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Application of nanocomposite material in the tennis equipment to avoid the injury

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Abstract. Nanotechnology, like any other revolutionary innovation in materials science, has significantly influenced the level of competition in sports. Nanotechnology provides various benefits and enormous potential to enhance athletic equipment, making players safer, more comfortable, and more agile. Various sporting equipment is being infused with nanomaterials, including carbon nanotubes (CNTs), silica nanoparticles (SNPs), nanoclays fullerenes, etc., to enhance athlete and equipment performance. Each of these nanomaterials gives athletic equipment an extra benefit like high strength and stiffness, longevity, decreased weight, abrasion resistance, etc. This paper mechanically analysis the structural strength of tennis equipment to avoid injury. As a result, the bending forces are applied to the reinforced structures to investigate their durability.
Keywords: bending analysis; composite material; nanomaterial; reinforced structures; sport equipment

1. Introduction

One of the leading types of constitutive material in structures is the composite. Composite materials cover a broad spectrum of materials, including reinforced composites (Ghabussi *et al*. 2020), nanocomposites, laminated composites (Moayedi *et al*. 2021), and functionally graded materials (Huang *et al*. 2021b). The properties of such materials are flexible enough to be altered in the desired form. Also, one of the other advantages of composites is that their higher stiffness, being lighter, etc. is not at the expense of any of their favorable properties (Duc *et al*. 2019). However, to manufacture these materials, they should be investigated and modeled theoretically to understand the impact of various parameters on their behaviors. One of the studies in which nano-composite is employed is the paper that deals with the dynamic as well as static analysis associated with nanocomposite disks subjected to thermal loads (Arshid *et al*. 2020). In this article, the formulations were attained via MSGT. Also, with the aid of VDQ along with FEM as solution procedures, the post-buckling behavior of reinforced composite plates with porosity was investigated through third-order shear deformation theory (Ansari *et al*. 2021). Also, Arshid *et al*. (2021) investigated the buckling of disks made of FG-reinforced nanocomposites subjected to thermal loading. The solution method in the article mentioned above was GDQM. Next, it can refer to a work in which the vibrational behavior of porous nanocomposite microbeams was formulated with the aid of NSGT in addition to hyperbolic shear deformation beam theory and solved via GDQM (Sahmani and Madyira 2021). Based on sinusoidal higher-order theory, the vibrational analysis of a three-layered shell, with nanocomposite face sheets, which is embedded in a viscoelastic medium and is subjected to thermal load was carried out (Soleimani-Javid *et al*. 2021). Additionally, Khorasani *et al*. (2022) analyzed vibrational characteristics associated with a three-layered beam, with nanocomposite face sheets and porous core, placed on a Vlasov's Foundation.

Nanotechnology, investigating the structures and material on the nanoscale, led to designing and manufacturing different types of new devices which are way more efficient than their previous versions (Naderi *et al*. 2021). Due to various equipment used, sports is one of the favorable areas in which nanotechnology can assist in making new devices (Tang *et al*. 2013). Harifi and Montazer (2015) presented a survey on the nanotechnology application in sports equipment. In addition, it was shown that using nanomaterials in some sports equipment, such as badminton and tennis racquets, led to intensifying their elasticity and stiffness in addition to reducing their weights (Li 2013). Boats made of nanocomposites are lighter and have less flow resistance, making them quite agile. Another example of using nanotechnology and nanomaterials in sports equipment is coating tennis balls with nano-clay, making more durable balls (Chunyan *et al*. 2011, Zhao and Shen 2012, Kai 2013, Song and Cai 2013, Su 2014).

One of the reasons which cause injuries for athletes is the fractures of sports equipment. These injuries caused by defective equipment can be even more severe. Carman and Chang (2001) investigated the damages caused by a treadmill. Also, Hennig (2007) presented a study on the racket's features and how they can result in tennis elbows in athletes. In addition, Pluim *et al*. (2006), by exploring the injuries and their causes in tennis, pointed out that equipment is one of the primary reasons for such injuries.

Regarding the issues with tennis equipment, scholars incorporated nanotechnology to design and manufacture more efficient devices. Fathy Saleh (2015) presented an

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experimental investigation to examine the kinematic factors in tennis rackets which are enhanced with the aid of nanotechnology. Also, Wang (2022) carried out an article regarding the material by which the rackets are made and how nanocomposites can affect the durability of tennis equipment.

