectangular tapered beam. As it was shown, the material properties are varied in beam length direction as well as in the thickness direction, where 'L' is the beam length, and 'h' is the beam thickness. Also, the beam thickness is changed gradually in the beam length direction, which means the nonuniform cross-section is considered. The function of cross-section changes ($h(x)$) is defined as follows:

$$h(x) = h_L(1 - \theta x) \tag{1}$$

where, 'h_L' is the beam thickness in the left side of beam, 'θ' is the rate of thickness changes, and 'x' is the variation in the beam length direction. The material properties function for the bi-directional functionally graded material are as follows (Wattanasakulpong and Chaikittiratana 2015, Shafiei *et al.* 2016e, Şimşek 2016, Kim *et al.* 2019):

$$F(x,z) = F_m + (F_c - F_m)\left(\frac{x}{L}\right)^{nx}\left(\frac{1}{2} + \frac{z}{h(x)}\right)^{nz} - \frac{1}{2}\beta(F_c + F_m) \tag{2}$$

where 'F' is a function of the 2D-FG material properties that can be the thermal distribution 'α', Poisson's ratio 'ν' or Young's modulus 'E'. Also, $()_c$ refers to the ceramic phase, and $()_m$ refers to the metal phase. 'nx' is the FG parameter in the beam length direction, called AFG parameter, and 'nz' is the FG parameter which is called FG parameter. Moreover, 'z' is the variation in the thickness direction, 'β' is the parameter of the porosity impact.

The material properties of both metal and ceramic phases are considered temperature-dependent, which means the material properties are changed with the temperature of the environment. To this aim, the temperature-dependent coefficients of ceramic and metal phases are represented in Table 1, and according to the Touloukian and Ho (1970) principle that is defined as the following function, the mechanical properties of Nickel as the metal phase and Si_3N_4 as the ceramic phase will be obtained.

2.1 Modeling in mathematics

To simulate the beam behavior, Euler-Bernoulli beam theory is used, on the basis of this theory, the following displacement functions in axial (u_1), width (u_2), and thickness (u_3) direction are considered.

$$u_1(x,z,t) = -z\frac{\partial w}{\partial x} + u(x,t) \tag{3a}$$

$$u_2(x,z,t) = 0 \tag{3b}$$

$$u_3(x,z,t) = w(x,t) \tag{3c}$$

where 'w' and 'u' are the lateral and axial displacement. The energy conservation principle as the following equation is used to derive the governing equations in the following form.

$$\delta S + \delta W = 0 \tag{4}$$

While 'S' is the strain energy and 'W' is the energy of external work. The strain energy is calculated in the following form:

$$\delta S = \delta\left(\frac{1}{2}\int_0^L \int_A \sigma_{ij}\left(\varepsilon_{ij} - \varepsilon^T\right)dA\,dx\right) \tag{5}$$

where 'ε' is mechanical strain and 'ε^T' is the thermal strains, that the mechanical strains are calculated as follows:

$$\varepsilon_{11} = \frac{\partial u_1}{\partial x} = -z\frac{\partial^2 w}{\partial x^2} + \frac{\partial u}{\partial x} \tag{6a}$$

$$\varepsilon_{12} = \varepsilon_{13} = \varepsilon_{22} = \varepsilon_{23} = \varepsilon_{33} = 0 \tag{6b}$$

And also, the thermal strain is defined in the following form:

$$\varepsilon^T = \alpha\left(x, T()(T - T_0)\right) \tag{7}$$

Consider the temperature gradient as a two-way temperature distribution. A nonlinear temperature gradient is defined as follows:

$$T = T_0 + \Delta T\left(\frac{1}{2} + \frac{z}{h}\right)^{\alpha z}\left(\frac{x}{L}\right)^{\alpha x} \tag{8}$$

Here the temperature reference is T_0. The energy of external works is assumed to be zero.

$$W = 0 \tag{9}$$

The following local governing equation and associated boundary conditions will be derived according to the Euler-Lagrange principle.

