

Nanocomposite reinforced structures to deal with injury in physical sports

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Abstract. The extensive use of polymeric matrix composites in the athletic sector may be attributed to its high strength-to-weight ratio, production economy, and a longer lifespan than conventional materials. This study explored the impact of carbon nanotubes on the properties of different composite field sports equipment components. The test specimens were fabricated using the compression molding technique. The insertion of carbon nanotubes increases mechanical properties related to the process parameters to account for an improvement in the stick sections' overall performance. The dynamic response of functionally graded reinforced nanocomposite wire structure is examined in this paper on the bases of high-order hyperbolic beam theory lined to the size-dependent nonclassical nonlocal theory under the external mechanical load due to the physical activities. Finally, the impact of different parameters on the stability of nanocomposite structures is discussed in detail.

Keywords: nanocomposite material; reinforced structures; physical sports equipment; stability analysis

1. Introduction

Sports equipment greatly influences athletes' technique, frequently made to lower the danger of damage or injury. The three primary Sports equipment design goals can be measured provident, safety improvement, and injury prevention. It is common knowledge that raising success levels through performance often increases the risk of injury because doing so always entails putting more strain on specific body components. However, a better understanding of equipment design may be able to lessen these risks and counteract such a damaging impact on the body. The running shoe is a prime illustration of how cutting-edge adjustments in the design and creation of new materials can give increased comfort, lower the risk of specific injuries, and simultaneously bring about major gains in athletes' performance (Dabnichki 1998). Several scientists have concentrated on this topic to improve the design and manufacture of protective equipment for various athletes. Female contact football players' clothing choices during practices and games and their assessments of how well it protected them against contact breast injuries were examined by Brisbane *et al.* (2020). By gathering information on damage areas and their causes, Jin and Lee (2022) examined various injuries and protective equipment used by amateur athletes and assessed various risk factors (Zhu *et al.* 2017, Gong *et al.* 2022, Su *et al.* 2023, Zhang *et al.* 2023a, b).

The physical characteristics of conventional sports

equipment, which primarily uses wood or metal components, place a heavy physical constraint on the strength of sports equipment today (Fu *et al.* 2020, Guo *et al.* 2022, Jiang *et al.* 2023, Shi *et al.* 2023, Zhai *et al.* 2023). As a result of developments in science and technology, new materials, including epoxy resin composites, carbon fiber composites, unsaturated polyester composites, and nylon fiber composites, are now extensively implemented in various equipment and have even replaced essential components in competitive sports. The outstanding features of many innovative materials, counting superior damping performance, strong designability, lightweight, wear resistance, specific modulus, high specific strength, etc., significantly improve sports equipment's performance (Moncalero 2017). In order to manufacture advanced sports equipment, several investigations in the field of utilizing novel materials have been done by researchers. Moncalero (2017) investigated the effects of novel polymeric materials on footwear and outdoor gear's mechanical, thermal, and ergonomic characteristics. Yang *et al.* (2014) looked into implementing high-tech materials modified for sports training. Rowson *et al.* (2014) illustrated the differences between various football helmet types and their influence on concussion risk reduction capabilities. Caine *et al.* (2012) looked into sports materials and technology.

The composite material is commonly used in sports equipment since that offers features such as fatigue resistance, break resistance, superior thermostability, friction resistance, abrasion resistance, and vibration attenuation. It's also lightweight, strong, and provides flexibility in design. Many sports equipment items are made of composite materials, such as kayaks, gigs, sailing boats, sailboards, and surfboards for water sports, tennis rackets, badminton rackets, softball bats, and backboards for

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basketball stands for indoor sports, snowboards, ski poles, sleds, and ice hockey sticks for winter sports, and high jump poles and bows for archery. Several sporting goods made of composite materials have been demonstrated to have significantly improved performance-enhancing characteristics (Wang 2012). The unique features of composite material have led to many studies on the use of these materials in the production of sports equipment. Bai and Li (2012) investigated the application of composite carbon fiber materials for sport goods. Tong (2019) examined a number of cutting-edge substances that have been widely used in sport equipment, including epoxy resin composites, carbon fiber composites, unsaturated polyester composites, and nylon fiber composites. Zhang (2013) has conducted a brief examination of the specialized use of carbon fiber composite materials in sports equipment. An introduction to fiber reinforced composite materials was offered by Jayan *et al.* (2021). Sun and Wang (2012) comprehensively described the utilization benefits of fiber reinforced composites materials in sport equipment, as well as selection guidelines, product diversity, and an application example, in order to serve as a manual for sport equipment manufacturing.

Nanomaterials are frequently used with bulk polymeric materials to enhance their qualities since they have unique features. Materials that have nanoparticle reinforcement are referred to as nanocomposites. Nanocomposites are divided into three categories based on the material used as the matrix: polymer matrix composites, metal matrix composites, and ceramic matrix composites. A nanocomposite material is made up of many phases with at least one, two, or three dimensions in the nanoscale range. Phase interfaces are produced when material dimensions are reduced to the nanoscale level, and they are crucial for improving the characteristics of materials. Understanding the link between structure and property is directly influenced by the ratio of reinforced material volume to surface area employed in the creation of nanocomposites. Nanocomposites provide possibilities for breaking down barriers in the medical, pharmaceutical, food packaging, electronics, and energy sectors on whole new scales (Parameswaranpillai *et al.* 2016). Numerous accomplishments have resulted from research on nanocomposites (Li *et al.* 2021a, Si *et al.* 2021, Zhang *et al.* 2021, 2022a, b, Cao *et al.* 2022a, b, Wang *et al.* 2022a). Zhang *et al.* (2002) employed the “bottom-top” method to create nanocomposite materials with periodic architectures using hybrid core-shell polymer–semi-conductor or polymer–metal microspheres. Using chemical treatments and an acid hydrolysis method, El Achaby *et al.* (2018) manufactured cellulose nanocrystals (CNC) from discarded vine shoots. Developments in the fabrication and use of nanoparticles (NPs) and nanohybrid/ nanocomposite materials based on spin-crossover (SCO) complexes were discussed by Salmon and Catala (2018). Muflikhun *et al.* (2019) examined the structural and mechanical properties of the silver-titanium dioxide nanocomposite material using atomic force microscopy (AFM).