One of the most crucial points that must be remembered in investigating small-scale structures is using non-classical continuum mechanic theories, e.g., nonlocal (Eringen and Edelen 1972), two-phase (Naderi *et al*. 2020), and strain gradient theory (Lam *et al*. 2003). With this in mind, various investigations on the vibration (Ebrahimi and Shafiei 2017, Ghadiri *et al*. 2017e, Mirjavadi *et al*. 2017a, Shafiei and Kazemi 2017a, Shafiei *et al*. 2017c, d, Azimi *et al*. 2018), buckling (Ehyaei *et al*. 2017, Ghadiri *et al*. 2017c, d, Mirjavadi *et al*. 2017d, Shafiei and Kazemi 2017b), and bending (Ghadiri *et al*. 2017a, b, Mirjavadi *et al*. 2017b, c, Shafiei *et al*. 2017a, b) of nano/microstructures have been carried out through nonlocal elasticity. For example, the nonlinear vibration and buckling of FG nanobeams placed on an elastic substrate were studied by means of an exact solution procedure (Niknam and Aghdam 2015). Also, Ebrahimi and Barati (2017) presented a paper that explores the vibration of viscoelastic beams made of functionally graded materials. The small-scale beams in the abovementioned paper were subjected to a hygrothermal environment. In another work, based on nonlocal as well as higher-order beam theories, they studied the vibrational behavior related to FG nanobeams situated on an elastic medium which are subjected to thermal loads (Ebrahimi and Reza Barati 2016).

Nanotechnology is one of the leading technologies in building new and more efficient equipment (Ebrahimi and Shafiei 2016, Shafiei *et al*. 2016c, d, f, Ebrahimi *et al*. 2017, Shivanian *et al*. 2017). One area that benefits from this technology is sports equipment and devices (Azimi *et al*. 2016, Ghadiri and Shafiei 2016a, c, Shafiei *et al*. 2016a, e, g). Nanotechnology made building stiffer, lighter, and generally better materials and devices possible. However, making such designs required theoretical investigations. In this regard, the current paper investigates the bending and buckling of a wire, a model that represents equipment used in tennis, made of FG materials. The energy method along with nonlocal elasticity are utilized to present the formulations. Then, the bending and buckling results are extracted by employing an analytic solution procedure. The current results are validated through a comparative study. Lastly, the impact of nonlocal parameters, different materials, and FGM parameters on the static behavior of this structure is explored in detail.

2. Methodology and data acquisition

In this section, mathematically simulate the behavior of a symbolic structure under the bending load (Ghadiri *et al*. 2016a, b, c, d, Ghadiri and Shafiei 2016b, Shafiei *et al*. 2016b). As mentioned before, the present paper's main aim is to investigate the application of nanocomposite materials to improve the durability of their structures to avoid or decrease injury by tennis equipment. A wire structure made of different types of material, such as homogeneous and non-homogeneous materials, is assumed in this analysis, and the stability due to the bending forces can predict the quality of the material (Shafiei and She 2018, Shafiei *et al*. 2019, 2020). The nanocomposite material, which is in the class of new composite material, is the functionally graded material, which is made of two different phases involving ceramic and metal phases (Shafiei and She 2018, Shafiei *et al*. 2019, 2020), in this type of composite material, the ceramics have the high stiffness while because of brittle performance of them, they coat on the metal due to better toughness implementation (Hou *et al*. 2021, Huang *et al*. 2021c, Xu *et al*. 2021, Wang *et al*. 2022). The final composition of the materials has both metals and ceramics, in other words, the composite material is stiffer than metals and contains more toughness than ceramics (Li *et al*. 2021, 2022e, Si *et al*. 2021, Cao *et al*. 2022, Cheng *et al*. 2022, Wang *et al*. 2022, Zhang *et al*. 2022). It is predicted that equipment made of this composition has better execution than other homogenous tools (Liu *et al*. 2020b, Habibi *et al*. 2021, He *et al*. 2021, Huang *et al*. 2021a, Liu *et al*. 2021b, Zhang *et al*. 2021). For the bending analysis, the wire structure has been considered based on the classical beam theory (Adamian *et al*. 2020, Al-Furjan *et al*. 2020a, b, Li *et al*. 2020b, Zare *et al*. 2020, Dai *et al*. 2021b), Young's modulus of the materials is needed for this purpose (Al-Furjan *et al*. 2020c, d, f, Bai *et al*. 2020, Li *et al*. 2020a, Zhang *et al*. 2020, Guo *et al*. 2021b, Liu *et al*. 2021a). In homogeneous structures, the modulus of Young (E) is defined as follows:

$$E = E_{Metal} \qquad E = E_{Ceramic} \tag{1a}$$

While inhomogeneous (functionally graded) structures, the modulus of Young is defined as follows (Hashemi *et al*. 2019, Al-Furjan *et al*. 2020e, Cheshmeh *et al*. 2020, Lori *et al*. 2020, Najaafi *et al*. 2020, Shariati *et al*. 2020c):

$$E = E_{Metal} + \left(E_{Ceramic} - E_{Metal}\right)\left(r / R\right)^{\kappa} \tag{1b}$$

where 'R' is the radius of the wire structures, and 'κ' is the FG power indexes or FG parameter (Hashemi *et al*. 2019, Moayedi *et al*. 2019, 2020a, b, Oyarhossein *et al*. 2020, Shariati *et al*. 2020b). The core of the wire is made of metal and ceramic coated on it, and the outer surface of the wire is made of ceramic (Ebrahimi *et al*. 2019a, b, 2020b, Mohammadi *et al*. 2019, Mohammadgholiha *et al*. 2019, Habibi *et al*. 2020, Shariati *et al*. 2020a, Shokrgozar *et al*. 2020). The different types of materials, involving the ceramics and metals, and their Young's modulus are listed in Table 1.

This paper assumes a wire structure: 'L' is the wire length, and 'R' is the wire radius plotted in Fig. 1.

Based on the classical beam theory, the virtual strain energy (δS) is defined as follows (Habibi *et al*. 2018, 2019b, d, e, Pourjabari *et al*. 2019, Safarpour *et al*. 2019a):

$$\delta S = 0.5\iiint \sigma_{ij} : \varepsilon_{ij}\ dv \tag{2}$$

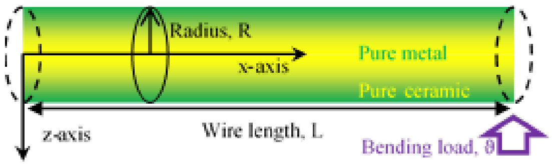

Fig. 1 A schematic of material distribution and geometric of the composite wire structure (Habibi *et al.* 2019a, Safarpour *et al.* 2019b, Alipour *et al.* 2020, Ebrahimi *et al.* 2020a, Chen *et al.* 2022)

Table 1 The Young modulus of different materials (Habibi *et al.* 2017, 2019c, Safarpour *et al.* 2018, 2020, Ghazanfari *et al.* 2020)

Material	Young's modulus (GPa)
Si_3N_4	348.43
Al_2O_3	349.55
Zirconia	244.27
Nickel	223.95
SUS304	201.04

Table 2 The comparison of the results of the current study with the results of Reddy (2007) for both bending deflection ($-100wY_3/\vartheta L^4$) and buckling force ($L^2\gamma/Y_3$)

	Bending deflection		Buckling load	
	(Reddy 2007)	Current study	(Reddy 2007)	Current study
$(ea/L)^2$=0	1.313	1.3128687	9.8996	9.89861
$(ea/L)^2$=0.5	1.3809	1.3807619	9.4055	9.4045595
$(ea/L)^2$=1	1.4487	1.4485551	8.983	8.9821017
$(ea/L)^2$=1.5	1.5165	1.5163484	8.5969	8.5960403
$(ea/L)^2$=2	1.5844	1.5842416	8.2426	8.2417757
$(ea/L)^2$=2.5	1.6522	1.6520348	7.9163	7.9155084
$(ea/L)^2$=3	1.7201	1.719928	7.6149	7.6141385
$(ea/L)^2$=3.5	1.7879	1.7877212	7.3356	7.3348664
$(ea/L)^2$=4	1.8558	1.8556144	7.0761	7.0753924
$(ea/L)^2$=4.5	1.9236	1.9234076	6.8343	6.8336166
$(ea/L)^2$=5	1.9914	1.9912009	6.6085	6.6078392

