Advances in Nano Research, *Vol. 17, No.2 (2024) 167-179*
https://doi.org/10.12989/anr.2024.17.2.167

Improve the stability of high resistance badminton net via reinforced light material: development of industry and sport economy

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(*Received May 21, 2024, Revised July 23, 2024, Accepted August 1, 2024*)

Abstract. This study investigates the stability and performance of high-resistance badminton nets through the integration of reinforced lightweight materials. By focusing on the structural and economic impacts, the research aims to enhance both the durability and practicality of badminton nets in professional and recreational settings. Using a combination of advanced material engineering techniques and economic analysis, we explore the development of nets constructed from innovative composites. These composites offer improved resistance to environmental factors, such as weather conditions, while maintaining lightweight properties for ease of installation and use. The study employs high-order shear deformation theory and high-order nonlocal theory to assess the mechanical behavior and stability of the nets. Partial differential equations derived from energy-based methodologies are solved using the Generalized Differential Quadrature Method (GDQM), providing detailed insights into the thermal buckling characteristics and overall performance. The findings demonstrate significant improvements in net stability and longevity, highlighting the potential for broader applications in both the sports equipment industry and related economic sectors. By bridging the gap between material science and practical implementation, this research contributes to the advancement of high-performance sports equipment and supports the growth of the sport economy.
Keywords: high-resistance badminton nets; reinforced lightweight materials; sport economy development; sports equipment durability; structural stability analysis; thermal buckling characteristics

1. Introduction

Functionally graded materials (FGMs) are advanced materials with properties that vary gradually in a controlled manner, making them ideal for various engineering applications. Recent research has focused on the stability and thermoelastic behavior of FGMs in different structural forms. Eldeeb *et al.* (2023a) introduced a novel method for reducing thermoelastic stresses in rotating discs with variable thickness, demonstrating significant stress alleviation through material gradation. In another study, Eldeeb *et al.* (2023d) investigated the thermoelastic stress mitigation and weight reduction in multilayer nonuniform thickness discs, highlighting the efficiency of FGMs in improving stress distribution and structural efficiency. Furthermore, the study on two-dimensional functionally graded cylinders under asymmetric loading by Eldeeb *et al.* (2023b) emphasized the robust capabilities of FGMs in managing asymmetric thermal and mechanical loads, thereby enhancing structural integrity. These studies underscore the critical role of FGMs in advancing engineering applications through effective stress management and structural optimization. However, there remains a need for further research on the stability of beams and nanobeams within FGM contexts to fully leverage their potential in complex engineering designs. Functionally graded materials are a type of material that can be tailored to specific needs by varying microstructure and composition, resulting in superior properties and eliminating weaknesses of traditional composites, powder metallurgy was used by Pasha and Rajaprakash (2022) to fabricate FGMs, and the materials' optical microscopy, hardness, and relative density were used to evaluate the materials' attributes (Mirjavadi *et al.* 2020c, d, f, Afshari *et al.* 2022).

Porosity dependent materials are advanced materials whose properties are affected by the presence of pores. The porosity in these materials can be controlled to obtain specific properties suitable for various engineering applications (Huang *et al.* 2024, Wei *et al.* 2024, Wu *et al.* 2024). In this literature review, we will explore the recent research on porosity-dependent materials, including their fabrication methods, properties, and applications. Several methods have been developed to fabricate porosity-dependent materials. One of the most commonly used methods is powder metallurgy, where the porosity is controlled by the amount of space left between the powder particles during compaction (Medani *et al.* 2019, Ramteke Prashik *et al.* 2019, Bamdad *et al.* 2020, Jia *et al.* 2020, Mirjavadi Seyed *et al.* 2020, Zhou *et al.* 2020). Another method is the use of sacrificial templates, where a template is used to create pores, which are later filled with the desired material. Other methods include the use of foaming agents, freeze casting, and electrospinning. Each of these methods has its advantages and disadvantages and is suitable for different types of porosity dependent materials

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http://www.techno-press.org/?journal=journal=anr&subpage=5
ISSN: 2287-237X (Print), 2287-2388 (Online)

(Zhang *et al*. 2017, 2020a, b). The properties of porosity dependent materials depend on the size, shape, and distribution of the pores. Materials with high porosity exhibit lower density, thermal conductivity, and mechanical strength. The pore size and distribution can also affect the surface area, which is an essential property for materials used in catalysis, adsorption, and energy storage applications. Recent studies by Eldeeb *et al*. (2024) have demonstrated the importance of porosity in the performance of heterogeneous smart discs under hygrothermal loading conditions. Additionally, Eldeeb *et al*. (2023c) highlighted the enhancement of hygrothermoelastic performance in rotating cylindrical smart sensors through controlled. Porosity dependent materials have found several applications in different fields such as energy storage, catalysis, and biomedical industries (Forsat *et al*. 2020, Mirjavadi *et al*. 2020a, 2022). One of the most prominent applications of these materials is in the design of batteries and supercapacitors. The high surface area of these materials enables them to store more energy compared to traditional materials. Porous materials are also used in catalysis, where they can provide more surface area for reactant molecules to interact with the catalyst. In the biomedical field, porous materials are used for the fabrication of scaffolds for tissue engineering and drug delivery systems. The unique characteristics of porosity-dependent materials, such as controlled pore size and distribution, significantly enhance their suitability for various engineering applications. The fabrication methods and porosity characteristics determine their properties, which include improved energy storage, catalysis, and biomedical applications. The applications of these materials in different fields highlight their potential in the development of advanced materials for various applications (Zhou *et al*. 2021, Dai *et al*. 2022a, Zhang *et al*. 2024).

