Structural Engineering and Mechanics, *Vol. 67, No. 3 (2018) 311-316*
DOI: https://doi.org/10.12989/sem.2018.67.3.311

Numerical study for vibration response of concrete beams reinforced by nanoparticles

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(Received April 16, 2018, Revised May 27, 2018, Accepted May 28, 2018)

Abstract. Vibration of concrete beams reinforced by agglomerated silicon dioxide (SiO_2) nanoparticles is studied based on numerical methods. The structure is simulated by Euler-Bernoulli beam model and the Mori-Tanaka model is used for obtaining the effective material properties of the structure. The concrete beam is located in soil medium which is modeled by spring elements. The motion equations are derived based on energy method and Hamilton's principle. Based on exact solution, the frequency of the structure is calculated. The effects of different parameters such as volume percent of SiO_2 nanoparticles and agglomeration, soil medium and geometrical parameters of beam are shown on the frequency of system. The results show that with increasing the volume percent of SiO_2 nanoparticles, the frequency increases.

Keywords: vibration; SiO_2 nanoparticles; soil medium; concrete beam; exact solution

1. Introduction

Concrete can be nano-engineered by incorporating nano-sized building blocks or objects (e.g., nanoparticles and nanotubes) to control material behaviour and add novel properties, or by grafting molecules onto cement particles, cement phases, aggregates, and additives (including nano-sized additives) to provide surface functionality, which can be adjusted to promote specific interfacial interactions. The nanoparticle is the elementary building block in nanotechnology and is comprised of up to thousands of atoms combined into a cluster of 1-100 nm.

Mechanical analysis of nanostructures has been reported by many researchers (Zemri 2015, Larbi Chaht 2015, Belkorissat 2015, Ahouel 2016, Bounouara 2016). For the nanocomposite structures, Wuite and Adali (2005) performed a stress-strain analysis of reinforced carbon nanotubes. They concluded that the presence of carbon nanotubes as a booster phase can increase the stability and rigidity of the system. Matsuna (2007) examined the stability of composite cylindrical shells with the help of third-order shear theory. Formica (2010) studied the vibrations of reinforced carbon nanotubes sheets and used the Mori-Tanaka model to match the composite-equivalent properties. Liew *et al.* (2014) analyzed buckling nanocomposite layers. In this study, the mixing rule was used to obtain the equivalent properties of nanocomposites. A non-mesh method was also used to analyze and calculate the buckling load of a nanosized composite structure. In another similar work, Lei *et al.* (2014) analyzed the dynamic stability of panels reinforced with carbon nanotubes. They used the Mori-Tanaka model to simulate nanocomposite properties and obtained the system instability with the help of Ritz's method. The buckling analysis of polymer plates reinforced with carbon nanotubes was carried out by Kolahchi *et al.* (2013). In this work, the mixing rule was used to compute the equivalent properties of the composite. They used the square difference method to obtain the buckling load of the structure. In another work by Kolahchi *et al.* (2016), the dynamic buckling of reinforced carbon nanotube plates was investigated in a functionalized form. The plate properties were considered as temperature dependent and the elastic environment surrounding the structure was simulated using the orthotropic Pasternak model.

In the field of mathematical modeling of concrete structures, very limited work has been done. Le *et al.* (2016) presented the experiment results for three large-scale concrete composite beams with a newly puzzle shape of crestbond. The RC specimens were produced by Saribiyik and Caglar (2016) taking into consideration the RC beams with insufficient shear and tensile reinforcement having been manufactured with the use of concrete with low strength. As a buckling example, reinforced concrete columns reinforced with carbon nanoparticles polymerized by Zamanian *et al.* (2017) along with Safari Bilouei *et al.* (2017). Jafarian Arani *et al.* (2016) studied buckling of reinforced concrete columns with carbon nanotubes, concluding that an increase in the volume of nanotubes resulted in increased buckling load. Analysis of the stresses of concrete pipes reinforced with iron oxide nanoparticles reinforced by iron oxide nanoparticles by Heidarzadeh *et al.* (2017). Arbabi *et al.* (2017) analyzed the buckling of reinforced concrete beams reinforced with zinc oxide nanoparticles under the electric field.