$$\delta w:\ -\frac{\partial^2}{\partial x^2}\left[C\frac{\partial^2 w}{\partial x^2} + \bar{M} - B\frac{\partial u}{\partial x}\right] - \frac{\partial}{\partial x}\left(\bar{N}\frac{\partial w}{\partial x}\right) + (e_0 a)^2\frac{\partial^2}{\partial x^2}\left[\frac{\partial}{\partial x}\left(\bar{N}\frac{\partial w}{\partial x}\right)\right] = 0 \tag{10a}$$

$$\delta u:\ \frac{\partial}{\partial x}\left[A\left(\frac{\partial u}{\partial x}\right) - B\frac{\partial^2 w}{\partial x^2} - \bar{N}\right] = 0 \tag{10b}$$

$$A\frac{\partial u}{\partial x} - B\frac{\partial^2 w}{\partial x^2} - \bar{N} = 0 \ \text{ or } \ u = 0 \tag{10c}$$

$$\frac{\partial}{\partial x}\left(B\frac{\partial u}{\partial x} - C\frac{\partial^2 w}{\partial x^2} - \bar{M}\right) + \left(A\frac{\partial u}{\partial x} - B\frac{\partial^2 w}{\partial x^2} - \bar{N}\right)\frac{\partial w}{\partial x} = 0 \ \text{ or } \ w = 0 \tag{10d}$$

$$\left(C\frac{\partial^2 w}{\partial x^2} - B\frac{\partial u}{\partial x}\right) - \bar{M} = 0 \ \text{ or } \ \frac{\partial w}{\partial x} = 0 \tag{10e}$$

where

$$(A,B,C) = \int_{\frac{-h}{2}}^{\frac{h}{2}}\int_{\frac{-b}{2}}^{\frac{b}{2}} E(x,z,T)(1,z,z^2)dy\,dz \tag{11a}$$

$$\left(\bar{N},\bar{M}\right) = \int_A E(x,z,T)\alpha(x,z,T)(T - T_0)(1,z)dA \tag{11b}$$

2.2 Nonlocal theory of Eringen

The governing equations of the thermal buckling of the nanoscale beam will be reformed to the following form according to Eringen's nonlocal theory:

$$\frac{dA}{dx}\frac{\partial u}{\partial x} + A\frac{\partial^2 u}{\partial x^2} - \frac{dB}{dx}\frac{\partial^2 w}{\partial x^2} - B\frac{\partial^3 w}{\partial x^3} = \Delta T_{Cr}\frac{dN^T}{dx} \tag{12a}$$

$$\begin{gathered}\frac{d^2B}{dx^2}\frac{\partial u}{\partial x} + 2\frac{dB}{dx}\frac{\partial^2 u}{\partial x^2} + B\frac{\partial^3 u}{\partial x^3} - \frac{d^2C}{dx^2}\frac{\partial^2 w}{\partial x^2} + 2\frac{dC}{dx}\frac{\partial^3 w}{\partial x^3} - C\frac{\partial^4 w}{\partial x^4} \\ = \Delta T_{Cr}\left[\begin{gathered}\frac{d^2M^T}{dx^2} + \frac{dN^T}{dx}\frac{\partial w}{\partial x} + N^T\frac{\partial^2 w}{\partial x^2} \\ -(e_0 a)^2\left(\begin{gathered}\frac{d^3N^T}{dx^3}\frac{\partial w}{\partial x} + N^T\frac{\partial^4 w}{\partial x^4} \\ +3\frac{d^2N^T}{dx^2}\frac{\partial^2 w}{\partial x^2} + 3\frac{dN^T}{dx}\frac{\partial^3 w}{\partial x^3}\end{gathered}\right)\end{gathered}\right]\end{gathered} \tag{12b}$$

where 'ΔT_{Cr}' is the temperature of the thermal buckling, and '$e_0 a$' is the nonlocal parameter, also, 'M^T' and 'N^T' are defined as follows:

$$M^T = \int_A E(x,z,T)\alpha(x,z,T)\left(\frac{x}{L}\right)^{\alpha x}\left(\frac{1}{2} + \frac{z}{h}\right)^{\alpha z} z\,dA \tag{13a}$$

$$N^T = \int_A E(x,z,T)\alpha(x,z,T)\left(\frac{x}{L}\right)^{\alpha x}\left(\frac{1}{2} + \frac{z}{h}\right)^{\alpha z} dA \tag{13b}$$