Thermal stability analysis is an important technique used to evaluate the behavior of materials at high temperatures. Understanding the thermal stability of materials is essential for many engineering applications, including aerospace, automotive, and construction industries. In this literature review, we will explore recent research on thermal stability analysis, including its principles, methods, and applications. Thermal stability analysis involves the study of how materials behave at high temperatures (Omidi *et al*. 2013, Azimi *et al*. 2016, Ghadiri *et al*. 2016a, b, c, Shafiei *et al*. 2016, 2017, Mousavi *et al*. 2017). This analysis can be performed by measuring the changes in the properties of the materials, such as their melting point, heat capacity, and thermal conductivity. The principles of thermal stability analysis are based on thermodynamics and heat transfer, which determine the behavior of materials at different temperatures (Ebrahimi *et al*. 2017, Ehyaei *et al*. 2017, Ghadiri *et al*. 2017a, b, c, Shivanian *et al*. 2017, Shahabinejad *et al*. 2018, Shafiei *et al*. 2020). Several methods have been developed to analyze the thermal stability of materials, including thermogravimetric analysis (TGA), differential scanning calorimetry (DSC), and thermal conductivity measurements. TGA measures the weight loss of a sample as a function of temperature or time, providing information on the thermal stability of the material. DSC measures the heat absorbed or released by a sample as a function of temperature, providing information on the phase transitions and thermal stability of the material (Wang *et al*. 2022a, b, Xiao *et al*. 2023). Thermal conductivity measurements can be used to determine the thermal stability of materials by measuring their ability to conduct heat. Thermal stability analysis has found numerous applications in different fields, including aerospace, automotive, and construction industries. In the aerospace industry, thermal stability analysis is used to evaluate the performance of materials in high-temperature environments, such as rocket engines and hypersonic vehicles. In the automotive industry, thermal stability analysis is used to evaluate the performance of materials in high-temperature environments, such as exhaust systems and engine components. In the construction industry, thermal stability analysis is used to evaluate the fire resistance of building materials. Thermal stability analysis is an essential technique for evaluating the behavior of materials at high temperatures. The principles of thermal stability analysis are based on thermodynamics and heat transfer, and several methods have been developed to perform this analysis. The applications of thermal stability analysis in different fields highlight its potential in the development of advanced materials for various applications, including aerospace, automotive, and construction industries. Further research is needed to optimize the methods and applications of thermal stability analysis for specific materials and applications. Jabbari *et al*. (2014) investigated the buckling behavior of a thermally loaded solid circular plate made of porous material, where the material properties vary across the thickness and the edge of the plate is clamped, with a focus on the effect of pores distribution and thermal distribution on the critical buckling temperature, using equilibrium and stability equations based on the Sanders non-linear strain-displacement relation and the variational formulation (Liu *et al*. 2020, Habibi *et al*. 2021, He *et al*. 2021, Huang *et al*. 2021, Liu *et al*. 2021, Zhang *et al*. 2021).

Several methods have been developed to model the mechanical behavior of nano-scale structures, including molecular dynamics simulations, finite element analysis, and atomistic simulations. Molecular dynamics simulations are used to model the behavior of atoms and molecules, providing insights into the deformation mechanisms and fracture behavior of nano-scale structures. Finite element analysis is used to model the mechanical behavior of structures at different scales, including the nano-scale, and can provide insights into the mechanical properties of materials (Ding and She 2021, Cuong Bui 2022, Soltanieh *et al*. 2022, Wu *et al*. 2022). Atomistic simulations are used to study the behavior of atoms and molecules, providing insights into the deformation mechanisms and fracture behavior of nano-scale structures. Several methods have been developed to model the mechanical behavior of nano-scale structures, including molecular dynamics simulations, finite element analysis, and atomistic simulations. Molecular dynamics simulations are used to model the behavior of atoms and molecules, providing insights into the deformation mechanisms and fracture behavior of nano-scale structures. Finite element analysis is used to model the mechanical behavior of structures at different scales, including the nano-scale, and can provide insights into the mechanical properties of materials (Dan *et al*. 2015, Turkeli *et al*. 2017, Zhai *et al*. 2018, Shakouri *et al*. 2021, Mekki *et al*. 2022, Oumedour and Lazzali 2022). Atomistic simulations are used to study the behavior of atoms and molecules, providing insights into the deformation mechanisms and fracture behavior of nano-scale structures. Recent studies have highlighted the importance of understanding the mechanical behavior of nano-scale beams. Taima *et al*. (2020) conducted a free vibration analysis of multistepped nonlocal Bernoulli–Euler beams using the dynamic stiffness matrix method, demonstrating significant insights into the dynamic behavior of such beams. In another study, Taima *et al*. (2022) analyzed the longitudinal vibration of a stepped nonlocal rod embedded in several elastic media, emphasizing the impact of nonlocal elasticity on the vibration characteristics of nano-scale structures. These studies underscore the importance of advanced modeling techniques in capturing the unique mechanical responses of nano-scale beams. The mechanical modeling of nano-scale structures has found numerous applications in different fields, including materials science, electronics, and biomedicine. In materials science, mechanical modeling is used to design advanced materials with improved mechanical properties, such as strength, stiffness, and ductility. In electronics, mechanical modeling is used to design nano-scale devices, such as transistors and sensors, with optimized mechanical properties (Dai *et al*. 2022b, Gu *et al*. 2023). In biomedicine, mechanical modeling is used to design nano-scale drug delivery systems and implants with optimized mechanical properties (Xiao *et al*. 2022, Wang *et al*. 2023). Mechanical modeling of nano-scale structures is an essential technique for understanding the mechanical behavior of materials at the nano-scale. The principles of mechanical modeling are based on continuum mechanics, molecular dynamics, and atomistic simulations, and several methods have been developed to perform this analysis. The applications of mechanical modeling in different fields highlight its potential in the development of advanced materials and devices for various applications, including materials science, electronics, and biomedicine. Further research is needed to optimize the methods and applications of mechanical modeling for specific materials and applications (Azarbarmas *et al*. 2018, Mirjavadi *et al*. 2020b, Mirjavadi *et al*. 2020e, Mirjavadi *et al*. 2023).