where 'ε' is the strain tensor, which is defined as follows (Ma *et al.* , Huang *et al.* 2021d, Liu *et al.* 2021c, Yu *et al.* 2022):

$$\varepsilon_{xx} = u_{,x} - zw_{,xx} \tag{3}$$

where displacements along the different axes are defined as follows (Zhao *et al.* , Jiao *et al.* 2021, Moradi *et al.* 2021):

$$u_x = u - zw_{,x}; \quad u_z = w \tag{4}$$

Moreover, 'σ' is the stress tensor and is defined as follows:

$$\sigma_{ij} = E\varepsilon_{ij} \tag{5}$$

The bending load (ϑ) along with the buckling force (γ) are applied to the current wire structure, and the virtual energy (δϵ) of this external load which can be because of ball impact in the tennis action, is calculated as follows:

$$\delta\in = \iiint \gamma w_{,x}\,\delta(\partial w/\partial x)\,dv - \iiint \vartheta\delta w\;dv \tag{6}$$

The nonlocal theory, which Eringen and Edelen (1972) introduced, impacts the stresses according to the following equation:

$$\left(1-(ea)^2\nabla^2\right)\sigma_{ij} = E\varepsilon_{ij} \tag{7}$$

where '*ea*' is the nonlocal parameter. By applying the nonlocal parameter on the stress resultant, and based on the following energy conservation method, which is presented as follows:

$$\delta S + \delta\in = 0 \tag{8}$$

The following governing equations as well as boundary conditions for bending analysis of functionally graded nanowire, will be acquired (Hao *et al.* 2022, He *et al.* 2022, Li *et al.* 2022a, b, c, d, Liu *et al.* 2022).

$$\partial/\partial x\left(Y_1 u_{,x} - Y_2 w_{,xx}\right) = 0 \tag{9a}$$

$$\begin{aligned} &-Y_2 w_{,xxxx} + Y_1 u_{,xxx} - \gamma w_{,xx} - \vartheta \\ &+(ea)^2\gamma w_{,xxxx} + (ea)^2\partial^2\vartheta/\partial x^2 = 0 \end{aligned} \tag{9b}$$

$$\delta(u): Y_1 u_{,x} - Y_2 w_{,xx} - \gamma = 0 \tag{9c}$$

$$\delta(w): Y_2 u_{,xx} - Y_3 w_{,xxx} - \lambda w_{,x} = 0 \tag{9d}$$

$$\delta(w_{,x}): Y_2 u_{,x} - Y_3 w_{,xx} = 0 \tag{9e}$$

where

$$\begin{Bmatrix} Y_1 \\ Y_2 \\ Y_3 \end{Bmatrix} = \int E \begin{Bmatrix} 1 \\ r\sin(\theta) \\ r^2\sin^2(\theta) \end{Bmatrix} dA \tag{10}$$

3. Analytical procedure

In this section, the exact solution for bending and buckling analysis of functionally graded nanowires is presented according to the following assumptions:

$$u = \sum_{p=1}^{\infty} U_p \cos(p\pi x/L) \tag{11a}$$

$$w = \sum_{p=1}^{\infty} W_p \sin(p\pi x/L) \tag{11b}$$

3.1 Bending analysis

For the static analysis, due to the bending response of the FG nanowire, the following mathematical equation for the bending load is presented.