The challenge of doing molecular research remains incredibly difficult despite all the developments in

contemporary nanotechnology. Experiments and hands-on work with novel materials play an undeniably essential role. The technology for producing nanoscale things may, however, be enhanced and optimized with the use of theoretical research techniques (Fedotov *et al.* 2021). Guo *et al.* (2020) introduced anharmonic phonon nonequilibrium inside a more accurate theoretical framework. The Green’s function formalism for both one-dimensional and three-dimensional nanostructures was demonstrated using a diagrammatic perturbation expansion and the inclusion of Fourier’s representation to both harmonic and anharmonic components. By fully linking the LLG model with elastodynamics, or by utilizing the intrinsic relationship between partial differential equations, Liang *et al.* (2014) performed analytical work with the intention of significantly improving the modeling of finite structures. The multiscale continuum model of solids was developed by Lurie *et al.* (2003) to account for the unusual properties of thin structures and composite materials with thin structures that were connected to certain sorts of local interactions between nanoparticles and matrix. A detailed explanation of multi-scale modeling and simulation of advanced materials for structural applications provided by Gates *et al.* (2005).

According to the literature review, the extensive use of polymeric matrix composites in the athletic sector may be attributed to its high strength-to-weight ratio, production economy, and longer lifespan than conventional materials. This study will be explored the impact of carbon nanotubes on the properties of different composite field sports equipment components. The test specimens will be fabricated using the compression molding technique. The insertion of carbon nanotubes leads to an increase in mechanical properties, which is related to the process parameters to account for an improvement in the stick sections’ overall performance. The dynamic response of functionally graded reinforced nanocomposite wire structure is examined in this paper on the bases of high-order hyperbolic beam theory lined to the size-dependent nonclassical nonlocal theory under the external mechanical load due to the physical activities. Finally, the impact of different parameters on the stability of nanocomposite structures will be discussed in detail.

2. Problem description

2.1 Material and structures for sport equipment

Typical sports equipment is now made from metal or wood, both of which have inherent weaknesses that severely restrict their usefulness as athletic tools. Novel materials are being employed in multiple sports equipment, and their quality has become a crucial aspect in competitive sports as science and technology have advanced. Due to its ability to greatly enhance the act related to sports equipment, it has become increasingly popular in recent years. This is because of the excellent properties associated with different novel materials, including specific modulus, wear resistance, high specific strength, lightweight, good

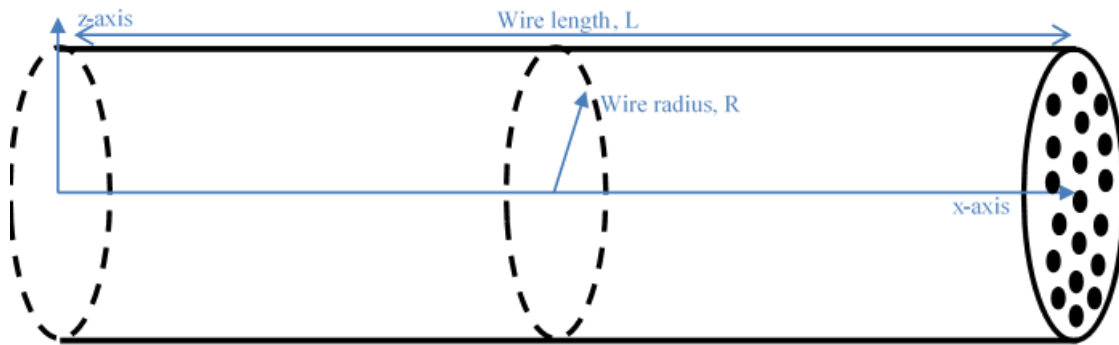


Fig. 1 A schematic of functionally graded reinforced nanocomposite structure in a wire frame made of carbon nanotube into the isotropic matrix

damping performance, strong designability, etc. Graphene composites, carbon fiber composites, unsaturated polyester composites, nylon fiber composites, and epoxy resin composites are just a few of the modern materials utilized in sports gear. (Tong 2019).

2.2 New materials in sports equipment

As a theoretical model, graphene's structure was previously dismissed as a result of its extremely high surface tension. Graphene, a nanomaterial that may be as thin as a single carbon atom, has outstanding electrical conductivity, is hundred times stronger than steel, and is very flexible. Adding the right proportion of graphene to polymer nanocomposites can dramatically enhance their heat resistance, toughness, size stability, and mechanical characteristics. (Tong 2019).

Around 1960, DuPont created aromatic polyamides to increase the durability of nylon under high temperatures. The primary outputs are polyterephthaloyl p-phenylenediamine (Kevlar fiber) and polyisophthalic m-phenylenediamine (Nomex fiber). Because of the benzene ring, the molecular chain of Nomex fibers can't rotate inward on itself. The formation of coupled systems between the benzene ring and the amide group is facilitated by the formation of hydrogen bonds between the molecular chains by the strong polar amide groups. The rigidity of the polymer's molecular chains allows it to exhibit exceptional performance qualities like those listed below: resistance to chemical corrosion, heat, strength, high-energy radiation, stiffness, and flame retardancy, among others. (Tong 2019).

Whenfield and Dikeon, two British chemists working in the early 1940s, looked to Dupont's research on the synthesis related to polyester from aliphatic dicarboxylic acid and glycol for guidance. There was a successful laboratory synthesis of polyethylene terephthalate using terephthalic acid and glycol, which led to the creation of polyester fibers. It was the first company to publish a patent for making polyester fibers, which it did in 1946. The molecular chain of unsaturated polyester resin contains unsaturated bonds, counting double bonds. In order to prepare the linear polyester for cross-linking and solidification, dibasic acid and diol are reacted to form an ester, and the resulting ester is then dissolved in a specific

amount of cross-linked monomer (for example styrene). (Tong 2019).

In its most basic form, carbon fiber is a very unusual type of fiber. In general, its carbon content is more than 90%, however it varies by kind. In addition to the properties shared by other carbon-based materials, such as heat conduction, friction resistance, corrosion resistance, high temperature resistance, and electrical conductivity, carbon fiber is also soft, easily processed into different fabrics, and exhibits high strength in the direction of the fiber axis. In addition to its high specific strength, carbon fiber also possesses a tiny specific gravity. (Tong 2019).

With the help of the right reagents, molecules containing epoxy groups may cross-link into a reticulated cured structure in three dimensions, making epoxy resin a type of essential thermosetting resin. Bisphenol A and epichlorohydrin are condensed to form bisphenol an epoxy resin, which accounts for more than 90% of the total. When it comes to the molecular structure of epoxy resins, you'll find aliphatic hydroxyl groups, epoxy groups and ether bonds. These polar groups have pronounced interactions with the polar surfaces of metals and silicates. Epoxy groups, in particular, can react with active hydrogen on the surface of materials to generate chemical bonds. Simultaneously, the existence of ether bonds in the resins' molecular chain provides flexibility. This allows for efficient diffusion in a material's outermost layer. (Tong 2019).