Nanostructures, such as nanorods, nanotubes, and microbeams, have garnered significant attention in the field of nanotechnology due to their unique mechanical and vibrational properties. These structures exhibit behavior that is distinct from their macroscale counterparts, necessitating specialized analysis methods to understand their dynamics (Qi *et al*. , Wang *et al*. 2022c, Jia *et al*. 2023, Zhang *et al*. 2023a, Zhang *et al*. 2023b, Zhang *et al*. 2023c, Wang *et al*. 2024, Yan *et al*. 2024). One crucial aspect of studying nanostructures is the consideration of boundary conditions, particularly elastic spring boundary conditions, which play a pivotal role in determining their vibrational characteristics and stability. Recent research has focused on developing analytical and numerical methods to investigate the longitudinal, torsional, and buckling behavior of various nanostructures under different boundary conditions, including deformable and elastic spring constraints (Yaylı 2015). These studies have revealed that the dynamic response of nanostructures is significantly influenced by factors such as material composition, geometric parameters, and the nature of the surrounding medium. Understanding the interplay between nanostructures and their boundary conditions is essential for designing and optimizing nanoscale devices and materials for a wide range of applications in fields such as sensors, actuators, and nanoelectromechanical systems. Yayli (2016) performed a thorough buckling analysis of microbeams embedded in an elastic medium with deformable boundary conditions, illustrating the complex interaction between boundary flexibility and buckling behavior. Further, Yayli (2017) proposed a compact analytical method to examine the vibrations of micro-sized beams under various boundary conditions, demonstrating the significant impact of boundary restraints on vibrational characteristics. Extending these investigations, Yayli (2018a) explored the buckling behavior of Euler columns within an elastic medium, emphasizing the role of general elastic boundary conditions. This study underscores the importance of boundary elasticity in the stability of nanostructures. Additionally, Yayli (2018b) investigated the free longitudinal vibration of nanorods with elastic spring boundary conditions made of functionally graded materials, revealing how material gradation and boundary elasticity influence vibrational responses. another research into the torsional vibrations of nanostructures, including nanotubes (Yayli 2018c) and nanorods (Yayli 2018d), elucidates the effects of elastic medium embedding and boundary restraints. These studies utilized non-local elasticity theory and modified couple stress theory, respectively, to provide a comprehensive understanding of torsional dynamics in nanostructures. Moreover, Yayli (2018e, 2019) analyzed the torsional vibrations and free vibrations of rotationally restrained nanotubes using advanced theoretical frameworks, capturing the complex vibrational behavior of functionally graded nanostructures. Also, Yayli (2020) examined the axial vibrations in Rayleigh nanorods with deformable boundaries, integrating previous findings to offer a holistic view of how boundary deformability influences axial vibrational modes.

Despite the significant advancements in the understanding and application of functionally graded temperature-dependent materials and porosity-dependent materials, there are still notable gaps in the current literature. Most existing research has concentrated on the thermoelastic behavior and stress distribution in various structural forms of FGMs, with limited exploration of their stability, especially in the context of beams and nanobeams. Additionally, while porosity-dependent materials have been studied for their fabrication methods and applications, their thermal stability, particularly in truncated conical nano-beams, remains underexplored. This gap is evident in the lack of comprehensive studies addressing the thermal buckling characteristics of such structures under varying thermal and mechanical loads. The present study aims to bridge these gaps by focusing on the thermal buckling characteristics of a truncated conical cylindrical beam made of porous FGMs. Utilizing high-order shear deformation theory and high-order nonlocal theory, this research addresses the two-dimensional nature of FGMs where material properties vary along both axial and radial directions. The novelty of this manuscript lies in its comprehensive approach to modeling and analyzing the thermal stability of small-scale structures using advanced mathematical methods. By employing the generalized differential quadratic method to solve the resulting partial differential equations, this study provides new insights into the interaction between material composition, structural geometry, and thermal loading at the nanoscale. This contributes significantly to the field by enhancing the understanding of the behavior of two-dimensional functionally graded structures under thermal stress, which is crucial for their application in nano-research and advanced engineering designs

2. Mathematical simulation

The mathematical simulation for material distribution for a two-dimensional functionally graded porous cylindrical pipe can be complex and may depend on several factors such as the desired properties of the material, the distribution of the porosity, and the loading conditions. However, here is an overview of one possible mathematical model for such a pipe:

Let 'r' and 'θ' be the radial and circumferential coordinates, respectively, and let 'x' be the axial coordinate. The distribution of the material properties and porosity can be described by a set of functions that vary with the radial coordinate 'r', namely:

- The material density, $\rho(\mathrm{r},\theta,x)$
- The elastic modulus, $E(\mathrm{r},\theta,x)$
- The Poisson's ratio, $v(\mathrm{r},\theta,x)$
- The porosity, $\beta(\mathrm{r},\theta,x)$

Using these functions, the stress-strain relations for the pipe can be written using the theory of elasticity and poroelasticity. The governing equations for the radial, circumferential, and axial stresses can then be derived and solved using numerical methods such as the finite element method.

The mathematical simulation for material distribution for a two-dimensional functionally graded porous cylindrical beam involves modeling the material properties and distribution of the beam using appropriate mathematical equations. Here is a general approach for such a simulation:

- Define the geometry of the cylindrical beam, including its length, radius, and thickness.
- Specify the material properties of the beam as a function of its radial position. For a functionally graded porous cylindrical beam, the material properties may vary continuously across the radial direction.
- Model the deformation of the beam using the theory of elasticity. This involves solving the equations of equilibrium, strain-displacement relations, and the constitutive equations for the material properties of the beam.
- Solve the governing equations using appropriate numerical methods, such as the finite element method or the boundary element method, to obtain the displacement and stress distributions in the beam.

The specific mathematical equations used for the simulation will depend on the details of the material properties and geometry of the beam, as well as the numerical method used for the analysis. Therefore, it is difficult to provide a general mathematical simulation for a two-dimensional functionally graded porous cylindrical beam without further information on the specifics of the problem.

2.1 Functionally graded porosity-dependent materials

Functionally graded porosity-dependent materials are a specific type of material that display variations in both their porosity and material properties in different regions. These materials have attracted considerable attention in recent years as they have the potential for use in various engineering applications such as aerospace, biomedical, and energy systems.