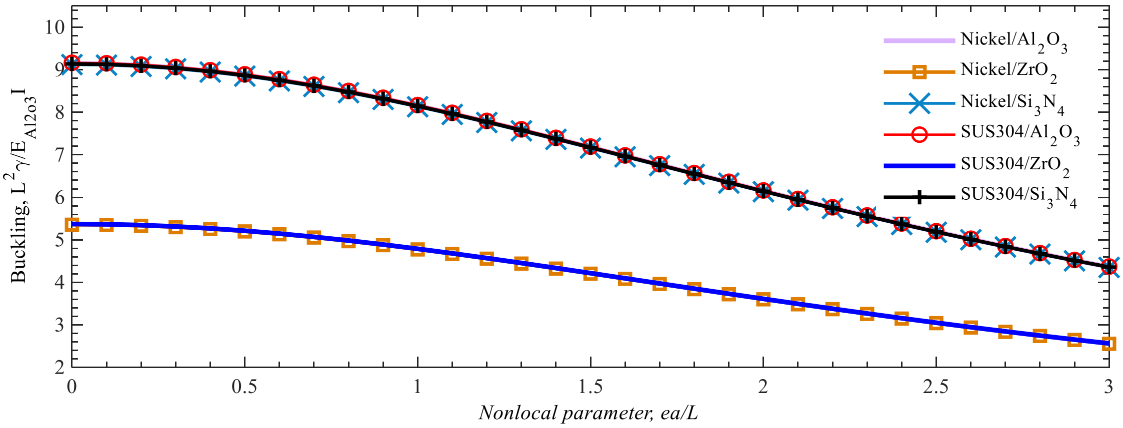

Fig. 2 Impact of different nanomaterials on the stability of tennis equipment to avoid the damage due to the buckling forces versus the various values of nonlocal parameters (*ea*/*L*), L=40R, κ=1

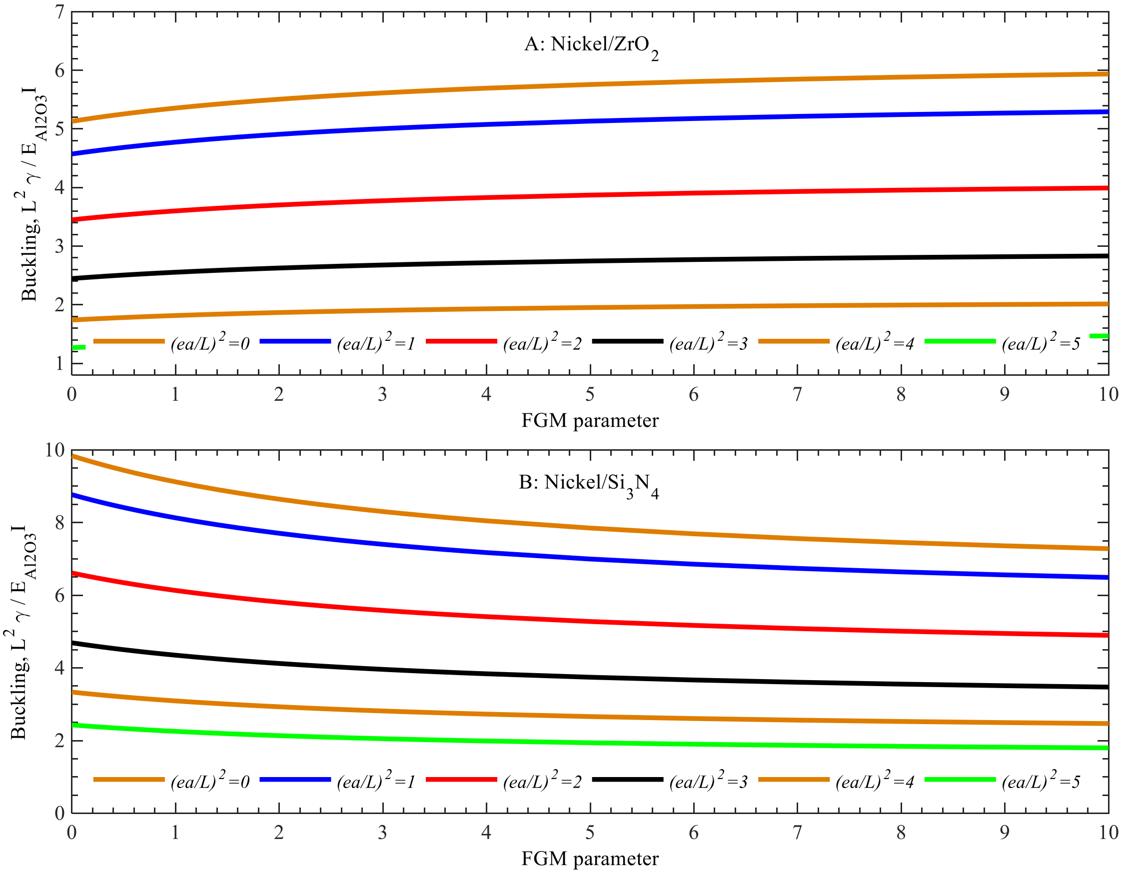

Fig. 3 Effect of the nonlocal parameter (*ea*) as well as FG parameters (κ) on the stability of the tennis tools regarding the buckling analysis (buckling load, γ) for two different ceramic phases, L=40R