In this paper, vibration of concrete beam reinforced by SiO_2 nanoparticles is presented. The Euler-Bernoulli beam model is used for mathematical modeling. The structure is located in soil medium which is simulated by spring

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 ISSN: 1225-4568 (Print), 1598-6217 (Online)

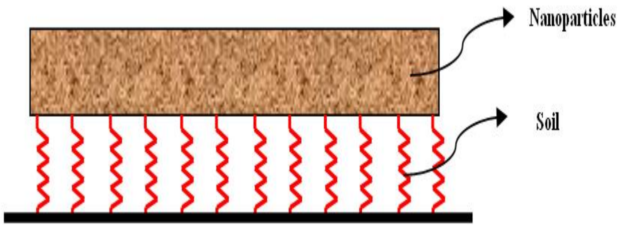

Fig. 1 Schematic of concrete beam reinforced with agglomerated SiO_2 nanoparticles

element. Based on exacts solution, the frequency of the structure is calculated. The effects of different parameters such as volume percent of SiO_2 nanoparticles, SiO_2 agglomeration, geometrical parameters and soil foundation on the frequency of concrete beam are shown.

2. Mathematical modelling

In Fig. 1, a concrete beam reinforced by agglomerated SiO_2 nanoparticles is shown. The structure is located in soil medium with spring elements.

There are many new theories for modeling of different structures. Some of the new theories have been used by Tounsi and co-authors (Bessaim 2013, Bouderba 2013, BelAbed 2014, Ait Amar Meziane 2014, Zidi 2014, Hamidi 2015, Bourada 2015, Bousahla *et al*. 2016a, b, Beldjelili 2016, Boukhari 2016, Draiche 2016, Bellifa 2015, Attia 2015, Mahi 2015, Ait Yahia 2015, Bennoun 2016, El-Haina 2017, Menasria 2017, Chikh 2017). Based on the Euler-Bernoulli beam model, the displacement field of structure can be written as (Brush and Almorth 1975)

$$\begin{aligned} u_1(x,z) &= U(x) - z\frac{\partial W(x)}{\partial x}, \\ u_2(x,z) &= 0, \\ u_3(x,z) &= W(x), \end{aligned} \tag{1}$$

where $U(x)$ and $W(x)$ are displacement components in the mid-plane. The strain-displacement relation can be written as

$$\varepsilon_x = \left(\frac{\partial U}{\partial x}\right) - z\left(\frac{\partial^2 W}{\partial x^2}\right). \tag{2}$$

Based on Hook's low, the stress-strain equation is

$$\sigma_{xx} = C_{11}\varepsilon_x, \tag{3}$$

where C_{11} is elastic constant which can be calculated by Mori-Tanaka model as

$$E = \frac{9KG}{3K+G}\quad , \tag{4}$$

$$\upsilon = \frac{3K-2G}{6K+2G}. \tag{5}$$

where the effective bulk modulus (K) and effective shear modulus (G) may be expressed as

$$K = K_{out}\left[1 + \frac{\xi\left(\frac{K_{in}}{K_{out}} - 1\right)}{1 + \alpha(1-\xi)\left(\frac{K_{in}}{K_{out}} - 1\right)}\right], \tag{6}$$

$$G = G_{out}\left[1 + \frac{\xi\left(\frac{G_{in}}{G_{out}} - 1\right)}{1 + \beta(1-\xi)\left(\frac{G_{in}}{G_{out}} - 1\right)}\right], \tag{7}$$

where

$$K_{in} = K_m + \frac{(\delta_r - 3K_m\chi_r)C_r\zeta}{3(\xi - C_r\zeta + C_r\zeta\chi_r)}, \tag{8}$$

$$K_{out} = K_m + \frac{C_r(\delta_r - 3K_m\chi_r)(1-\zeta)}{3[1-\xi - C_r(1-\zeta) + C_r\chi_r(1-\zeta)]}, \tag{9}$$

$$G_{in} = G_m + \frac{(\eta_r - 3G_m\beta_r)C_r\zeta}{2(\xi - C_r\zeta + C_r\zeta\beta_r)}, \tag{10}$$

$$G_{out} = G_m + \frac{C_r(\eta_r - 3G_m\beta_r)(1-\zeta)}{2[1-\xi - C_r(1-\zeta) + C_r\beta_r(1-\zeta)]}, \tag{11}$$

where two parameters ξ and ζ describe the agglomeration of nanoparticles and C_r is relates to the SiO_2 volume fraction. In addition, χ_r, β_r, δ_r, η_r may be calculated as