Mathematical simulations provide a robust method for examining the behavior of functionally graded porosity-dependent materials. These simulations involve the use of mathematical models, usually based on partial differential equations, to describe the material's behavior. By solving these equations numerically, researchers can gain insights into the material's properties and behavior, which may be challenging or impossible to obtain experimentally.

The particular mathematical model employed to simulate functionally graded porosity-dependent materials depends on the specific material properties and behavior being studied. One popular method is to use the porosity-dependent diffusion equation, which accounts for the effect of porosity gradients on the diffusion of species in the material. Other models may include additional factors to accommodate mechanical or thermal behavior and the interdependence between different material properties.

Overall, mathematical simulations offer a powerful means to explore the behavior of functionally graded porosity-dependent materials, providing researchers with a deeper understanding of these materials and their possible uses in engineering and other fields. According to the following mathematical formulation as figured in Fig. 1 the temperature and porosity-dependent properties of functionally graded materials involving the elastic modulus (E), density (ρ), thermal expansion parameter (α), and Poisson's ratio (v) are calculated that the external cylindrical surface is pure ceramic (Aluminum oxide), while internal surface is pure metal (Nickel) (Pan 2021).

$$E(r,x,T) = E_{FGM}(1 - B) \tag{1a}$$

$$\rho(r,x,T) = \rho_{FGM}(1 - B) \tag{1b}$$

$$\nu(r,x,T) = \nu_{FGM}(1 - B) \tag{1c}$$

where

Table 1 Temperature-dependent coefficients for different Nickel and Aluminium oxide (Al_2O_3) (Reddy and Chin 1998)

Materials	Proprieties	P_0	P_{-1}	P_1	P_2	P_3
Al_2O_3	E(Pa)	349.55e9	0	-3.853e-4	4.027e-7	-1.673e-11
	α (1/K)	6.8269e-6	0	1.838e-4	0	0
	ν	0.26	0	0	0	0
	$\rho(Kg/m^3)$	3750	0	0	0	0
Nickle	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
	$\rho(Kg/m^3)$	8900	0	0	0	0

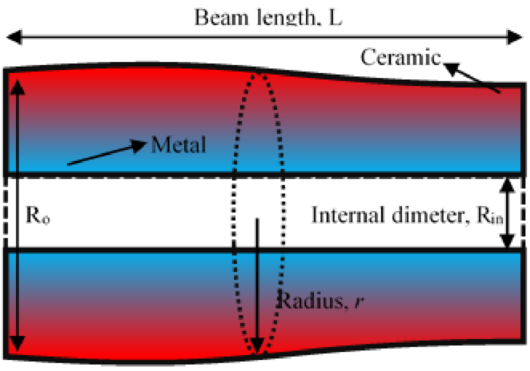

Fig. 1 A schematic of nonuniform cylindrical FG imperfect porous beam

$$E_{FGM} = (E_c - E_m)\left(\frac{r - R_{in}}{R_{out}(x) - R_{in}}\right)^{\tau} + E_m \qquad (2a)$$

$$\rho_{FGM} = (\rho_c - \rho_m)\left(\frac{r - R_{in}}{R_{out}(x) - R_{in}}\right)^{\tau} + \rho_m \qquad (2b)$$

$$\nu_{FGM} = (\nu_c - \nu_m)\left(\frac{r - R_{in}}{R_{out}(x) - R_{in}}\right)^{\tau} + \nu_m \qquad (2c)$$

$$\alpha_{FGM} = (\alpha_c - \alpha_m)\left(\frac{r - R_{in}}{R_{out}(x) - R_{in}}\right)^{\tau} + \alpha_m \qquad (2d)$$

$$B = \beta\, cos\left(0.5\pi\left(\frac{r - R_{in}}{R_{out}(x) - R_{in}}\right)\right) \qquad (2e)$$

In which, 'τ' is the volume fraction parameter, 'β' is the porosity parameter, 'R_{in}' is the internal cylindrical beam radius, '$R_{out}(x)$' is the external cylindrical beam radius, 'r' is the function of external radius which is changed along the beam length, and 'T' is the temperature (Kelvin). Here is the mathematical simulation for external radius of cylindrical beam sketched in Fig. 1.

$$R_{out}(x) = R_o \times \left(1 - \frac{\xi x}{L}\right)^2 \qquad (3)$$

where 'R_o' is the external beam radius at the left side (x=0). The temperature-dependent mechanical peripeties of both ceramic and metal material are defined in Table 1.

where the temperature-dependent mathematical equation for both Nickel and Aluminum oxide based on temperature (Kelvin) are formulated as follows (Touloukian and Ho 1970):

$$P = P_0(P_{-1}T^{-1} + 1 + P_1T + P_2T^2 + P_3T^3) \qquad (4)$$

In which, 'P_{-1}, P_0, P_1, P_2 and P_3' are temperature-dependent mechanical properties were defined in Table 1.

2.2 Generation of governing equations

According to the energy approach the following equation is considered.

$$\delta W + \delta S = 0 \qquad (5)$$

Here 'W' is the energy of external works that is due to the thermal conditions of thermal environment, and 'S' is the strain energy of the potential works. The external energy due to the thermal condition of thermal environment is calculated as follows:

$$\delta W = 0.5\delta \int \left(\iint E(x,r,T)\alpha(x,r,T)\Delta T dA\right) w_{,x}{}^2 dx \qquad (6)$$