2.3 Functionally graded reinforced nanocomposite structures

The functionally graded reinforced composite wire structures, which are shown in Fig. 1, are assumed in this study. The wire length is 'L', and the wire radius is 'R'. The functionally graded reinforced composite structure is made of a single-walled carbon nanotube through an isotropic matrix (Ke *et al.* 2010). The mixture of carbon nanotube into the isotropic matrix is the anisotropic structure that the mechanical properties involving the elastic modulus (E), Poisson ratio (ν), and density (ρ) are presented as following (Shen 2009):

$$E = V_{cnt}E_{cnt} + V_{mat}E_{mat} \quad (1a)$$

$$\nu = V_{cnt}\nu_{cnt} + V_{mat}\nu_{mat} \quad (1b)$$

$$\rho = V_{cnt}\rho_{cnt} + V_{mat}\rho_{mat} \tag{1c}$$

Here ‘ V_{mat} ’ is the volume fraction of matrix, ‘ V_{cnt} ’ is the volume fraction of carbon nanotube, also, subscript ‘ $(_{cnt})$ ’ refers to the mechanical properties of carbon nanotube, while subscripting ‘ $(_{mat})$ ’ directs to the mechanical properties of isotropic matrix, that they are listed in Table 1.

2.4 Mathematical simulation for the nanostructures

The current study investigates the stability behavior of functionally graded carbon nanotube-reinforced nano-Compos. Struct., The high-order beam theory based on the wire structures is assumed, which the displacements fields according to the Hyperbolic shear deformation beam theory are defined as follows:

$$u_x = u + R \sinh\left(\frac{r \sin(\theta)}{R}\right) (\psi - w_{,x}) - zw_{,x} - r \sin(\theta) \cosh\left(\frac{1}{2}\right) (\psi - w_{,x}) \tag{2a}$$

$$u_y = 0 \tag{2b}$$

$$u_z = w \tag{2c}$$

Here ‘ u_x ’, ‘ u_y ’, and ‘ u_z ’ are the displacements fields along the x -, y -, and z -axis. Also, ‘ u ’ is the axial displacement, ‘ w ’ is the lateral displacement, and ‘ ψ ’ is rotation component. Moreover, ‘ R ’ is the wire radius. The strain tensors, based on the presented displacement fields, are defined as follows:

$$\varepsilon_{xx} = u_{,x} + R \sinh\left(\frac{r \sin(\theta)}{R}\right) (\psi_{,x} - w_{,xx}) - zw_{,xx} - r \sin(\theta) \cosh\left(\frac{1}{2}\right) (\psi_{,x} - w_{,xx}) \tag{3a}$$

$$2\varepsilon_{xy} = \frac{\partial}{\partial y} \left(R \sinh\left(\frac{r \sin(\theta)}{R}\right) \right) (\psi - w_{,x}) - \frac{\partial}{\partial y} \left(r \sin(\theta) \cosh\left(\frac{1}{2}\right) \right) (\psi - w_{,x}) \tag{3b}$$

$$2\varepsilon_{xz} = \frac{\partial}{\partial z} \left(R \sinh\left(\frac{z}{R}\right) \right) (\psi - w_{,x}) - \frac{\partial}{\partial z} \left(z \cosh\left(\frac{1}{2}\right) \right) (\psi - w_{,x}) \tag{3c}$$

The potential energy (P) is obtained based on the following equations (Liu *et al.* 2020, Wang *et al.* 2020, Zhou *et al.* 2020, Dai *et al.* 2021a, Guo *et al.* 2021, Shao *et al.* 2021, Wu and Habibi 2021):

$$P = \iiint \sigma : \varepsilon dV \tag{4}$$

where ‘ σ ’ is the stress tensors, and the virtual potential energy (δP) will be obtained via following equation (Adamian *et al.* 2020, Al-Furjan *et al.* 2020a, b, Li *et al.* 2020, Zare *et al.* 2020, Dai *et al.* 2021b):

$$\delta P = - \int_0^L \frac{\partial}{\partial x} \left(Q_1 \frac{\partial u}{\partial x} \right) dx \delta(u) + Q_2 \psi|_0^L \delta(w) \tag{5}$$

$$\begin{aligned} & - \int_0^L \frac{\partial}{\partial x} (Q_2(\psi)) dx \delta(w) + \int_0^L \frac{\partial^2}{\partial x^2} \left(Q_3 \frac{\partial^2 w}{\partial x^2} \right) dx \delta(w) \\ & - \int_0^L \frac{\partial}{\partial x} \left(Q_3 \frac{\partial \psi}{\partial x} \right) dx \delta(\psi) - \int_0^L \frac{\partial}{\partial x} \left(Q_3 \frac{\partial^2 w}{\partial x^2} \right) dx \delta(\psi) \\ & + Q_3 \frac{\partial \psi}{\partial x} \Big|_0^L \delta(\psi) + \int_0^L \frac{\partial^2}{\partial x^2} \left(Q_3 \frac{\partial \psi}{\partial x} \right) dx \delta(w) \\ & \int_0^L \frac{\partial}{\partial x} \left(Q_5 \frac{\partial^2 w}{\partial x^2} \right) dx \delta(\psi) - Q_5 \frac{\partial^2 w}{\partial x^2} \Big|_0^L \delta(\psi) \\ & - Q_5 \frac{\partial \psi}{\partial x} \Big|_0^L \delta\left(\frac{\partial w}{\partial x}\right) + \int_0^L Q_2 \psi \delta(\psi) + Q_2 \frac{\partial w}{\partial x} \delta(\psi) dx \\ & + Q_2 \frac{\partial w}{\partial x} \Big|_0^L \delta(w) - \int_0^L \frac{\partial^2}{\partial x^2} \left(Q_5 \frac{\partial \psi}{\partial x} \right) dx \delta(w) \\ & + \int_0^L \frac{\partial^2}{\partial x^2} \left(Q_4 \frac{\partial^2 w}{\partial x^2} \right) dx \delta(w) + Q_4 \frac{\partial^2 w}{\partial x^2} \Big|_0^L \delta\left(\frac{\partial w}{\partial x}\right) \\ & + Q_3 \frac{\partial \psi}{\partial x} \Big|_0^L \delta\left(\frac{\partial w}{\partial x}\right) - \frac{\partial}{\partial x} \left(Q_3 \frac{\partial \psi}{\partial x} \right) \Big|_0^L \delta(w) \\ & - 2 \int_0^L \frac{\partial^2}{\partial x^2} \left(Q_5 \frac{\partial^2 w}{\partial x^2} \right) dx \delta(w) - \frac{\partial}{\partial x} \left(Q_4 \frac{\partial^2 w}{\partial x^2} \right) \Big|_0^L \delta(w) \\ & - 2 Q_5 \frac{\partial^2 w}{\partial x^2} \Big|_0^L \delta\left(\frac{\partial w}{\partial x}\right) + 2 \frac{\partial}{\partial x} \left(Q_5 \frac{\partial^2 w}{\partial x^2} \right) \Big|_0^L \delta(w) \\ & + \frac{\partial}{\partial x} \left(Q_5 \frac{\partial \psi}{\partial x} \right) \Big|_0^L \delta(w) - \int_0^L \frac{\partial}{\partial x} \left(Q_2 \frac{\partial w}{\partial x} \right) dx \delta(w) \\ & + Q_3 \frac{\partial^2 w}{\partial x^2} \Big|_0^L \delta\left(\frac{\partial w}{\partial x}\right) - \frac{\partial}{\partial x} \left(Q_3 \frac{\partial^2 w}{\partial x^2} \right) \Big|_0^L \delta(w) \\ & + Q_3 \frac{\partial^2 w}{\partial x^2} \Big|_0^L \delta(\psi) + Q_1 \frac{\partial u}{\partial x} \Big|_0^L \delta(u) \end{aligned}$$