3. Approach to solving the problem

The numerical methodology of the generalized differential quadrature method (GDQM) is used to solve temperature-dependent partial differential equations (Azimi *et al*. 2016, Ebrahimi and Shafiei 2016, Ghadiri *et al*. 2016a, b, c, d, Ghadiri and Shafiei 2016a, b, c, Shafiei *et al*. a, b, c, d, e, f, g) that the eigenvalue problem of the thermal buckling will be solved according to the following shape:

$$\{[K] - \Delta T_{Cr}[M]\}\{\lambda\} = 0 \tag{14}$$

where 'K' and 'M' will be expressed as follows:

$$K=\begin{bmatrix} \frac{dA}{dx}\sum_{s=1}^{n}C_{rs}{}^{(1)}+A\sum_{s=1}^{n}C_{rs}{}^{(2)} & -\frac{dB}{dx}\sum_{s=1}^{n}C_{rs}{}^{(2)}-B\sum_{s=1}^{n}C_{rs}{}^{(3)} \\ \frac{d^2B}{dx^2}\sum_{s=1}^{n}C_{rs}{}^{(1)}+2\frac{dB}{dx}\sum_{s=1}^{n}C_{rs}{}^{(2)}+C\sum_{s=1}^{n}C_{rs}{}^{(3)} & -\frac{d^2C}{dx^2}\sum_{s=1}^{n}C_{rs}{}^{(2)}+2\frac{dC}{dx}\sum_{s=1}^{n}C_{rs}{}^{(3)}-C\sum_{s=1}^{n}C_{rs}{}^{(4)} \end{bmatrix} \quad (15a)$$

$$M=\begin{bmatrix} \frac{dN^T}{dx} & \frac{dN^T}{dx} \\ \frac{d^2M^T}{dx^2} & \frac{d^2M^T}{dx^2}+\frac{dN^T}{dx}\sum_{s=1}^{n}C_{rs}{}^{(1)}+N^T\sum_{s=1}^{n}C_{rs}{}^{(2)}-(e_0a)^2\begin{pmatrix}\frac{d^3N^T}{dx^3}\sum_{s=1}^{n}C_{rs}{}^{(1)}+N^T\sum_{s=1}^{n}C_{rs}{}^{(4)} \\ +3\frac{d^2N^T}{dx^2}\sum_{s=1}^{n}C_{rs}{}^{(2)}+3\frac{dN^T}{dx}\sum_{s=1}^{n}C_{rs}{}^{(3)}\end{pmatrix} \end{bmatrix} \quad (15b)$$

where '$C^{(r)}$' is the weighting coefficient, and defined as follows (Moayedi *et al*. 2020a, Oyarhossein *et al*. 2020, Shariati *et al*. 2020a, Zhou *et al*. 2020, Dai *et al*. 2021b, Guo *et al*. 2021a, b, He *et al*. 2021, Huang *et al*. 2021a, Huo *et al*. 2021, Liu *et al*. 2021b, Peng *et al*. 2021, Shao *et al*. 2021, Zhang *et al*. 2021a, b):

$$\begin{aligned} &C_{ij}^{(1)}=\frac{M(x_i)}{(x_i-x_j)M(x_j)},i, \\ &j=1,2,\ldots,n \quad and\ i\neq j \\ &C_{ij}^{(1)}=-\sum_{j=1,i\neq j}^{n}C_{ij}^{(1)},i=j \end{aligned} \quad (16)$$

where

$$M(x_i)=\prod_{j=1,j\neq i}^{k}(x_i-x_j) \quad (17)$$

and

$$\begin{aligned} &C_{ij}^{(r)}=r\left[C_{ij}^{(r-1)}C_{ij}^{(1)}-\frac{C_{ij}^{(r-1)}}{(x_i-x_j)}\right],i, \\ &j=1,2,\ldots,k,i\neq j \\ &and\ 2\leq r\leq k-1 \\ &C_{ii}^{(r)}=-\sum_{j=1,i\neq j}^{n}C_{ij}^{(r)},i, \\ &j=1,2,\ldots,k \\ &and\ 1\leq r\leq k-1 \end{aligned} \quad (18)$$

4. Discussion of numerical results

In the current paper, the partial differential equations of thermal buckling behavior of the bi-directional functionally graded non-uniform and imperfect nanoscale rectangular beam have been emanated on the basis of the classical beam theory linked with the nonlocal theory of Eringen, so before the discussion of the obtained results, the comparison of obtained results with the published results are necessary, to this aim, Table 2 have been prepared to confirm the validity of numerical results. Comparison of the findings reported here with those of Shafiei *et al*. (2017c) proves that the presented results and numerical approach are in good agreement with earlier studies.