Moreover, the potential energy due to the strain energy according to the higher-order Sinusoidal shear deformation beam theory is formulated as follows:

$$\delta S = \delta \iiint \begin{pmatrix} 0.5\sigma_{xx}(\varepsilon_{xx}) + \\ (\sigma_{xy}\varepsilon_{xy} + \sigma_{xz}\varepsilon_{xz}) \end{pmatrix} dv \qquad (7)$$

where 'σ' is stress tensor, and 'ε' is the strain tensors are defined as follows:

$$\begin{aligned} \sigma_{ij} &= E\varepsilon_{ij} i = j \\ \sigma_{ij} &= G\varepsilon_{ij}, i \neq j \end{aligned} \qquad (8)$$

where

$$2G = \frac{E}{1+\nu} \qquad (9)$$

and

$$\varepsilon_{ij} = u_{i,j} \qquad (10)$$

while

$$\varepsilon_{xx} = \frac{\partial u_1}{\partial x} \qquad (11a)$$

$$\varepsilon_{xy} = \frac{1}{2}\left(\frac{\partial u_1}{\partial y} + \frac{\partial u_2}{\partial x}\right) \tag{11b}$$

$$\varepsilon_{xz} = \frac{1}{2}\left(\frac{\partial u_1}{\partial z} + \frac{\partial u_3}{\partial x}\right) \tag{11c}$$

Also, the displacement fields are defined as follows:

$$u_1(x, r, \theta) = u - z w_{,x} + \Xi(\psi + w_{,x}) \tag{12a}$$

$$u_2(x, r, \theta) = 0 \tag{12b}$$

$$u_3(x, r, \theta) = w(x, t) \tag{12c}$$

where 'u' is the axial movement, 'w' is the lateral movement, and 'ψ' is the rotation. Based on the Sinusoidal shear deformation beam theory, the following function (Ξ) is defined as follows:

$$\Xi = sin\left(\frac{\pi r \theta}{(R_{out}(x) - R_{in})}\right)\frac{(R_{out}(x) - R_{in})}{\pi} \tag{13}$$

The total strain energy (Eq. (7)) which is a combination of mentioned equations (substitution of Eqs. (11) and (8) into (7)) is coupled with the energy of external works (Eq. (6)), as mentioned in Eq. (5), then the governing equation will be generated.

2.3 Nonlocal theory

The Nonlocal Eringen theory, also called Eringen's nonlocal elasticity theory, is a mathematical framework that allows for modeling material behavior that takes nonlocal effects into account. This theory was developed by Mustafa Arıkan Eringen (Eringen 1972). The Nonlocal Eringen theory considers that the deformation of a material at a point is influenced not only by the state of deformation at that point but also by the state of deformation in the surrounding area. This nonlocal effect is modeled using a length scale parameter that characterizes the range of influence of the surrounding material on the material's behavior at a given point. The theory has found applications in various areas, such as elasticity, plasticity, fracture mechanics, and wave propagation. It has also been used to study the behavior of materials at the nanoscale, where nonlocal effects are more pronounced. The Nonlocal Eringen theory is useful in fields such as materials science, biomechanics, and civil engineering, as it provides a more accurate description of material behavior in situations where traditional theories may not capture important phenomena. According to this high-order theory, the stresses are changed as follows:

$$\sigma_{ij} = (ea)^2 \nabla^2 \sigma_{ij} + C : \varepsilon_{ij} \tag{14}$$

Here, 'ea' is the nonlocal parameter, and 'C' is the elasticity tensor. By applying the nonlocal impact on the stress resultant due to the potential energy and energy of external work, the following governing equations regarding the thermal buckling behavior of nonlocal high-order nanobeam will be obtained.

$$\delta(u): \Lambda_1 u_{,xx} + \Lambda_1' u_{,x} = 0 \tag{15a}$$

$$\begin{aligned} \delta(w):\ & \Lambda_2 w_{,xxxx} + 2\Lambda_2' w_{,xxx} + \Lambda_2'' w_{,xx} \\ & +\Lambda_3'' \psi_{,x} + 2\Lambda_3' \psi_{,xx} + \Lambda_3 \psi_{,xxx} \\ & -\Lambda_4'(w_{,x} + \psi) - \Lambda_4(w_{,xx} + \psi_{,x}) \\ & -\Lambda_1' u_{,x} w_{,x} - \Lambda_1 u_{,xx} w_{,x} \\ & = \left(0.5 \iint E(x,r,T)\alpha(x,r,T)dA\right)' \Delta T w_{,x} \\ & + \left(0.5 \iint E(x,r,T)\alpha(x,r,T)dA\right) \Delta T w_{,xx} \\ & -(ea)^2 \Delta T \frac{\partial^2}{\partial x^2}\left(\begin{array}{c} \left(0.5 \iint \begin{array}{c} E(x,r,T) \times \\ \alpha(x,r,T)dA \end{array}\right)' w_{,x} \\ + \left(0.5 \iint \begin{array}{c} E(x,r,T) \times \\ \alpha(x,r,T)dA \end{array}\right) w_{,xx} \end{array}\right) \end{aligned} \tag{15b}$$

$$\begin{aligned} \delta(\psi):\ & \Lambda_3' w_{,xx} + \Lambda_3 w_{,xxx} + \Lambda_5' \psi_{,x} \\ & +\Lambda_5 \psi_{,xx} - \Lambda_4(w_{,x} + \psi) = 0 \end{aligned} \tag{15c}$$

where

$$\begin{Bmatrix} \Lambda_1 \\ \Lambda_2 \\ \Lambda_3 \\ \Lambda_4 \\ \Lambda_5 \end{Bmatrix} = \begin{Bmatrix} \int E r dr d\theta \\ \int E\Xi^2 r dr d\theta - 2\int E\Xi r\theta r dr d\theta + \int E r^2 r\, sin^2(\theta)\, r dr d\theta \\ \int E\Xi^2 r dr d\theta - \int E\Xi r\, sin(\theta)\, r dr d\theta \\ \int K_S G(\Xi_{,y} + \Xi_{,z}) r dr d\theta \\ \int E\Xi^2 r dr d\theta \end{Bmatrix} \tag{16}$$

where 'K_S' is the shear deformation correction factor and defined as follows:

$$\begin{aligned} & K_S = \frac{\Theta_1}{\Theta_2} \\ & \Theta_1 = 6\left(1 + \left(\frac{R_{in}}{R_{out}(x)}\right)^2\right)^2 (1 + \nu)^2 \\ & \Theta_2 = (7 + 14\nu + 8\nu^2)\left(1 + \left(\frac{R_{in}}{R_{out}(x)}\right)^2\right)^2 \\ & +4\left(\frac{R_{in}}{R_{out}(x)}\right)^2 (5 + 10\nu + 4\nu^2) \end{aligned} \tag{17}$$