where

$$\xi = R \sinh(r \sin(\theta) R^{-1}) - r \sin(\theta) \cosh(0.5) \tag{7}$$

The nanostructure is under the external dynamic load, which the virtual energy due to this load is defined as follows:

$$\delta W = \int_V \tau \times \zeta \sin\left(\frac{n\pi}{L} x\right) \sin(\omega t) dV \delta(w) \tag{8}$$

‘ τ ’ is the dynamic external bending load, and the ‘ ω ’ is the external excitation frequency, and ‘ ζ ’ is the length of beam under the loading (Hashemi *et al.* 2019, Al-Furjan *et al.* 2020c, Cheshmeh *et al.* 2020, Lori *et al.* 2020, Najaafi *et al.* 2020, Shariati *et al.* 2020c). Also, the virtual Kinetic energy (δK) is defined as follows:

$$\begin{aligned} \delta K = \int_0^L \bar{k} dx, \bar{k} = \\ q_0 [(\dot{w}_{,x} + \dot{\psi})\delta(\dot{w}_{,x}) + (\dot{w}_{,x} + \dot{\psi})\delta(\dot{\psi})] \\ - q_1 [(2\dot{w}_{,x} + \dot{\psi})\delta(\dot{w}_{,x}) + (\dot{w}_{,x})\delta(\dot{\psi})] \\ + q_2 [\dot{w}_{,x}\delta(\dot{w}_{,x})] + q_3 [\dot{u}\delta(\dot{u}) + \dot{w}\delta(\dot{w})] \end{aligned} \tag{9}$$

where

$$\begin{Bmatrix} q_0 \\ q_1 \\ q_2 \\ q_3 \end{Bmatrix} = \iint \rho \begin{Bmatrix} \xi^2 \\ \xi r \sin(\theta) \\ z^2 \\ 1 \end{Bmatrix} dA \tag{10}$$

According to the nonlocal theory, the stress tensors are impacted by the small-scale parameters in the following

Table 1 The mechanical properties of Poly (methyl methacrylate) as the isotropic matrix and carbon nanotube (Ke *et al.* 2010, Civalek *et al.* 2021)

	Matrix	Nanotube
Elastic modulus (GPa)	2.5	600
Poisson ratio	0.3	0.19
Density (Kg/m ³)	1190	1400

mathematical form (Hashemi *et al.* 2019, Moayedi *et al.* 2019, 2020a, b, Oyarhossein *et al.* 2020, Shariati *et al.* 2020b):

$$C: \varepsilon_{ij} = (1 - (ea)^2 \nabla^2) \sigma_{ij} \quad (11)$$

According to the Hamilton principle in the following form (Ebrahimi *et al.* 2019b, c, 2020b, Mohammadgholiha *et al.* 2019, Mohammadi *et al.* 2019, Habibi *et al.* 2020, Shariati *et al.* 2020a, Shokrgozar *et al.* 2020):

$$C: \varepsilon_{ij} = (1 - (ea)^2 \nabla^2) \sigma_{ij} \quad (12)$$

And using the virtual potential energy, Kinetic energy, the energy of external loading, and also based on the nonlocal theory, the following nonlocal governing equations and related boundary conditions are obtained (Habibi *et al.* 2017, 2019c, Safarpour *et al.* 2018, 2020, Ghazanfari *et al.* 2020).

Governing equations:

$$\begin{aligned} \delta(\psi): \\ \left(1 - \frac{(ea)^2 \partial^2}{\partial x^2}\right) [q_0(\ddot{w}_x + \ddot{\psi}) - q_1 \ddot{w}_x] = \\ Q_3(w_{xxx} + \psi_{xx}) - Q_5 w_{xxx} - Q_2(w_x + \psi) \end{aligned} \quad (13a)$$

$$\begin{aligned} \delta(u): \\ Q_1 u_{xx} = \left(1 - (ea)^2 \frac{\partial^2}{\partial x^2}\right) q_3 \ddot{u} \end{aligned} \quad (13b)$$

$$\begin{aligned} \delta(w): \\ Q_3(w_{xxxx} + \psi_{xxx}) + Q_4 w_{xxxx} - Q_2(w_{xx} + \psi_x) \\ - Q_5(w_{xxx} + \psi_{xx}) + \left(1 - (ea)^2 \frac{\partial^2}{\partial x^2}\right) L^D \\ = \left(1 - \frac{(ea)^2 \partial^2}{\partial x^2}\right) [(q_0 - q_1)(\ddot{w}_{xx} + \ddot{\psi}_x)] \\ + \left(1 - \frac{(ea)^2 \partial^2}{\partial x^2}\right) [(q_2 - q_1)\ddot{w}_{xx}] \\ - \left(1 - \frac{(ea)^2 \partial^2}{\partial x^2}\right) (q_3 \ddot{w}) - Q_5 w_{xxxx} \end{aligned} \quad (13c)$$