$$\gamma = \sum_{p=1}^{\infty} Q_p \sin\left(p\pi x / L\right) \tag{12a}$$

$$Q_p L = 2\int \gamma \sin\left(p\pi x / L\right) dx \tag{12b}$$

Moreover, the raining information in the total precipitation of the region in the agricultural year. The temperature is also the mean temperature of the cultivation season to harvest of the crop. Agricultural crops in the region is typically wheat of chickpea. In the region under investigation the amount of crops yields during years of 2011 to 2021 is collected as tons per hectare for 47 sites. The region of the study has elevation of 1500m to 2300m. The precipitation ranges from 300mm/annual to 1100mm/annual. Moreover, mean temperature of the region in the range of 2011 to 2021 are varied from -2°C to 4°C. A plot of the region is depicted in Fig. 1.

The following equations will be obtained by neglecting the buckling force and substituting Eqs. (11) and (12) into

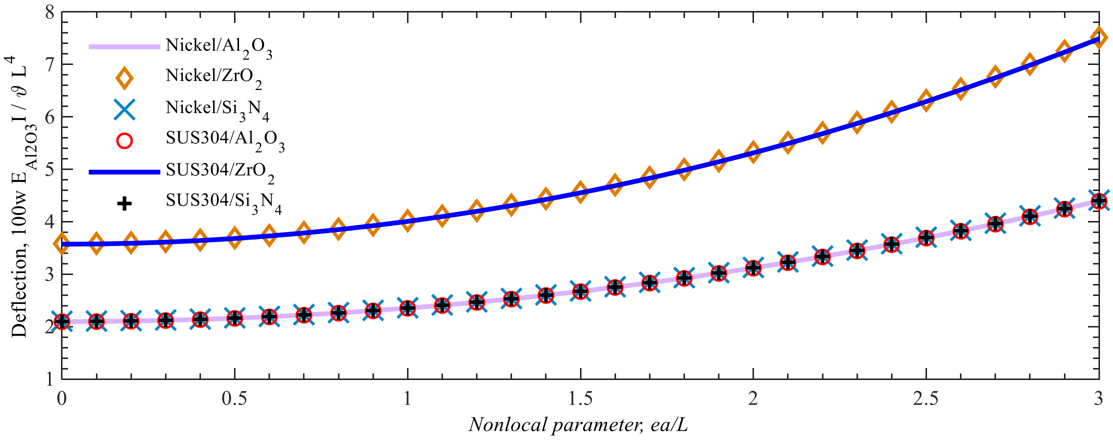

Fig. 4 Impact of different nanomaterials on the strength of tennis supplies to evade the impairment due to the central bending load of ball impact versus the different values of nonlocal parameters (*ea*/*L*), L=40R, κ=1

