RECENT ADVANCES AND INNOVATIONS FOR BUCKLING BEHAVIOR OF SMART BEAMS UNDER ELECTRIC FIELD

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Abstract - For improved building materials, concrete quality is now becoming more important. Among them, nanotechnology views this from a different perspective. In this paper, an experimental study is presented regarding buckling of horizontal concrete columns reinforced by ZnO nanoparticles. The applied ZnO nanoparticles have piezoelectric characteristics, and the size can give intelligent controllability based on the application of electric fields. For the column supported by vertical springs with constant shear modulus, the model is generated using exponential shear deformation theory (ESDT). The equivalent properties of the system are provided from a micro-electro-mechanical model, while equations of motion are derived based on nonlinear stress-strain relations, energy method, and Hamilton's principle. To find the buckling load, the Difference Quadrature Method (DQM) is used. In this paper, a mathematical model is proposed in order to find the buckling load and investigate the nanotechnology and electric field effects on the buckling behavior of the structures. The results show that the buckling load and stiffness of the column increase by using a negative external voltage. The buckling load of the column can also be increased by incorporating ZnO nanoparticles.

Keywords: Smart beam; Buckling; Numerical method; ZnO nanoparticles.

I. INTRODUCTION

The studies about the structural behavior have long been the backbone of civil and structural engineering when it comes to various conditions. Among these, buckling acts on beams that are under axial load and is one of the very serious factors as it may lead to catastrophic failure if not properly managed. Over the last few years, developments within material science and engineering have introduced new methods to enhance the performance and reliability of structural components. One of the most important technologies being developed and integrated today are those related to smart materials and structures, which restructured the way we do design and analysis.

In recent years, Mirza et. al (1991) were able to show that strength of a short composite steel concrete beam column is a function of variations in the strengths of concrete and steel, cross sectional dimensions of concrete and steel section, steel section and placement of reinforcing bars and the strength model itself. Tan and Tong, (2001) presented Micro-electromechanical model for calculating properties of composites. Kadoli and Ganesan, (2003) performed free vibration of composite cylindrical shell containing fluid flow. Wuite and Adali, (2005) investigated stress analysis of beams reinforced with carbon nanotubes. They concluded that the presence of carbon nanotubes as reinforcing phase can increase system stability and rigidity. Matsuna, (2007) analyzed stability of composite cylindrical shell with the help of third order shear theory. Formica (2010) considered the vibrating plate reinforced with carbon nanotubes and for modeling composite properties, the Mori-Tanaka model was used. Axial failure of RC columns damaged by shear reversals was presented by Henkhaus et. al (2013). General information about the definition of slenderness in the well-known standards and ten selected industrial reinforced concrete (RC) chimneys were given by Karaca and Türkeli (2014). Liewet al. (2014) studied the postbuckling nano composite cylindrical panels under axial compression. In the analysis of this research, the mixture low was used to receive the nanocomposite properties and meshless method applied to analyze and calculate buckling load of the nanocomposite structure. Buckling analysis of polymeric plates reinforced with carbon nanotubes was studied by Kolahchi et. al (2013). They used DQM to obtain structural buckling load. In a work by Kolahchi et. Al (2016a,b), the dynamic buckling of plates reinforced with functionally graded carbon nanotubes was investigated. In that study, temperature-dependent properties are considered and the orthotropic Pasternak model is used to simulate the elastic foundation. As far as the scientific search in the database world can reach, there is no work related to investigating the effects of ZnO nanoparticles and electric field on buckling of the concrete column.

In this regard, the recent works have focused on the fundamental understanding and exploitation of the smart material's interaction with the electric field in realizing optimum buckling behavior. So far, such progress of researches has been carried out with the development of sophisticated mathematical modeling and computational techniques that predict and control

the buckling response of the smart beams with a high degree of accuracy.The paper reports the recent advances and innovations related to the buckling behavior of smart beams under electric fields. It aims to provide a critical review of the state of research with regard to major findings, methodologies, and practical applications. In the light of the latest developments within this field, the study also aims to contribute to such continuous efforts to improve the structural performance by utilizing modern approaches and technologies.

II. FORMULATION

Fig. 1 presents a smart beam with ZnO nanoparticles which is located in elastic foundation.

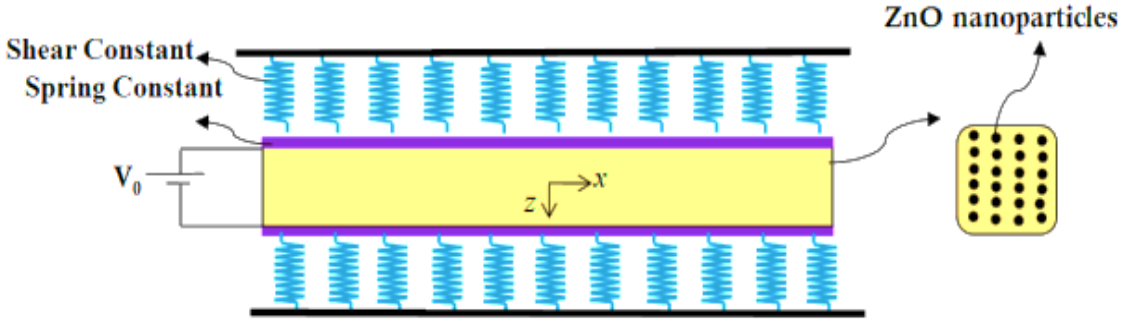

Fig. 1 Schematic of a smart beam with Zno nanoparticles

Based onESDT, the displacement fields are (Thai and Vo, 2012):