$$\chi_r = \frac{3(K_m + G_m) + k_r - l_r}{3(k_r + G_m)}, \tag{12}$$

$$\beta_r = \frac{1}{5}\left\{\begin{aligned} &\frac{4G_m + 2k_r + l_r}{3(k_r + G_m)} + \frac{4G_m}{(p_r + G_m)} \\ &+ \frac{2[G_m(3K_m + G_m) + G_m(3K_m + 7G_m)]}{G_m(3K_m + G_m) + m_r(3K_m + 7G_m)} \end{aligned}\right\}, \tag{13}$$

$$\delta_r = \frac{1}{3}\left[n_r + 2l_r + \frac{(2k_r - l_r)(3K_m + 2G_m - l_r)}{k_r + G_m}\right], \tag{14}$$

$$\eta_r = \frac{1}{5}\left[\begin{aligned} &\frac{2}{3}(n_r - l_r) + \frac{4G_m p_r}{(p_r + G_m)} \\ &+ \frac{8G_m m_r(3K_m + 4G_m)}{3K_m(m_r + G_m) + G_m(7m_r + G_m)} \\ &+ \frac{2(k_r - l_r)(2G_m + l_r)}{3(k_r + G_m)} \end{aligned}\right]. \tag{15}$$

where k_r, l_r, n_r, p_r, m_r are the Hills elastic modulus for the nanoparticles (Mori and Tanaka 1973); K_m and G_m are the bulk and shear moduli of the matrix which can be written as

$$K_m = \frac{E_m}{3(1-2\upsilon_m)} \quad , \tag{16}$$

$$G_m = \frac{E_m}{2(1+\upsilon_m)}. \tag{17}$$

where E_m and υ_m are Young's modulus and the Poisson's ratio of concrete beam, respectively. Furthermore, β, α can be obtained from

$$\alpha = \frac{(1+\upsilon_{out})}{3(1-\upsilon_{out})}, \tag{18}$$

$$\beta = \frac{2(4-5\upsilon_{out})}{15(1-\upsilon_{out})}, \tag{19}$$

$$\upsilon_{out} = \frac{3K_{out}-2G_{out}}{6K_{out}+2G_{out}}. \tag{20}$$

The strain energy of the nanocomposite concrete beam can be expressed as

$$U = \frac{1}{2}\int_0^L \int_A (\sigma_{xx}\varepsilon_{xx})\, dAdx \tag{21}$$

Submitting Eqs. (2) and (3) into (21) yields

$$U = \frac{1}{2}\int_0^L \left\{ N_x \frac{\partial U}{\partial x} - M_x \frac{\partial^2 W}{\partial x^2} \right\} dx \tag{22}$$

where the resultant force (N_x) and bending moment M_x, are defined as

$$N_x = \int_A \sigma_{xx}\, dA, \tag{23}$$

$$M_x = \int_A \sigma_{xx} z\, dA, \tag{24}$$

The kinetic energy of the structure can be written as

$$K = \frac{\rho}{2}\int_0^L \int_A \left[(\dot{u}_1)^2 + (\dot{u}_2)^2 + (\dot{u}_3)^2 \right] dV\,, \tag{25}$$

The external work due to the soil foundation can be expressed as

$$W = \int_0^L (-k_w w) w dx\,, \tag{26}$$

where k_w is spring constant of soil foundation. Using Hamilton's principle as follows

$$\int_0^t (\delta U - \delta K - \delta W)\, dt = 0. \tag{27}$$

The motion equations of the structure can be derived as follows

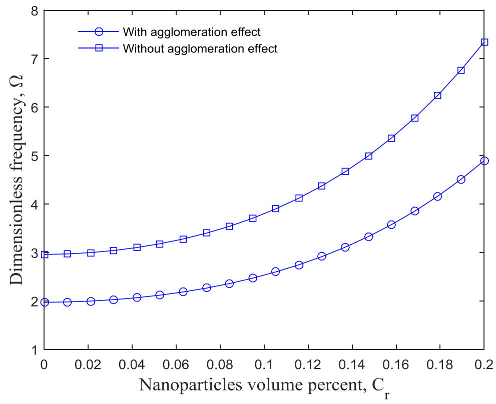

Fig. 2 The effect of nanoparticles agglomeration on the frequency of the concrete beam