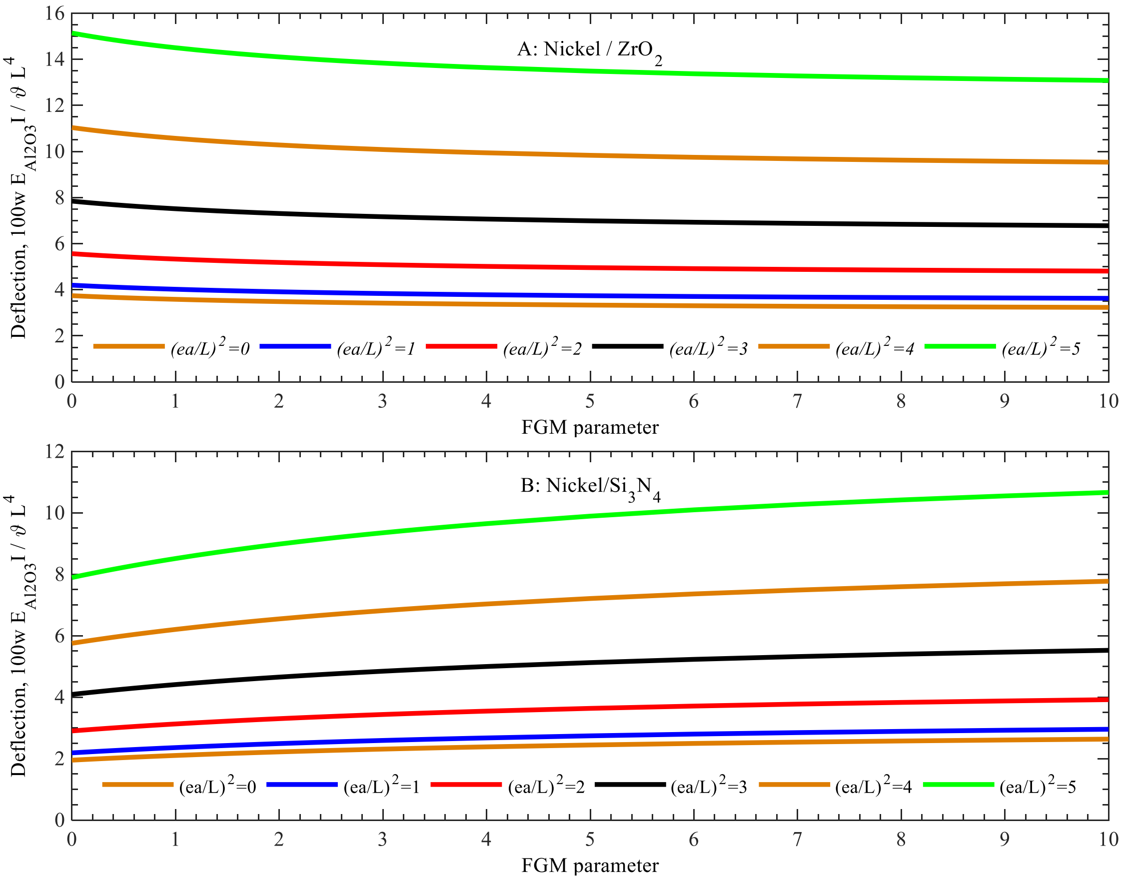

Fig. 5 Effect of the FG parameter along with the nonlocal parameter on the bending load concerning the ball impact on the tennis racket regarding the different composite structures, L=40R

governing equations (Eqs. (9)).

$$Y_1 (p\pi / L)^2 - Y_2 (p\pi / L)^3 = 0 \quad (13a)$$

$$-Y_2 (p\pi / L)^4 + Y_1 (p\pi / L)^3 - \vartheta + (ea)^2 \partial^2 \vartheta / \partial x^2 = 0 \quad (13b)$$

So, the deflection due to the bending load is calculated as follows:

$$w = \sum_{p=0}^{\infty} \xi_1 \sin(xp\pi / L) / \xi_2 \quad (14a)$$

where

$$\xi_1 = \left[1 + (ea)^2 (p\pi / L)^2\right] Q_p \quad (14b)$$

$$\xi_2 = \left[Y_3 (p\pi / L)^4\right] \quad (14c)$$

3.2 Buckling analysis

By neglecting the bending load and substituting Eq. (11) into governing equations (Eqs. (9)), the following mathematical relation will be obtained:

$$Y_1\left(p\pi/L\right)^2 - Y_2\left(p\pi/L\right)^3 = 0 \tag{15a}$$

$$-Y_2\left(p\pi/L\right)^4 + Y_1\left(p\pi/L\right)^3 - \gamma\left(p\pi/L\right)^2 + \left(ea\right)^2\gamma\left(p\pi/L\right)^4 = 0 \tag{15b}$$

Then, the critical buckling force will be obtained according to the following equations:

$$\gamma = \bar{\gamma}_1 / \bar{\gamma}_2 \tag{16a}$$

where

$$\bar{\gamma}_1 = Y_2\left(p\pi/L\right)^4 - Y_1\left(p\pi/L\right)^3 \tag{16b}$$

$$\bar{\gamma}_2 = \left(ea\right)^2\gamma\left(p\pi/L\right)^4 - \left(p\pi/L\right)^2 \tag{16c}$$

4. Analytical results

The primary purpose of the current study is to investigate the nanocomposite material for reinforcement of tennis equipment in order to avoid injury along the physical actions. The homogeneous structures involving different types of metals and ceramics are considered in this paper. Also, they are composed of functionally graded structures, in this research, a different aspect of these suggested structures is examined in detail compared to the homogenous structures. The tennis equipment is mathematically modeled via nanowire structures according to a couple of classical beam theories and nonlocal theories. The validation of the analytical results is necessary before the discussion of the new results, so the current results are compared to the results of Reddy (2007) in Table 2, and it can be confirmed that an excellent agreement has existed.