Boundary conditions are:

$$\delta(u): \Lambda_1 u_{,x} = 0 \tag{18a}$$

$$\begin{aligned} & \delta(w): \left(0.5 \iint E(x,r,T)\alpha(x,r,T)dA\right) \Delta T w_{,x} \\ & -\frac{\partial}{\partial x}(\Lambda_2 w_{,xx}) - \frac{\partial}{\partial x}(\Lambda_3 \psi_{,x}) + \Lambda_5(\psi + w_{,x}) = \\ & (ea)^2 \left(0.5 \iint E(x,r,T)\alpha(x,r,T)dA\right) \Delta T w_{,xx} \end{aligned} \tag{18b}$$

$$\delta(\psi): \Lambda_3 w_{,xx} + \Lambda_5 \psi_{,x} = 0 \tag{18c}$$

$$\delta(w_{,x}): \Lambda_2 w_{,xx} + \Lambda_3 \psi_{,x} = 0 \tag{18d}$$

3. Numerical solution methodology

The Generalized Differential Quadrature Method (GDQM) is a numerical technique that has gained popularity

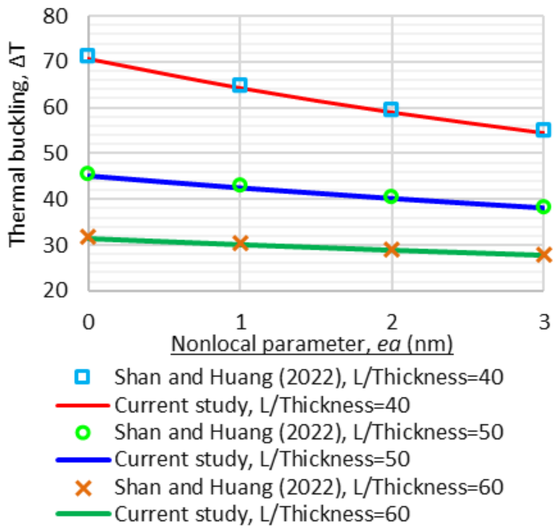

Fig. 2 The validation and comparison between the current thermal buckling (ΔT) results and the results of Shan and Huang (2022) for different aspect ratio (L/(R_{out}-R_{in}) Or L/thickness) and nonlocal parameters (*ea*)

in recent years for solving a wide range of differential equations. The method is based on the concept of expanding the unknown function in terms of a set of discrete points, and then using differential quadrature to approximate the derivatives. GDQM is a flexible technique that allows for the use of irregularly spaced grid points and arbitrary boundary conditions. It has been successfully applied to problems in mechanics, fluid dynamics, and electro-magnetics, among others.

The GDQM approach involves two main steps: first, the unknown function is discretized using a set of collocation points, and second, the derivatives are approximated using a weighted combination of function values at these points. The weighting coefficients are obtained by solving a system of algebraic equations that arise from enforcing the boundary conditions. Compared to other numerical methods, GDQM is relatively easy to implement and can provide accurate solutions with fewer grid points, making it an efficient and effective tool for solving differential equations. This methodology changed the differential derivative functions ($\partial^p/\partial x^p$) to the weighting coefficient ($\sum \Phi^{(p)}$) according to the following transformation.

$$\frac{\partial^p f(x)}{\partial x^p}=\sum_{j=1}^{n}\Phi_{ij}^{(p)} f(x_i) \tag{19}$$

By applying the GDQM to the obtained governing equations, the following eigen-value problem will be generated.

$$\delta(u):\ \Lambda_1 \textstyle\sum_{j=1}^{n}\Phi_{ij}^{(2)}u_j+\Lambda_1{}'\sum_{j=1}^{n}\Phi_{ij}^{(1)}u_j=0 \tag{20a}$$

$$\begin{aligned}
&\delta(w):\\
&\Lambda_2\sum_{j=1}^{n}\Phi_{ij}^{(4)}w_j+2\Lambda_2{}'\sum_{j=1}^{n}\Phi_{ij}^{(3)}w_j+\Lambda_2{}''\sum_{j=1}^{n}\Phi_{ij}^{(2)}w_j\\
&+\Lambda_3{}''\sum_{j=1}^{n}\Phi_{ij}^{(1)}\psi_j+2\Lambda_3{}'\sum_{j=1}^{n}\Phi_{ij}^{(2)}\psi_j+\Lambda_3\sum_{j=1}^{n}\Phi_{ij}^{(3)}\psi_j\\
&-\Lambda_4{}'\left(\sum_{j=1}^{n}\Phi_{ij}^{(1)}w_j+\psi_j\right)-\Lambda_1{}'u_{,x}\sum_{j=1}^{n}\Phi_{ij}^{(1)}w_j\\
&-\Lambda_4\left(\sum_{j=1}^{n}\Phi_{ij}^{(2)}w_j+\sum_{j=1}^{n}\Phi_{ij}^{(1)}\psi_j\right)-\Lambda_1 u_{,xx}\sum_{j=1}^{n}\Phi_{ij}^{(1)}w_j\\
&=\left(0.5\iint E(x,r,T)\alpha(x,r,T)dA\right)'\Delta T\sum_{j=1}^{n}\Phi_{ij}^{(1)}w_j\\
&+\left(0.5\iint E(x,r,T)\alpha(x,r,T)dA\right)\Delta T\sum_{j=1}^{n}\Phi_{ij}^{(2)}w_j-\\
&(ea)^2\Delta T\frac{\partial^2}{\partial x^2}\left(\begin{aligned}&\left(0.5\iint \begin{aligned}&E(x,r,T)\times\\&\alpha(x,r,T)dA\end{aligned}\right)'\sum_{j=1}^{n}\Phi_{ij}^{(1)}w_j\\&+\left(0.5\iint \begin{aligned}&E(x,r,T)\times\\&\alpha(x,r,T)dA\end{aligned}\right)\sum_{j=1}^{n}\Phi_{ij}^{(2)}w_j\end{aligned}\right)
\end{aligned} \tag{20b}$$

$$\begin{aligned}
&\delta(\psi):\\
&\Lambda_3{}'\sum_{j=1}^{n}\Phi_{ij}^{(2)}w_j+\Lambda_3\sum_{j=1}^{n}\Phi_{ij}^{(3)}w_j+\Lambda_5{}'\sum_{j=1}^{n}\Phi_{ij}^{(1)}\psi_j\\
&+\Lambda_5\sum_{j=1}^{n}\Phi_{ij}^{(2)}\psi_j-\Lambda_4\left(\sum_{j=1}^{n}\Phi_{ij}^{(1)}w_j+\psi_j\right)=0
\end{aligned} \tag{20c}$$