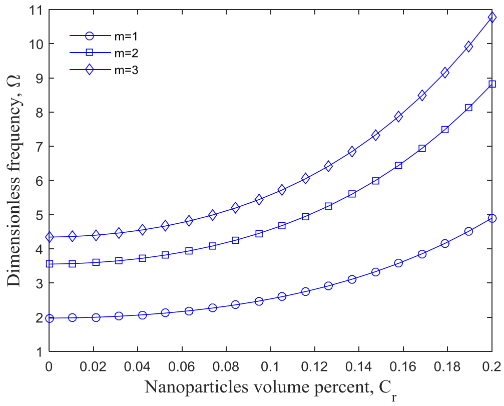

Fig. 3 The effect of mode numbers on the frequency of the concrete beam

$$\delta U : \frac{\partial N_x}{\partial x} = 0, \tag{28}$$

$$\delta W : \frac{\partial^2 M_x}{\partial x^2} - \frac{\partial}{\partial x}\left(N_x^M \frac{\partial W}{\partial x} \right) + q = 0. \tag{29}$$

3. Exact solution

Considering the simply supported boundary condition, we have

$$u(x,t) = u_0 \cos\left(\frac{m\pi x}{L} \right) e^{i\omega t}, \tag{30}$$

$$w(x,t) = w_0 \sin\left(\frac{m\pi x}{L} \right) e^{i\omega t}, \tag{31}$$

where m is the mode number and ω is the frequency of the structure. Using above relations, the motion equations can be written as

$$\left\{ [K] - \omega^2 [M] \right\} [d] = [0], \tag{32}$$

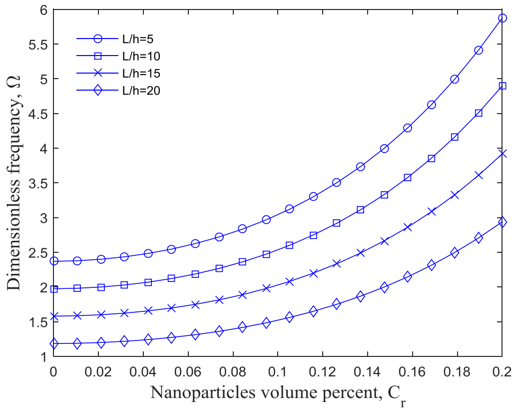

Fig. 4 The effect of length to thickness ratio on the frequency of the concrete beam

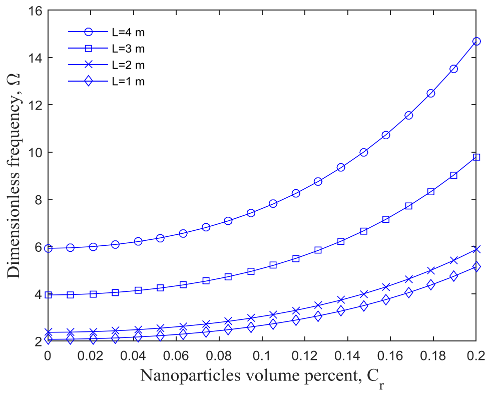

Fig. 5 The effect of length on the frequency of the concrete beam

Where $[d]=[u_0 w_0]^T$; $[K]$ is stiffness matrix and $[M]$ is the mass matrix.

4. Numerical results

In this section, a concrete beam with Yong modulus of E_m=20 *Gpa* and Poison's ratio of v_m=0.3 is considered which has length to thickness ration of *L/h*=10.

For showing the convergence of Fig. 2 shows the frequency of the concrete beam versus the SiO_2 nanoparticles volume percent for two cases of with and without agglomeration effects. It can be seen that with considering agglomeration of nanoparticles, the frequency decreases due to increase in the stiffness of the structure. In addition, with increasing the SiO_2 nanoparticles volume percent, the frequency is enhanced since the stiffness of the structure is improved.

Fig. 3 illustrates the influence of mode numbers on the frequency versus the volume percent of SiO_2 nanoparticles. As can be seen, with increasing the mode numbers, the frequency is increased.

The effects of length to thickness ratio and length of the concrete beam on the frequency versus the volume percent of SiO_2 nanoparticles are depicted in Figs. 4 and 5, respectively. It can be found that with increasing the length and length to thickness ratio of the concrete beam, the frequency is decreased. It is since with increasing the length and length to thickness ratio of the concrete beam, the stiffness decreases.