The following non-dimensional nonlocal parameter (μ) is defined to have a better description of the different parameter impacts.

$$M\mu=\frac{e_0a}{L} \quad (19)$$

Fig. 2 investigates the impact of both FG and AFG parameters on the thermal buckling characteristics of a fully clamped beam. Due to the fact that ceramics are stiffer than metals, the increment of functionally graded parameters decreases the thermal buckling of the beam. This conclusion is valid for both the axial functionally graded parameter (*nx*) and also FG parameter in the thickness direction (*nz*). In fact, stability of the functionally graded beam decreases with FG parameters, and the thermal buckling happens in lower temperatures.

Table 2 Validity of the thermal buckling of the uniform pinned nanobeam versus the different nonlocal parameters in comparison with results of Shafiei *et al*. (2017c)

	L/h = 40		L/h = 50		L/h = 60	
	Current study	Shafiei *et al*. (2017c)	Current study	Shafiei *et al*. (2017c)	Current study	Shafiei *et al*. (2017c)
(e_0a) = 0(nm)	71.281596	71.36165	45.646769	45.67146	31.709175	31.71629
(e_0a) = 1(nm)	64.8783573	64.95122	42.934776	42.958	30.376704	30.38352
(e_0a) = 2(nm)	59.530703	59.59756	40.5269584	40.54888	29.1516989	29.15824
(e_0a) = 3(nm)	54.9974941	55.05926	38.3748625	38.39562	28.0216724	28.02796

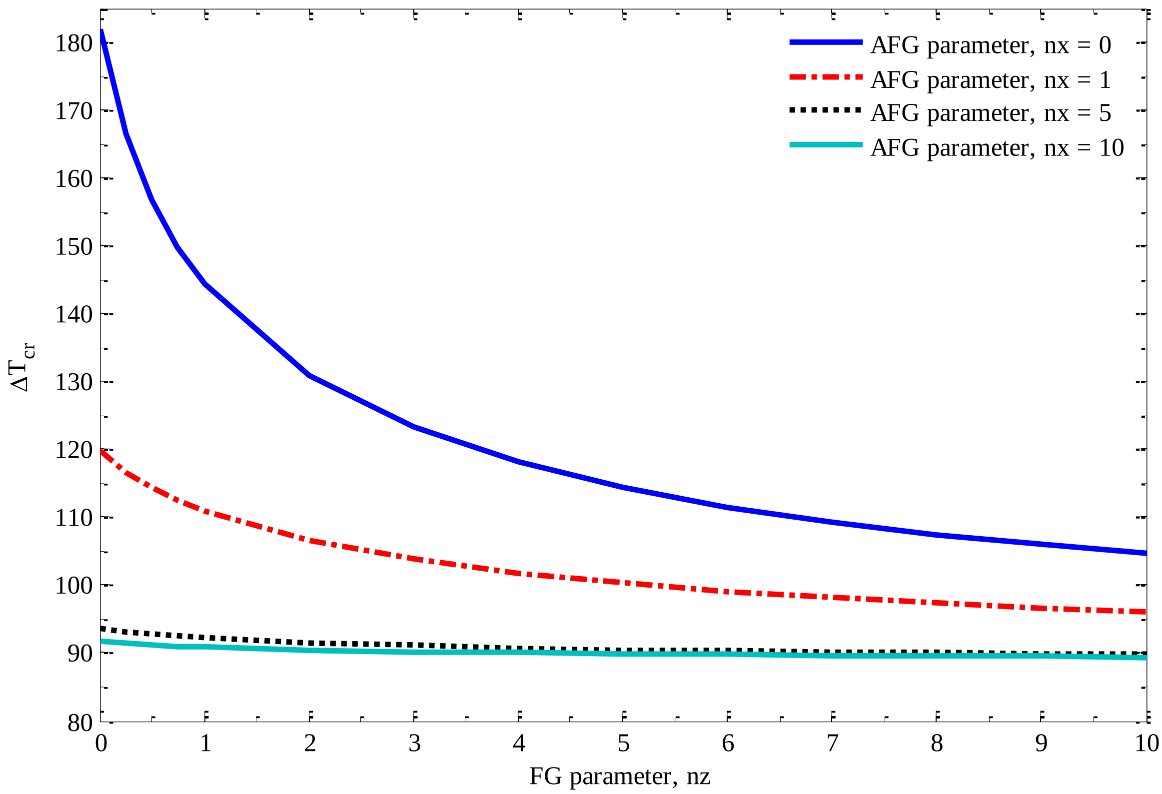

Fig. 2 Thermal buckling of a functionally graded clamped and uniform beam versus different FG parameters in the axial and thickness direction, L/h = 50