$$u_1(x,z,t) = u(x,t) - z\frac{\partial w(x,t)}{\partial x} + f\psi(x,t)\ , \tag{1}$$

$$u_2(x,z,t) = 0\ , \tag{2}$$

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

where uis the deflection; ψ is the rotationand $f = \exp\left(-\pi z / h\right).$ The nonlinear strain relations are:

$$\varepsilon_{xx} = \frac{\partial u}{\partial x} - z\frac{\partial^2 w}{\partial x^2} + \frac{1}{2}\left(\frac{\partial w}{\partial x}\right)^2 + f\frac{\partial \psi}{\partial x}, \tag{4}$$

$$\varepsilon_{xz} = \cos\left(\frac{\pi z}{h}\right)\psi. \tag{5}$$

For the smart structures, stress (σ) and the strain (ε) from the mechanical side and electricdisplacement (D) and electric field (E) from the electrostatic side can be coupled as:

$$\begin{bmatrix}\sigma_{xx}\\ \sigma_{yy}\\ \sigma_{zz}\\ \tau_{yz}\\ \tau_{xz}\\ \tau_{xy}\end{bmatrix} = \begin{bmatrix} Q_{11} & Q_{12} & Q_{13} & 0 & 0 & 0\\ Q_{12} & Q_{22} & Q_{23} & 0 & 0 & 0\\ Q_{13} & Q_{23} & Q_{33} & 0 & 0 & 0\\ 0 & 0 & 0 & Q_{44} & 0 & 0\\ 0 & 0 & 0 & 0 & Q_{55} & 0\\ 0 & 0 & 0 & 0 & 0 & Q_{66}\end{bmatrix}\begin{Bmatrix}\varepsilon_{xx}\\ \varepsilon_{yy}\\ \varepsilon_{zz}\\ \gamma_{yz}\\ \gamma_{xz}\\ \gamma_{xy}\end{Bmatrix} - \begin{bmatrix} 0 & 0 & e_{31}\\ 0 & 0 & e_{32}\\ 0 & 0 & e_{33}\\ 0 & e_{24} & 0\\ e_{15} & 0 & 0\\ 0 & 0 & 0\end{bmatrix}\begin{Bmatrix}E_x\\ E_y\\ E_z\end{Bmatrix}, \tag{6}$$

$$\begin{bmatrix}D_x\\ D_y\\ D_z\end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 & e_{15} & 0\\ 0 & 0 & 0 & e_{24} & 0 & 0\\ e_{31} & e_{32} & e_{33} & 0 & 0 & 0\end{bmatrix}\begin{Bmatrix}\varepsilon_{xx}\\ \varepsilon_{yy}\\ \varepsilon_{zz}\\ \gamma_{yz}\\ \gamma_{xz}\\ \gamma_{xy}\end{Bmatrix} + \begin{bmatrix}\in_{11} & 0 & 0\\ 0 & \in_{22} & 0\\ 0 & 0 & \in_{33}\end{bmatrix}\begin{Bmatrix}E_x\\ E_y\\ E_z\end{Bmatrix}, \tag{7}$$

where Q_{ij} , e_{ij} and $\in_{ij}$ are elastic, piezoelectric and dielectric constants, respectively. The potential energy is:

$$U = \frac{1}{2}\int_V \left(\sigma_{xx}\varepsilon_{xx} + \sigma_{xz}\varepsilon_{xz} - D_x E_x - D_z E_z\right) dV, \tag{8}$$

The external work due to the foundation is:

$$F = -k_w w + k_g \nabla^2 w, \tag{9}$$

where k_w and k_g respectively are spring and shear constants. Finally, using Hamilton's principle we have:

$$\delta u : \frac{\partial^2 u}{\partial x^2} + \frac{\partial w}{\partial x}\frac{\partial^2 w}{\partial x^2} = 0, \tag{10}$$

$$\delta w : -Q_{11} I \frac{\partial^4 w}{\partial x^4} + \frac{24 Q_{11} I}{\pi^3}\frac{\partial^3 \psi}{\partial x^3} - \left(2e_{31}V_0 + N_x^M\right)\frac{\partial^2 w}{\partial x^2} - k_w w + k_g \nabla^2 w = 0, \tag{11}$$

$$\delta \psi : -\frac{24 Q_{11} I}{\pi^3}\frac{\partial^3 w}{\partial x^3} + \frac{6 Q_{11} I}{\pi^2}\frac{\partial^2 \psi}{\partial x^2} + \frac{e_{31} h}{2}\frac{\partial \phi}{\partial x} - \frac{Q_{55} A}{2}\psi + \frac{e_{15} h}{2}\frac{\partial \phi}{\partial x} = 0, \tag{12}$$

$$\delta \phi : -\frac{2h}{\pi}\frac{\partial^2 w}{\partial x^2} + \frac{h}{2}\frac{\partial \psi}{\partial x} - \frac{\pi^2 \in_{33}}{2h}\phi + \frac{h}{2}\frac{\partial \psi}{\partial x} + \frac{h \in_{11}}{2}\frac{\partial^2 \phi}{\partial x^2} = 0. \tag{13}$$