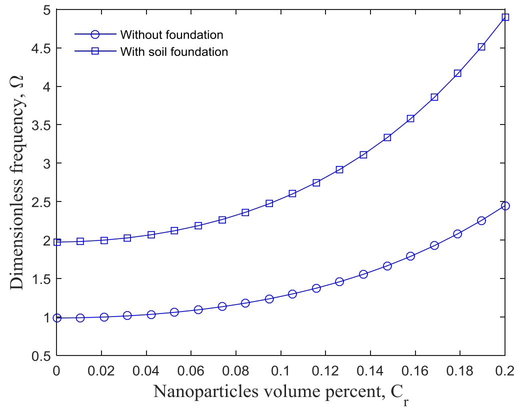

Fig. 5 The effect of soil medium on the frequency of the concrete beam

The effect of soil foundation on the frequency of the concrete beam versus the volume percent of SiO_2 nanoparticles is sown in Fig. 6. It can be seen that with considering soil medium, the frequency increases due to increase in the stiffness of the structure.

6. Conclusions

In this paper, vibration analysis of concrete beam reinforced by SiO_2 nanoparticles was presented. The structure was simulated by Euler-Bernoulli beam model and the effect of nanoparticles agglomeration was considered by Mori-Tanaka model. Using exact solution, the frequency of the structure was obtained and the effects of SiO_2 nanoparticles volume percent and agglomeration, geometrical parameters of the beam, soil medium and mode numbers were assumed. Results show that with considering agglomeration of nanoparticles, the frequency decreases due to increase in the stiffness of the structure. In addition, with increasing the SiO_2 nanoparticles volume percent, the frequency was enhanced since the stiffness of the structure was improved. It can be found that with increasing the length and length to thickness ratio of the concrete beam, the frequency was decreased. Furthermore, with considering soil medium, the frequency increases due to increase in the stiffness of the structure.

References

Ahouel, M., Houari, M.S.A., Adda Bedia, E.A. and Tounsi, A. (2016), "Size-dependent mechanical behavior of functionally graded trigonometric shear deformable nanobeams including neutral surface position concept", *Steel Compos. Struct.*, **20**(5), 963-981.

Arbabi, A., Kolahchi, R. and Rabani Bidgoli, M. (2017), "Concrete columns reinforced with zinc oxide nanoparticles subjected to electric field: Buckling analysis", *Wind Struct.*, **24**(5), 431-446.

Attia, A., Tounsi, A., Adda Bedia, E.A. and Mahmoud, S.R.

(2015), "Free vibration analysis of functionally graded plates with temperature-dependent properties using various four variable refined plate theories", *Steel Compos. Struct.*, **18**(1), 187-212.

Belabed, Z., Houari, M.S.A., Tounsi, A., Mahmoud, S.R. and Bég, O.A. (2014), "An efficient and simple higher order shear and normal deformation theory for functionally graded material (FGM) plates", *Compos.: Part B*, **60**, 274-283.

Beldjelili, Y., Tounsi, A. and Mahmoud, S.R. (2016), "Hygro-thermo-mechanical bending of S-FGM plates resting on variable elastic foundations using a four-variable trigonometric plate theory", *Smart Struct. Syst.*, **18**(4), 755-786.

Belkorissat, I., Houari, M.S.A., Tounsi, A. and Hassan, S. (2015), "On vibration properties of functionally graded nano-plate using a new nonlocal refined four variable model", *Steel Compos. Struct.*, **18**(4), 1063-1081.

Bellifa, H., Benrahou, K.H., Hadji, L., Houari, M.S.A. and Tounsi, A. (2016), "Bending and free vibration analysis of functionally graded plates using a simple shear deformation theory and the concept the neutral surface position", *J. Braz. Soc. Mech. Sci. Eng.*, **38**(1), 265-275.

Bennoun, M., Houari, M.S.A. and Tounsi, A. (2016), "A novel five variable refined plate theory for vibration analysis of functionally graded sandwich plates", *Mech. Adv. Mater. Struct.*, **23**(4), 423-431.

Bessaim, A., Houari, M.S.A. and Tounsi, A. (2013), "A new higher-order shear and normal deformation theory for the static and free vibration analysis of sandwich plates with functionally graded isotropic face sheets", *J. Sandw. Struct. Mater.*, **15**(6), 671-703.