Boundary conditions:

$$\begin{aligned} \delta(\psi): \\ -(ea)^2 q_0(\ddot{w}_{xx} + \ddot{\psi}_x) + (ea)^2 q \ddot{w}_{xx1} \\ + (Q_3 - Q_5)w_{xx} + Q_3 \psi_x = 0 \end{aligned} \quad (13d)$$

$$\begin{aligned} \delta(u): \\ Q_1 w_x - (ea)^2 q_3 \ddot{u}_x = 0 \end{aligned} \quad (13e)$$

$$\begin{aligned} \delta(w_x): \\ (Q_3 - Q_5)(w_{xx} + \psi_x) + (Q_4 - Q_5)w_{xx} \end{aligned} \quad (13f)$$

$$\begin{aligned} + (ea)^2 q_3 \ddot{w} - (ea)^2 (q_0 - q_1)(\ddot{w}_{xx} + \ddot{\psi}_x) \\ + (ea)^2 (q_1 - q_2) \ddot{w}_{xx} = 0 \end{aligned}$$

$$\begin{aligned} \delta(w): \\ (ea)^2 (q_1 - q_0)(\ddot{w}_{xxx} + \ddot{\psi}_{xx}) + (ea)^2 q_3 \ddot{w}_x \\ + (Q_5 - Q_3)(w_{xx} + \psi_x) + (Q_5 - Q_4)w_{xxx} \\ + (ea)^2 (q_1 - q_2) \ddot{w}_{xxx} + Q_2(w_x + \psi) = 0 \end{aligned} \quad (13g)$$

where

$$L^D = \tau \times \zeta \sin\left(\frac{n\pi}{L} x\right) \sin(\omega t) \quad (14)$$

3. Methodology and solving method

In this section, the obtained governing equations will be solved in two-step, first, the natural frequency based on the eigenvalue problem will be solved, and then the time-dependent results according to the Newmark beta technique will be solved (Habibi *et al.* 2019a, Safarpour *et al.* 2019b, Alipour *et al.* 2020, Ebrahimi *et al.* 2020a, Chen *et al.* 2022). The Newmark-beta technique is a numerical integration method used to solve differential equations (Habibi *et al.* 2018a, 2019b, d, e, Pourjabari *et al.* 2019, Safarpour *et al.* 2019a). It is commonly used in the numerical study of the dynamic response of structures and solids, such as finite element analysis, to represent dynamic systems (Habibi *et al.* 2016, 2018b, Ebrahimi *et al.* 2019a, Esmailpoor Hajilak *et al.* 2019). The following assumptions are necessary to calculate the natural frequency according to the generalized differential quadrature method (GDQM) (Sobhani 2022a, b).

$$\psi = \bar{\psi} e^{i\omega t} \quad (15a)$$

$$w = \bar{w} e^{i\omega t} \quad (15b)$$

$$u = \bar{u} e^{i\omega t} \quad (15c)$$

In which ‘ ω ’ is the natural frequency. The generalized differential quadrature technique will select a limited number of grid points to discretize the problem and solve it numerically (Hou *et al.* 2021, Huang *et al.* 2021a, Xu *et al.* 2021, Wang *et al.* 2022b). Based on this method, the different order of weighting coefficients ($D^{(g)}$) is presented in the following format (Huang *et al.* 2021b, Liu *et al.* 2021, Ma *et al.* 2021, Yu *et al.* 2022).

$$D_{ji}^{(g)} g^{-1} = D_{ij}^{(g-1)} (x_j - x_i)^{-1} - D_{ij}^{(1)} D_{ij}^{(g-1)} \quad (16)$$

where ‘ g ’ is the order, and first order of weighting coefficient ($D_{ij}^{(1)}$) is defined as follow (Jiao *et al.* 2021, Moradi *et al.* 2021, Zhao *et al.* 2021):

$$D_{ji}^{(1)} = \frac{\prod_{j=1, j \neq i}^n (x_i - x_j)}{\prod_{i=1, i \neq j}^n (x_j - x_i)} (x_i - x_j)^{-1} \quad (17)$$

Here ‘ x_i ’ are the grid points and defined according to the Chebyshev-Gauss-Lobatto approach according to the following mathematical relation (Shafiei and She 2018, Shafiei *et al.* 2019, 2020)

$$x_i = \frac{1}{2}L - \frac{1}{2}L \cos\left(\pi \frac{i-1}{\vartheta-1}\right) \quad (18)$$

where ‘ ϑ ’ is the number of grid points along the structure length (Ebrahimi and Shafiei 2017, Ghadiri *et al.* 2017e, Mirjavadi *et al.* 2017a, Shafiei and Kazemi 2017a, Shafiei *et al.* 2017d, Azimi *et al.* 2018). Now, the eigenvalue problem of GDQM will be obtained by substituting the obtained weighting coefficient (Eq. (15)) and initial assumption (Eq. (16)) into the nonlocal governing equation in the following form (Ehyaei *et al.* 2017, Ghadiri *et al.* 2017c, d, Mirjavadi *et al.* 2017d, Shafiei and Kazemi 2017b, Shafiei *et al.* 2017c):

$$\{[M] - [M]\omega^2\} \begin{Bmatrix} \bar{w} \\ \bar{u} \\ \bar{\psi} \end{Bmatrix} = \begin{Bmatrix} L^D - (ea)^2 L^D \\ 0 \\ 0 \end{Bmatrix} \quad (19)$$

where (Ghadiri *et al.* 2017a, b, Mirjavadi *et al.* 2017b, c, Shafiei *et al.* 2017a, b)

$$[K] = \begin{bmatrix} K_{11} & 0 & K_{13} \\ 0 & K_{22} & 0 \\ K_{31} & 0 & K_{33} \end{bmatrix} \quad (20a)$$

$$[M] = \begin{bmatrix} M_{11} & 0 & M_{13} \\ 0 & M_{22} & 0 \\ M_{31} & 0 & M_{33} \end{bmatrix} \quad (20b)$$

where mass matrices are (Ebrahimi and Shafiei 2016, Shafiei *et al.* 2016d, c, f, Ebrahimi *et al.* 2017, Shivanian *et al.* 2017):

$$M_{11} = -(ea)^2(q_2 + q_0 - 2q_1) \sum_{j=1}^{\vartheta} D_{ij}^{(4)} - q_3 + (q_2 + q_0 - 2q_1) \sum_{j=1}^{\vartheta} D_{ij}^{(2)} + (ea)^2 q_3 \sum_{j=1}^{\vartheta} D_{ij}^{(2)} \quad (21a)$$

$$M_{13} = (q_0 - q_1) \sum_{j=1}^{\vartheta} D_{ij}^{(1)} - (ea)^2(q_0 - q_1) \sum_{j=1}^{\vartheta} D_{ij}^{(3)} \quad (21b)$$