4.1 Buckling response

Now, the nondimensional buckling load of a wire made of nanocomposite material is plotted in Fig. 2 for various values of nonlocal parameters. Several materials for the metal and ceramic phases are considered in this plot. Firstly, it is obvious that increasing the nonlocality leads to softening of the wire, which means that the equipment is more prone to fracture and causing injury. Thus, the safest type of wire is a wire with zero nonlocality. Also, the buckling load of the system is higher for any nonlocal parameter in the cases in which Nickel/Si_3N_4, SUS304/Si_3N_4, and SUS304/Al_2O_3 are utilized. Thus, it can be concluded that the abovementioned materials can yield safer tennis equipment.

Here, in Fig. 3, the nondimensional buckling loads associated with FG wire made of Nickel/ZrO_2 and Nickel/Si_3N_4 are presented against the FGM parameters. In this figure, different cases with different nonlocality are considered. Similarly, this figure reveals that, regardless of the wire material, the higher the nonlocality is, the softer the wire is, and thus the more fracture prone the system is. Also, intensifying the FGM parameter increases and decreases the buckling load of the wire made of Nickel/ZrO_2 and Nickel/Si_3N_4, respectively. Therefore, the higher and lower FGM parameter in the equipment made of Nickel/ZrO_2 and Nickel/Si_3N_4 should be considered to avoid fracture and eventually injuries, respectively.

4.2 Bending response

This subsection investigates the impact of different parameters on the static bending of FG wire. In this regard, the bending of FG wire made of different constitutive materials is plotted against the nonlocal parameter in Fig. 4. It should be mentioned that, against the buckling load, the stiffer the wire is, the lower the bending value is. This figure reveals that higher nonlocal parameters soften the system and lead to an increase in bending value. Thus, it can be said that the wire with lower nonlocality is safer to be used as tennis equipment as they are less prone to fracture. Additionally, it can be understood that the wires made of Nickel/Si_3N_4, Nickel/Al_2O_3, SUS304/Si_3N_4, and SUS304/Al_2O_3 are stiffer and can be a better choice in making tennis equipment that has more durability.

Lastly, the effect of the FGM parameter on the bending value related to FG wire, which is a model of tennis equipment, is explored in Fig. 5. In this figure, the bending values are plotted for different nonlocality and two types of constitutive material—Nickel/ZrO_2 and Nickel/Si_3N_4. It is seen that heightening the FGM parameter causes the wire to be stiffer and softer, provided that it is made of Nickel/ZrO_2 and Nickel/Si_3N_4. In other words, the wire's bending is higher and lower with a higher FGM parameter if the wire is made of Nickel/ZrO_2 and Nickel/Si_3N_4, respectively. Similar to the previous figures, the system's bending is intensified by increasing the nonlocality, being more prone to fracture and causing injuries.

5. Conclusions

Nanotechnology is one of the leading technologies in building new and more efficient equipment. One area that benefits from this technology is sports equipment and devices. Nanotechnology made building stiffer, lighter, and generally better materials and devices possible. However, making such designs required theoretical investigations. In this regard, the current paper investigates the bending and buckling of a wire, a model that represents equipment used in tennis, made of FG materials. The energy method along with nonlocal elasticity are utilized to present the formulations. Then, the bending and buckling results are extracted by employing an analytic solution procedure. The current results are validated through a comparative study. Lastly, the impact of nonlocal parameters, different materials, and FGM parameters on the static behavior of this structure is explored in detail. The following are the highlighted conclusion:

• Heightening the FGM parameter causes the wire to be stiffer and softer, provided that it is made of Nickel/ZrO_2 and Nickel/Si_3N_4.

• Higher nonlocal parameters soften the system and lead to an increase in bending value.

• The wire with lower nonlocality is safer to be used as tennis equipment as they are less prone to fracture.

• The higher and lower FGM parameter in the equipment made of Nickel/ZrO_2 and Nickel/Si_3N_4 should be considered to avoid fracture and eventually injuries, respectively.

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