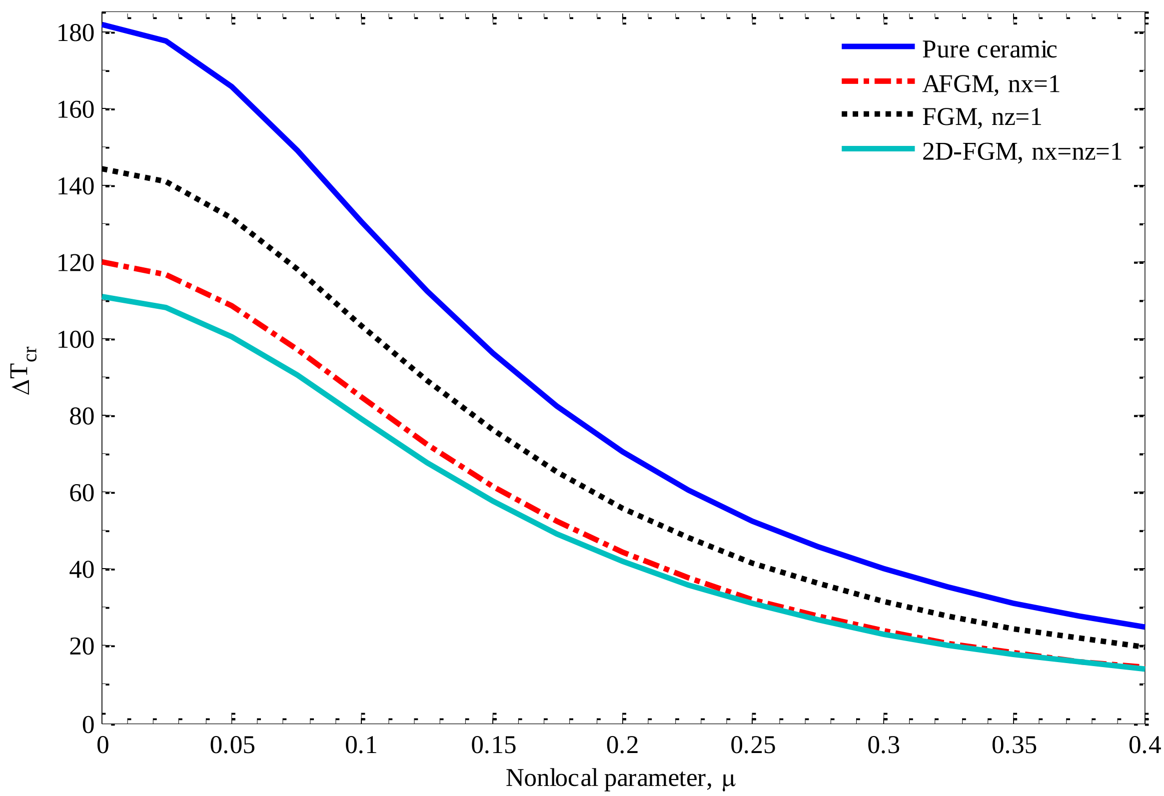

Fig. 3 Thermal buckling behavior of a nonlocal nanoscale clamped beam versus the different nonlocal parameters for both ceramic beam, AFG beam, FG beam, and 2D-FG beam, L/h = 50