Finally, the eigen-values are the temperature (T) of the thermal buckling ($\Delta T = T - T_0$, T_0=300K, is the reference point).

4. Discussion of results

This study analyzes the thermal stability because of the thermal buckling characteristics of high-order nonlocal Sinusoidal shear deformation cylindrical nonuniform porosity-dependent functionally graded beam theory using the numerical approach. The complicated partial differential governing equations and boundary conditions are generated based on the energy principle. It is necessary to validate the extracted equations and solution method before the deliberating the numerical results. According to the mentioned explanation, the prevailing results should be compared to the published results by other researchers. To verification of obtained results, the numerically calculated results are correlated to the results of Shan and Huang (2022) based on the classical beam theory in Fig. 2. The current thermal buckling (ΔT) results are analyzed with results of Shan and Huang (2022) for various aspect ratios (L/(R_{out}-R_{in}) Or L/thickness) and different nonlocal parameters (*ea*). The comparison proves that the obtained results have an excellent agreement with previously published results and it means both governing equations and numerical approach are confirmed.

Fig. 3 presents the behavior of a nanobeam under the thermal impacts due to the change of the temperature versus

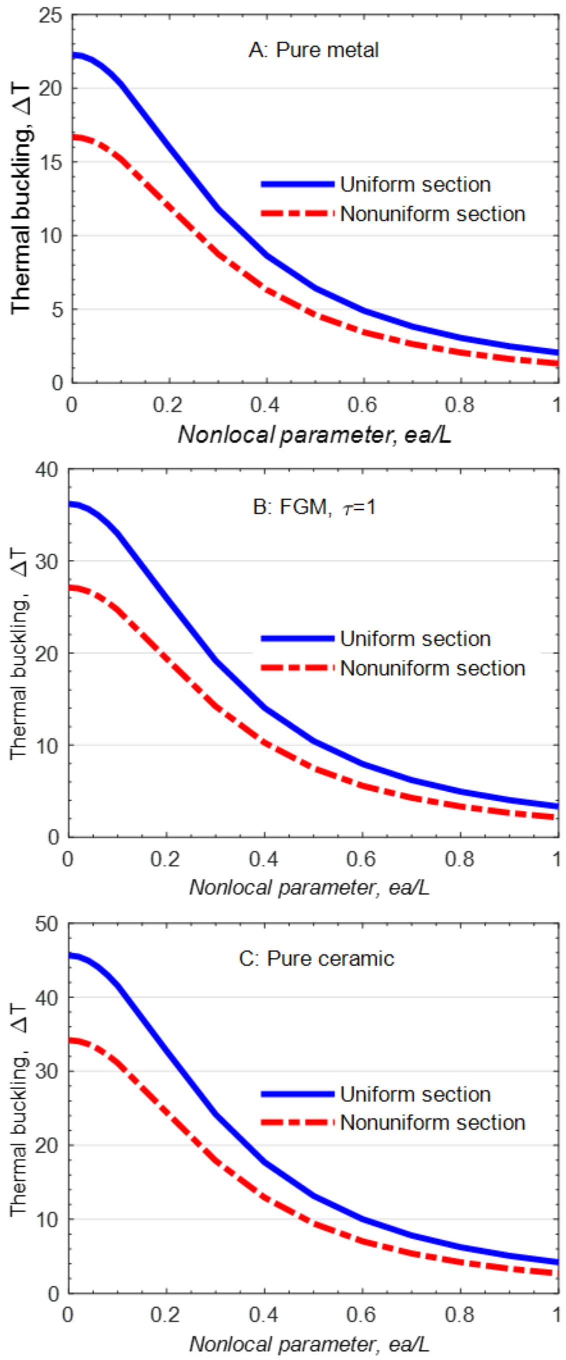

Fig. 3 Thermal buckling (ΔT) behavior of FGM pinned nanobeams versus the different nonlocal (*ea*) and FGM parameters (τ) for uniform and nonuniform nanobeams, β=0.05, $L/R_0=50$, $R_0/R_{in}=10$

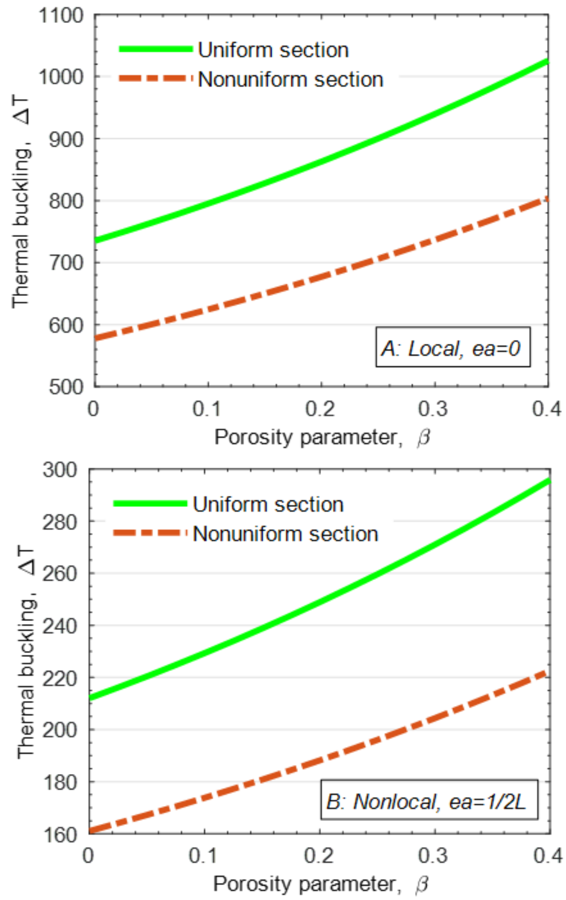

Fig. 4 Thermal buckling (ΔT) of uniform and nonuniform porous pinned nanobeam versus the nonlocal parameter (*ea*) as well as porosity parameter (β), τ=1, $L/R_0=25$, $R_0/R_{in}=2$