$$M_{22} = q_3 - (ea)^2 q_3 \sum_{j=1}^{\vartheta} D_{ij}^{(2)} \quad (21c)$$

$$M_{31} = (ea)^2 q_1 \sum_{j=1}^{\vartheta} D_{ij}^{(3)} - q_1 \sum_{j=1}^{\vartheta} D_{ij}^{(1)} + q_0 \sum_{j=1}^{\vartheta} D_{ij}^{(1)} - (ea)^2 q_0 \sum_{j=1}^{\vartheta} D_{ij}^{(3)} \quad (21d)$$

$$M_{33} = q_0 - (ea)^2 q_0 \sum_{j=1}^{\vartheta} D_{ij}^{(2)} \quad (21e)$$

Also, stiffening matrices are (Azimi *et al.* 2016, Ghadiri and Shafiei 2016a, c, Shafiei *et al.* 2016a, e, g):

$$K_{11} = (Q_3 + Q_4 - 2Q_5) \sum_{j=1}^{\vartheta} D_{ij}^{(4)} - Q_2 \sum_{j=1}^{\vartheta} D_{ij}^{(2)} \quad (22a)$$

$$K_{13} = (Q_3 - Q_5) \sum_{j=1}^{\vartheta} D_{ij}^{(3)} - Q_2 \sum_{j=1}^{\vartheta} D_{ij}^{(1)} \quad (22b)$$

$$K_{22} = Q_1 \sum_{j=1}^{\vartheta} D_{ij}^{(2)} \quad (22c)$$

$$K_{31} = (Q_3 - Q_5) \sum_{j=1}^{\vartheta} D_{ij}^{(3)} - Q_2 \sum_{j=1}^{\vartheta} D_{ij}^{(1)} \quad (22d)$$

$$K_{33} = Q_3 \sum_{j=1}^{\vartheta} D_{ij}^{(2)} - Q_2 \quad (22e)$$

Finally, using the natural frequency obtained by the eigenvalue problem by GDQM, the time-dependent response based on the Newmark beta technique will be calculated (Ghadiri *et al.* 2016a, b, c, d, Shafiei *et al.* 2016b).

4. Discussion on computed results

The presentation of time-dependent numerical results is the primary purpose in this section for the dynamic response of functionally graded reinforced carbon nanocomposite structure. Nevertheless, before the examination of obtained results, validation is necessary.

Before presenting numerical results and discussing them, it is necessary to validate the obtained results and generated governing equation. The validation has been done in Table 2. Comparing the presented results with others shows the excellent accuracy regarding the different volume fractions of the carbon nanotube phase.

Regarding the Table 3, growth in small-scale parameters causes a decrease in frequency values related to all cases. Moreover, by increasing the volume fraction of a nanocomposite in a specific (ea) value, a lower fundamental free frequency obtains. Furthermore, hard wood and plastic, assign the highest and lowest fundamental free frequency figures, respectively.

As demonstrated in Fig. 2, the maximum dynamic deflection value of wood occurs in a higher resonant frequency compared to that of composite materials. Moreover, regarding lower values of volume fraction, dynamic deflection gets its maximum values in lower resonant frequencies. It is worth mentioning that the dynamic deflection distribution pattern is more similar for composite materials associated with $V_{\text{cnt}}=0.12$ and $V_{\text{cnt}}=0.17$.

According to Fig. 3, in general, by increasing the external frequency (ω), dynamic deflection values associated with all types of material fluctuate in a wider range and also a shorter period. Moreover, the distribution pattern of dynamic deflection is more similar for composite materials, especially in $V_{\text{cnt}}=0.12$ and $V_{\text{cnt}}=0.17$, compared to that of wood in which the pattern gets a considerable difference in higher frequency amounts.

Table 2 Validation of dimensionless frequency ($\omega \sqrt{Q_{1(mat)}/q_{3(mat)}} L$) compared to presented study of Civalek *et al.* (2021) for different beam theories, L/R=15

Beam theory	Dimensionless frequency
Timoshenko beam theory, $V_{cnt}=0.12$, (Civalek <i>et al.</i> 2021)	1.0379
Sinusoidal beam theory, $V_{cnt}=0.12$, (Civalek <i>et al.</i> 2021)	1.1612
Present Hyperbolic beam theory, $V_{cnt}=0.12$	1.16119998
Timoshenko beam theory, $V_{cnt}=0.17$, (Civalek <i>et al.</i> 2021)	1.1977
Sinusoidal beam theory, $V_{cnt}=0.17$, (Civalek <i>et al.</i> 2021)	1.1987
Present Hyperbolic beam theory, $V_{cnt}=0.17$	1.19848833
Timoshenko beam theory, $V_{cnt}=0.28$, (Civalek <i>et al.</i> 2021)	1.4348
Sinusoidal beam theory, $V_{cnt}=0.28$, (Civalek <i>et al.</i> 2021)	1.4367
Present Hyperbolic beam theory, $V_{cnt}=0.28$	1.43636638

Table 3 Effect of the small-scale parameter (ea) along with the carbon nanotube volume fraction (V_{cnt}) on the fundamental free frequency ($\omega \sqrt{Q_{1(mat)}/q_{3(mat)}} L$) of FG composite nanowire structure, L/R=15

	Nanocomposite, $V_{cnt}=0.12$	Nanocomposite, $V_{cnt}=0.17$	Nanocomposite, $V_{cnt}=0.28$	Hard Wood (Alder, red)* E=9.5GPa, $\rho=410\text{Kg/m}^3$	Plastic (Thermoset Polyurethane)**, E=0.248GPa, $\rho=1500\text{Kg/m}^3$
$(ea)^2/L=0.0$	1.1596964	1.1969294	1.4344566	1.90420323	0.160851
$(ea)^2/L=0.5$	1.1468878	1.1836518	1.4181911	1.892564725	0.1598678
$(ea)^2/L=1.0$	1.1107902	1.1462323	1.372287	1.858889282	0.1570232
$(ea)^2/L=1.5$	1.0573462	1.090836	1.304224	1.806549261	0.152602
$(ea)^2/L=2.0$	0.9937808	1.0249656	1.2232661	1.740183736	0.146996
$(ea)^2/L=2.5$	0.9265022	0.9552782	1.1377434	1.664711033	0.1406207
$(ea)^2/L=3.0$	0.8600972	0.8865357	1.053633	1.584564135	0.1338505
$(ea)^2/L=3.5$	0.7973046	0.8215743	0.9744575	1.503286097	0.1269849
$(ea)^2/L=4.0$	0.7394502	0.7617604	0.9018604	1.423439955	0.1202401
$(ea)^2/L=4.5$	0.6869474	0.7075122	0.8362871	1.346711572	0.1137588
$(ea)^2/L=5.0$	0.6396897	0.6587102	0.7775196	1.274092097	0.1076245

*Hard Wood (Alder, red), E=9.5GPa, $\rho=410\text{Kg/m}^3$.