Bouderba, B., Houari, M.S.A. and Tounsi, A. (2013), "Thermomechanical bending response of FGM thick plates resting on Winkler-Pasternak elastic foundations", *Steel Compos. Struct.*, **14**(1), 85-104.

Bouderba, B., Houari, M.S.A., Tounsi, A. and Mahmoud, S.R. (2016b), "Thermal stability of functionally graded sandwich plates using a simple shear deformation theory", *Struct. Eng. Mech.*, **58**(3), 397-422.

Boukhari, A., Atmane, H.A., Tounsi, A., Adda Bedia, E.A. and Mahmoud, S.R. (2016), "An efficient shear deformation theory for wave propagation of functionally graded material plates", *Struct. Eng. Mech.*, **57**(5), 837-859.

Bounouara, F., Benrahou, K.H., Belkorissat, I. and Tounsi, A. (2016), "A nonlocal zeroth-order shear deformation theory for free vibration of functionally graded nanoscale plates resting on elastic foundation", *Steel Compos. Struct.*, **20**(2), 227-249.

Bourada, M., Kaci, A., Houari, M.S.A. and Tounsi, A. (2015), "A new simple shear and normal deformations theory for functionally graded beams", *Steel Compos. Struct.*, **18**(2), 409-423.

Bousahla, A.A., Benyoucef, S., Tounsi, A. and Mahmoud, S.R. (2016a), "On thermal stability of plates with functionally graded coefficient of thermal expansion", *Struct. Eng. Mech.*, **60**(2), 313-335.

Brush, D.O. and Almroth, B.O. (1975), *Buckling of Bars, Plates and Shells*, McGraw-Hill, New York, U.S.A.

Chikh, A., Tounsi, A., Hebali, H. and Mahmoud, S.R. (2017), "Thermal buckling analysis of cross-ply laminated plates using a simplified HSDT", *Smart Struct. Syst.*, **19**(3), 289-297.

Draiche, K., Tounsi, A. and Mahmoud, S.R. (2016), "A refined theory with stretching effect for the flexure analysis of laminated composite plates", *Geomech. Eng.*, **11**(5), 671-690.

El-Haina, F., Bakora, A., Bousahla, A.A. and Hassan, S. (2017), "A simple analytical approach for thermal buckling of thick functionally graded sandwich plates", *Struct. Eng. Mech.*, **63**(5), 585-595.

Formica, G., Lacarbonara, W. and Alessi, R. (2010), "Vibrations of carbon nanotube reinforced composites", *J. Sound Vibr.*, **329**(10), 1875-1889.

Heidarzadeh, A., Kolahchi, R. and Rabani Bidgoli, M. (2017), "Concrete pipes reinforced with AL2O3 nanoparticles considering agglomeration: Magneto-thermo-mechanical stress analysis", *Int. J. Civil Eng.*, In Press.

Henderson, J.P., Plummer, A. and Johnston, N. (2018), "An electro-hydrostatic actuator for hybrid active-passive vibration isolation", *Int. J. Hydromechatron*, **1**(1), 47-71.

Jafarian Arani, A. and Kolahchi, R. (2016), "Buckling analysis of embedded concrete columns armed with carbon nanotubes", *Comput. Concrete*, **17**(5), 567-578.

Kolahchi, R., Rabani Bidgoli, M., Beygipoor, G. and Fakhar, M.H. (2013), "A nonlocal nonlinear analysis for buckling in embedded FG-SWCNT-reinforced microplates subjected to magnetic field", *J. Mech. Sci. Technol.*, **5**, 2342-2355.

Kolahchi, R., Safari, M. and Esmailpour, M. (2016), "Dynamic stability analysis of temperature-dependent functionally graded CNT-reinforced visco-plates resting on orthotropic elastomeric medium", *Compos. Struct.*, **150**, 255-265.

Larbi Chaht, F., Kaci, A., Houari, M.S.A. and Hassan, S. (2015), "Bending and buckling analyses of functionally graded material (FGM) size-dependent nanoscale beams including the thickness stretching effect", *Steel Compos. Struct.*, **18**(2), 425-442.

Le, V.P.N., Bui, D.V., Chu, T.H.V., Kim, I.T., Ahn, J.H. and Dao, D.K. (2016), "Behavior of steel and concrete composite beams with a newly puzzle shape of crestbond rib shear connector: an experimental study", *Struct. Eng. Mech.*, **60**(6), 1001-1019.