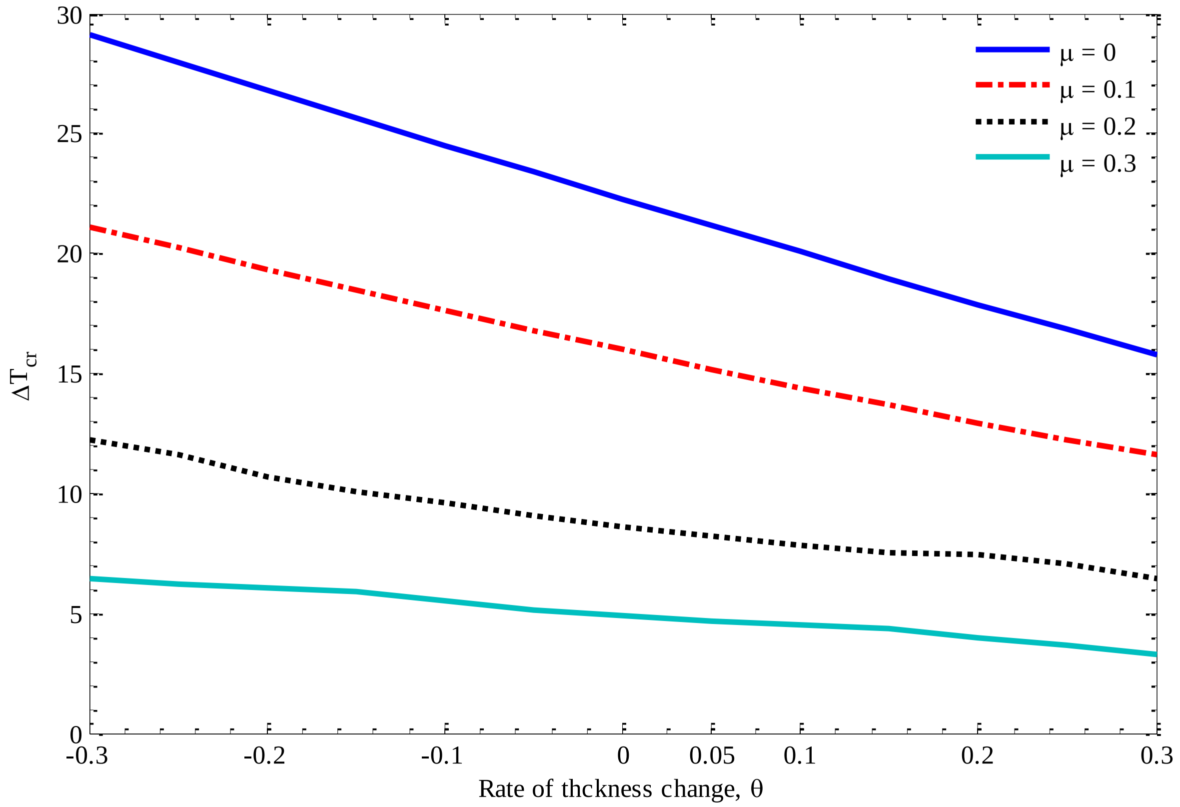

Fig. 4 Thermal buckling characteristics of the nanobeam affected by rate of thickness change (θ) for various values of nonlocal parameter, L/h = 100, *nx* = *nz* = ∞