the different values of nonlocal parameters concerning both uniform and nonuniform truncated conical cylindrical pinned nanobeam. The results are separated into three sections involving FGM and non-FGM types. Part A shows the thermal buckling for the pure metal beam, part B presents the behavior of the FGM beam, and part C explains the thermal buckling characteristics of the pure ceramic beam. All mentioned results and discussions are noted for uniform and nonuniform truncated conical beams. According to the calculated results, the thermal stability of the local and nonlocal uniform beam is better than the nonuniform one. Also, it is shown that the nonlocality decreases the thermal buckling, which means the nonlocality has an inverse impact on the stability of the nanobeam. Furthermore, the stiffness of aluminum oxide is greater than that of nickel, indicating that pure ceramic beams are more stable than metal beams. This conclusion may be seen in comparing parts A and C. FGMs are a hybrid combination of ceramics and metals, and their stability is expected to be higher than that of metals. Ceramics also outperform FGMS in terms of thermal buckling.

Fig. 4 depicts a porosity-dependent pinned nanobeam's numerical thermal buckling (ΔT) analysis based on the high-order shear deformation beam theory for local and nonlocal situations vs. the various porosity values (β). This study was carried out using the high-order shear deformation beam theory. For the purpose of calculating the cross-section of the nanobeam, both a uniform and a nonuniform truncated conical section have been taken into consideration, and the results have been reported for both of these sections. Because the nonlocal beam buckles at a lower temperature, the local beam is more stable than the nonlocal beam, as shown by the comparison between sections A and B. Nonlocality has a considerable influence on the stability of the nanobeam, as shown by the comparison between sections A and B. In addition, the porosity has a beneficial

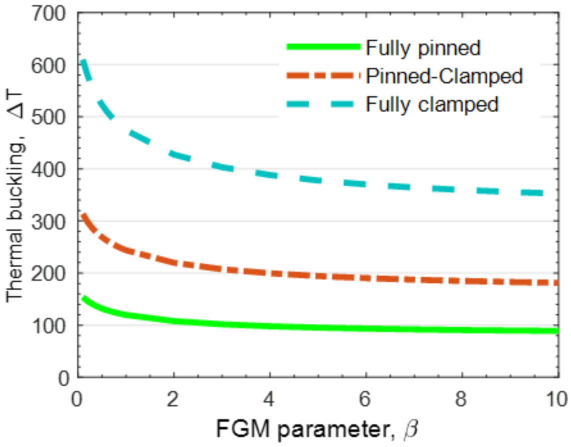

Fig. 5 Thermal buckling (ΔT) characteristics of nonuniform nonlocal FG porous nanobeam versus the different boundary conditions involving the pinned, and clamped, τ=1, β=0.25, *ea*=L, L/R_0=25, R_0/R_{in}=2

effect on both the local and nonlocal nanobeam as well as the uniform and nonuniform nanobeam. In point of fact, porosity causes a delay in the thermal buckling, and a higher value for the porosity parameter results in an improvement in the thermal stability. It should be noticed, as was said before, that the uniform portion is more stable than the nonuniform part. This is also true with regard to the porosity influence.

The influence of boundary conditions on the thermal stability caused by the thermal buckling study of a nonuniform truncated conical cylindrical functionally graded nano porous beam is shown in Fig. 5. This analysis was performed on clamped, pinned, and clamped-pinned nanobeams. The pinned type has the most degree of freedom, and the beam stiffness of the pinned nanobeam is lower than others, leading to lower stability. While the clamped type is more rigid than others, the clamped nanobeam is stiffer, and the boundary condition buckles in higher temperatures. Comparison between them proved that the clamped type is more stable than others, and also, the buckling in the pinned conditions happened in lower temperatures.

5. Conclusions

In this study, the thermal stability and buckling characteristics of high-resistance badminton nets constructed from reinforced lightweight materials were analyzed within a functionally graded material (FGM) framework. The mathematical modeling was based on high-order nonlocal theories and sinusoidal shear deformation theory. The partial differential governing equations were derived using the energy method and solved using the Generalized Differential Quadrature Method (GDQM). The key findings of this study are as follows:

• The thermal stability of nanobeams was adversely affected by nonuniform imperfections. It was observed that nonuniform beams exhibited buckling at lower temperatures compared to uniform beams.

• Functionally graded material (FGM) parameters significantly enhanced the stability of nanobeams compared to metal beams. Among the FGMs, ceramic nanobeams demonstrated superior stability over other FGM nanobeams.

• The inclusion of nonlocal effects reduced the stiffness and stability of the beams, leading to buckling at lower temperatures.

• Porosity increased the thermal stability of nanobeams. Porous beams buckled at higher temperatures compared to their non-porous counterparts.

• The thermal buckling and stability of nanobeams were highly sensitive to boundary conditions. Clamped nanobeams exhibited the highest strength and stability, while pinned nanobeams, due to their higher degree of freedom, buckled at lower temperatures.

These findings provide a comprehensive understanding of how reinforced lightweight materials and structural nonuniformity influence the thermal stability and buckling behavior of high-resistance badminton nets. This study offers valuable insights for the design and optimization of sports equipment, contributing to advancements in the sports industry and sport economy by enhancing equipment durability and performance.

Acknowledgement

This work was supported by 2022 Social Science Research Project of Yichang City (ysk22kt120).

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