Lei, Z.X., Zhang, L.W., Liew, K.M. and Yu, J.L. (2014), "Dynamic stability analysis of carbon nanotube-reinforced functionally graded cylindrical panels sing the element-free kp-Ritz method", *Compos. Struct.*, **113**, 328-338.

Li, C.H., Zhang, Y., Tu, W., Jun, C., Liang, H. and Yu, H. (2017), "Soft measurement of wood defects based on LDA feature fusion and compressed sensor images", *J. Forest Res.*, **28**(6), 1285-1292

Liew, K.M., Lei, Z.X., Yu, J.L. and Zhang, L.W. (2014), "Postbuckling of carbon nanotube-reinforced functionally graded cylindrical panels under axial compression using a meshless approach", *Comput. Meth. Appl. Mech. Eng.*, **268**, 1-17.

Mahi, A., Bedia, E.A.A. and Tounsi, A. (2015), "A new hyperbolic shear deformation theory for bending and free vibration analysis of isotropic, functionally graded, sandwich and laminated composite plates", *Appl. Math. Model.*, **39**(9), 2489-2508.

Matsuna, H. (2007), "Vibration and buckling of cross-ply laminated composite circular cylindrical shells according to a global higher-order theory", *Int. J. Mech. Sci.*, **49**(9), 1060-1075.

Mehri, M., Asadi, H. and Wang, Q. (2016), "Buckling and vibration analysis of a pressurized CNT reinforced functionally graded truncated conical shell under an axial compression using HDQ method", *Comput. Meth. Appl. Mech. Eng.*, **303**, 75-100.

Menasria, A., Bouhadra, A., Tounsi, A. and Hassan, S. (2017), "A new and simple HSDT for thermal stability analysis of FG sandwich plates", *Steel Compos. Struct.*, **25**(2), 157-175.

Meziane, M.A.A., Abdelaziz, H.H. and Tounsi, A.T. (2014), "An efficient and simple refined theory for buckling and free vibration of exponentially graded sandwich plates under various boundary conditions", *J. Sandw. Struct. Mater.*, **16**(3), 293-318.

Mori, T. and Tanaka, K. (1973), "Average stress in matrix and average elastic energy of materials with misfitting inclusions", *Acta Metall. Mater.*, **21**(5), 571- 574.

Safari Bilouei, B., Kolahchi, R. and Rabani Bidgoli, M. (2017), "Buckling of concrete columns retrofitted with nano-fiber reinforced polymer (NFRP)", *Comput. Concrete*, **18**(5), 1053-1063.

Sanada, K. (2018), “Real-time implementation of Kalman filter for unsteady flow measurement in a pipe”, *Int. J. Hydromechatron*, **1**(1), 3-15.

Saribiyik, A. and Caglar, N. (2016), “Flexural strengthening of RC beams with low-strength concrete using GFRP and CFRP”, *Struct. Eng. Mech.*, **58**(5), 825-845.

Stelson, K.A. (2018), “Academic fluid power research in the USA”, *Int. J. Hydromechatron*, **1**(1), 126-152.

Wuite, J. and Adali, S. (2005), “Deflection and stress behaviour of nanocomposite reinforced beams using a multiscale analysis”, *Compos. Struct.*, **71**(3-4), 388-396.

Yang, H. and Yu, L. (2017), “Feature extraction of wood-hole defects using wavelet based ultrasonic testing”, *J. Forest Res.*, **28**(2), 395-402.

Zamanian, M., Kolahchi, R. and Rabani Bidgoli, M. (2017), “Agglomeration effects on the buckling behaviour of embedded concrete columns reinforced with SiO2 nano-particles”, *Wind Struct.*, **24**(1), 43-57.

Zemri, A., Houari, M.S.A., Bousahla, A.A. and Tounsi, A. (2015), “A mechanical response of functionally graded nanoscale beam: An assessment of a refined nonlocal shear deformation theory beam theory”, *Struct. Eng. Mech.,* **54**(4), 693-710.

Zidi, M., Tounsi, A. and Bég, O.A. (2014), “Bending analysis of FGM plates under hygro-thermo-mechanical loading using a four variable refined plate theory”, *Aerosp. Sci. Technol.*, **34**, 24-34.

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