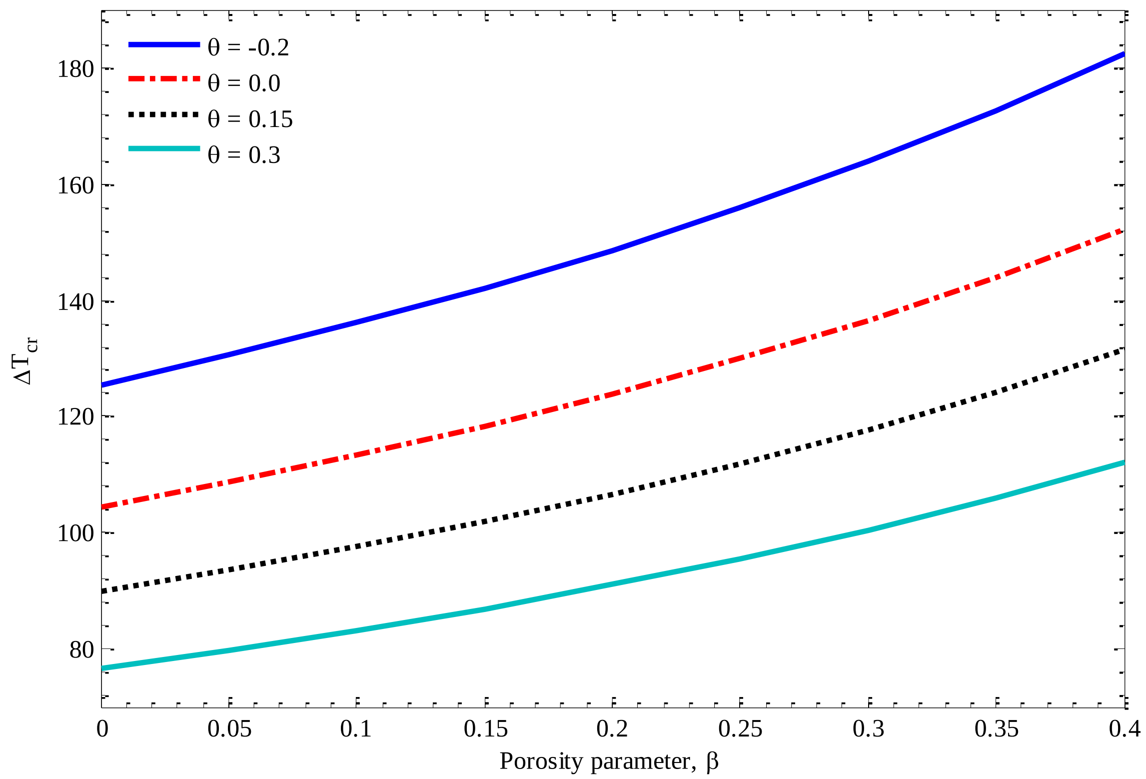

Fig. 5 Effect of imperfection on the thermal buckling characteristics of a clamped nanobeam versus the porosity parameter (β) for different values of the thickness change rate (θ), L/h = 40, μ = 0.1, *nx* = *nz* = 3

The impact of nonlocal parameters (μ) on the thermal buckling behavior of the functionally graded clamped nanobeam is presented in Fig. 3. It is shown the nonlocal parameter decreases the thermal buckling and stability of FG nanobeam. It is because of the softening phenomenon of the nonlocal parameter. Also, it was displayed the impact of the FG parameter (*nz*) is lower than the effect of the AFG parameter (*nx*). It means in the same value of '*nx*,' and '*nz*', the decreases of thermal buckling due to the 'nx' is more significant than '*nz*'. It is possible to deduce that the axially functionally graded parameter reduces the beam stiffness sooner than the FG parameter (*nz*).

Fig. 4 illustrates the effect of thickness change (θ) on the thermal buckling characteristics of the clamped nanobeam versus the nonlocal parameters (μ). As it was discussed, the thermal buckling decreases by nonlocal parameters due to the softening phenomenon of nonlocal impacts, and that nanobeams will be unstable with nonlocal parameters. In this section, the impact of thickness change is also examined, which is displayed an increment of thickness change tend to diminish the thermal buckling and stability of nanobeams, i.e., the tapered beam is unstable than the uniform beam, and it is because the uniform beam is stiffer than the tapered beam.

Fig. 5 indicates the temperature of the thermal buckling of uniform and nonuniform fully clamped beams for different thickness change rates (θ) and various values of porosity parameters (β). As it was explained, the rate of thickness change has a significant impact on the thermal buckling of the beam, and the increment of θ makes the beam unstable by decreasing the temperature of thermal buckling. It was concluded from the present figure that the imperfection also impacts the thermal buckling of nanobeam and the current type of porosity pattern leads to increases in the temperature of the thermal buckling, which means the porosity delays the buckling happens, and stability of the nanobeam increases with porosity void.

5. Conclusions

The main framework of the current study was investigated the numerical thermal buckling analysis of the porosity-dependent tapered nano-sized beam made of functionally graded material according to the classical beam theory coupled to the nonlocal theory of Eringen according to the conservation energy principle. The material distribution was changed in length and thickness direction, called 2D-FGM. The main concluding remarks which were obtained from the presented study are listed in follows:

• The FG and AFG parameters reduce the thermal buckling and stability of the beam.

• The nonlocal impacts limited the stability of the nanobeam, and the beam buckling happens in lower temperatures by an increment of the nonlocal parameter.

• The tapered beam shows an unstable behavior than the uniform beam, and the rate of thickness change diminishes the thermal buckling.

The imperfection of the porosity voids increases the stability and thermal buckling of both uniform and non-uniform beams.

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