** Plastic (Thermoset Polyurethane), E=0.248GPa, $\rho=1500\text{Kg/m}^3$.

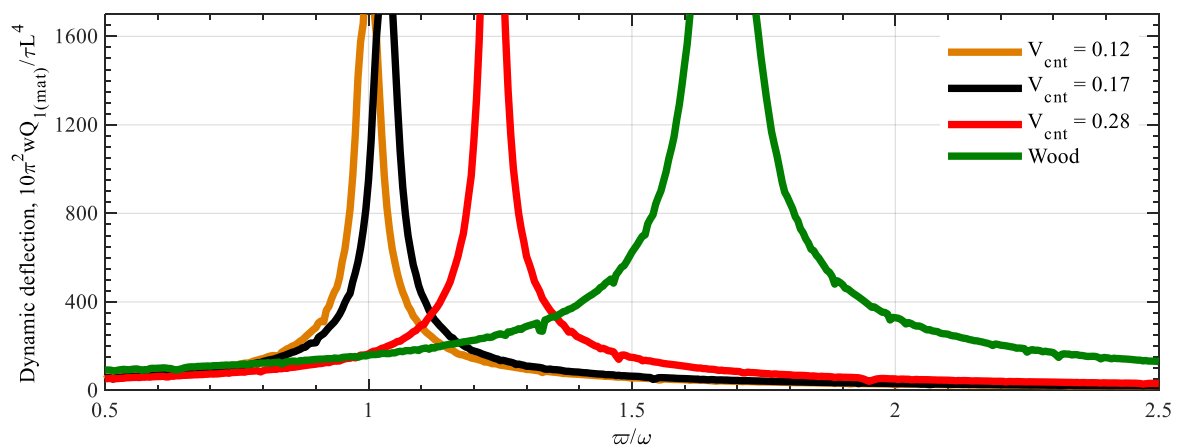


Fig. 2 Impact of volume fraction of carbon nanotube (V_{cnt}) on the resonant frequency ($\omega=\omega$) and maximum deflection of nanocomposite wire structures versus various excitation frequencies (ω) of the external harmonic load, $(ea)^2=L$, L=15R

Concerning the higher external frequency ($W=0.95w$), the maximum and minimum dynamic deflection amounts are related to wood material, except in the approximate time

range of 55 to 75 which the fluctuations are damped and get lower values of dynamic deflection compared to composite materials.

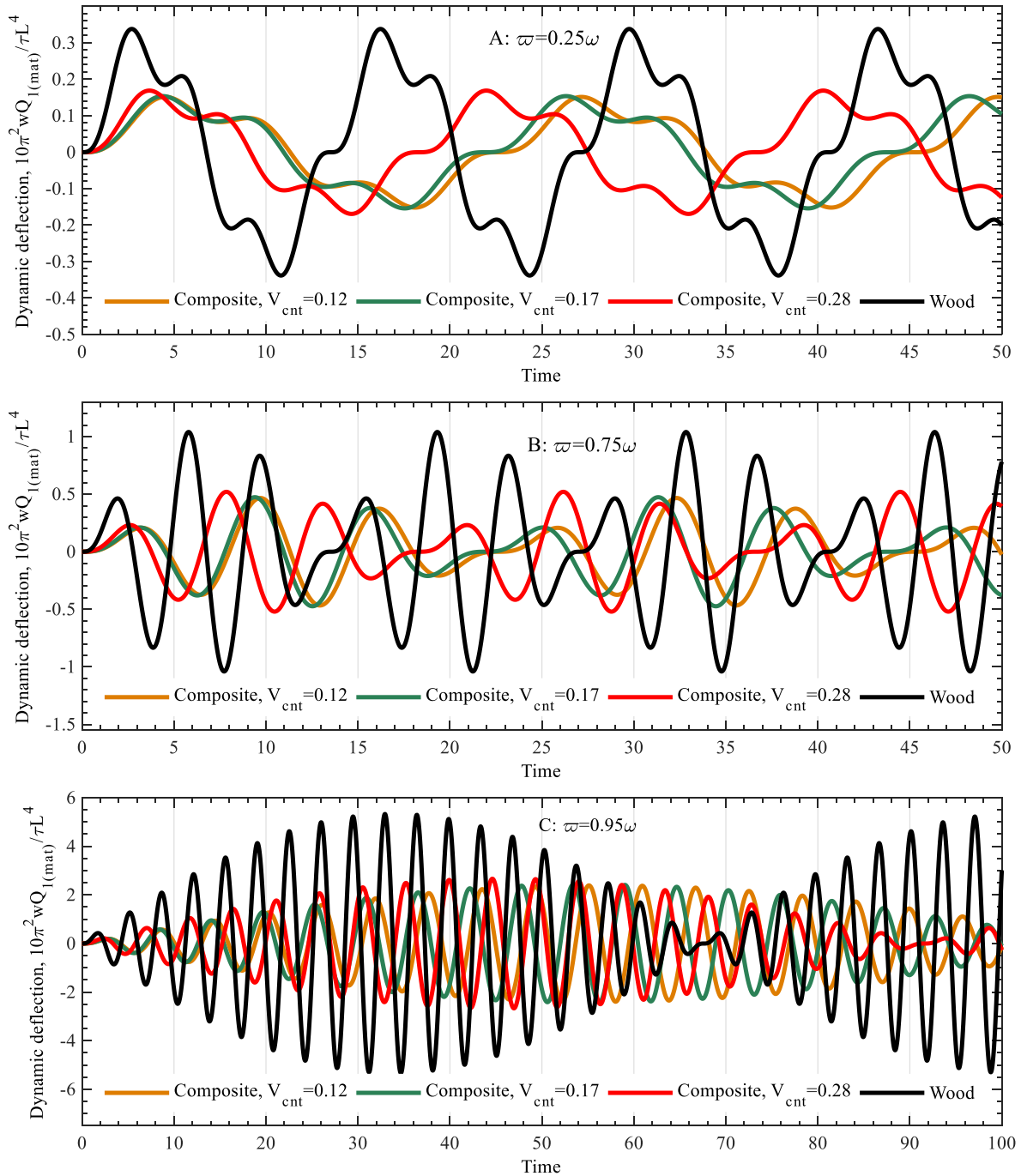


Fig. 3 Influence of material used for sports equipment involving the different nanocomposite structures ($V_{cnt}=0.12, 0.17, 0.28$) along with the wood versus the different excitation external frequency (ϖ) of harmonic load on the dimensionless dynamic deflection (w) nanowire, $L=15R, (ea)^2=L$

As it can be clearly seen in Fig. 4, in general, by moving forward through the time frame the fluctuation of the dynamic deflection pattern becomes more varied. Additionally, there is a similar range of dynamic deflection changes related to various small-scale parameters. Regarding the higher fractions of carbon nanotube, more fluctuations occur in a specific time period. It can be noted that the dynamic deflection associated with the lower ea values compared to higher ones is more oscillated. This fact is valid for various volume fraction amount.

5. Conclusions

This study explored the impact of carbon nanotubes on the properties of different composite field sports equipment components. The test specimens were fabricated using the compression molding technique. The insertion of carbon nanotubes led to an increase in mechanical properties, which was related to the process parameters to account for an improvement in the stick sections' overall performance. The dynamic response of functionally graded reinforced

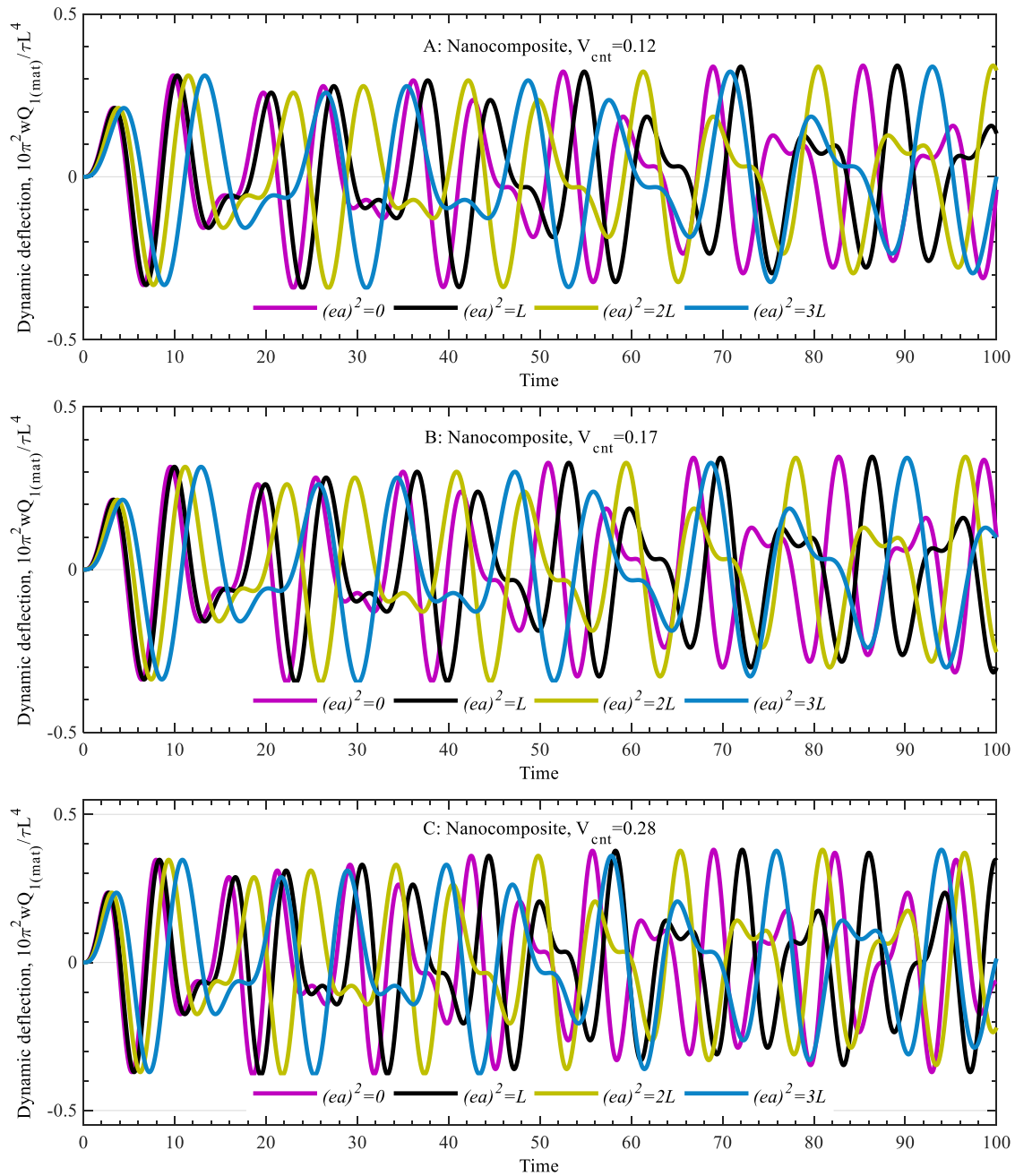


Fig. 4 Effect of the small-scale parameter (ea) as well as material production of sports equipment involving the different nanocomposite structures as well as wood structure on the dynamic deflection (w) of nanowire, $L=15R$, $\varpi=0.65\omega$

nanocomposite wire structure was examined in this paper on the bases of high-order hyperbolic beam theory lined to the size-dependent nonclassical nonlocal theory under the external mechanical load due to the physical activities. Finally, the impact of different parameters on the stability of nanocomposite structures was discussed in detail. All in all,

- By increasing the volume fraction of a nanocomposite in a specific (ea) value, a lower fundamental free frequency was obtained.
- Hard wood and plastic materials, assigned the highest and lowest fundamental free frequency figures, respectively.
- By increasing the external frequency (ϖ), dynamic

deflection values associated with all types of material fluctuated in a wider range and also a shorter period.

- The distribution pattern of dynamic deflection versus time was more similar for composites with lower fraction V_{cnt} values compared to wood.
- A wider range of fluctuation in dynamic deflection values was observed for wood material.
- The maximum dynamic deflection value of wood occurred in a higher resonant frequency compared to that of composite materials.
- The dynamic deflection distribution pattern was more similar for composite materials associated with $V_{cnt}=0.12$

and $V_{\text{cnt}}=0.17$.

- Regarding the higher fractions of carbon nanotube, more fluctuations occurred in a specific time period.

- The dynamic deflection associated with the lower e_a values compared to higher ones was more oscillated.

It should be mentioned that the nanocomposites have low cost than wood, and while the product of wood is timely, however, the dynamic stability of wood is better than nanocomposites, and the nanocomposites can produce specific aims. In addition, better stability can save the athlete from injury to poor equipment because some damages are due to the low quality of sports equipment.

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