Based on DQM for solution, we have (Kolahchi et. al 2016):

$$\frac{df}{dx}\overset{x=x_i}{\rightarrow} = \sum_{j=1}^{N} C_{ij} f_j, \tag{14}$$

where N is the number of grid points and C_{ij} presents weighting coefficients (Kolahchi et. al 2016b). The governing equations in DQm form may be given as:

$$\left(\left[\underbrace{K_L + K_{NL}}_{K}\right] + P\left[K_g\right]\right)\begin{Bmatrix}\{d_b\}\\ \{d_d\}\end{Bmatrix} = 0, \tag{15}$$

where P is the buckling load;, $[K_L]$, $[K_{NL}]$ and $[K_g]$ respectively, are the stiffness matrix linear, nonlinear part of stiffness matrix and geometric matrix . With the solution of above relation, the buckling load can be calculated.

III. NUMERICAL RESULTS

Here, the DQM is used in order to calculate the buckling load of the structure, and analyzes the influence of several parameters, including the volume fraction of ZnO nanoparticles, geometric characteristics, foundation properties, and external voltage on the buckling load of the column. Consider a concrete column with elastic modulus $E_m = 25\ GPa$ for this study, which is reinforced by ZnO nanoparticles with elastic modulus $E_r = 130\ GPa$.

This chapter is organized into three sections: the convergence analysis of the numerical method, the validation of the model, and the evaluation of the effects different parameters have on the buckling load. Note that the buckling load presented in this section is dimensionless, ($P = N_x^M/(E_m h)$).

Figure 2 shows the variation of structural buckling load of the column with a number of grid points. It can be observed that the buckling load decreases with an increase in the number of grid points and converges at NN. Thus, in the present study, all the calculations have been carried out using 15 grid points.

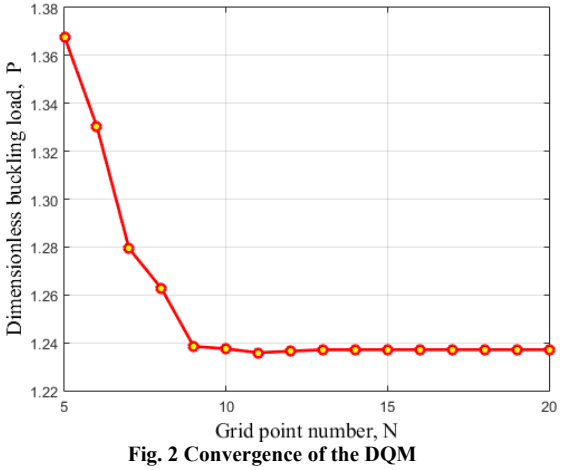

Fig. 2 Convergence of the DQM

Fig. 3 Dimensionless buckling load of the structure versus the number of longitudinal mode for various values of ZnO nanoparticle volume fraction. It can be seen that the critical buckling load which is the minimum buckling load takes place at the third longitudinal mode. Also, it can be realized that by

increasing the volume fraction of nanoparticles, buckling load in column is increased. This is because an increased volume of nanoparticles results in more and more particles being included in the column, hence decreased surface area and increased stiffness of it. Further, the presence of ZnO nanoparticles becomes more profound at higher modes. Fig.4 presents the influence of the foundation on the dimensionless buckling load as a function of the longitudinal mode number. Three cases are considered: no foundation, the foundation modelled as vertical springs (Winkler), and foundation accounted for vertical springs combined with a shear layer (Pasternak). It can be understood from the results that the buckling load of the column increases when considering any type of foundation. Also, the column resting on a Pasternak foundation carries a higher buckling load compared to that on the Winkler foundation. This would be expected since the model of Pasternak provides in addition the shear forces supplied by the springs.

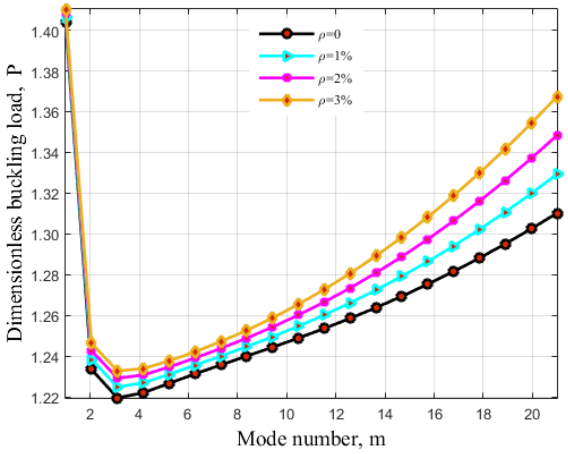

Fig. 3 The effect of ZnO on the dimensionless buckling load

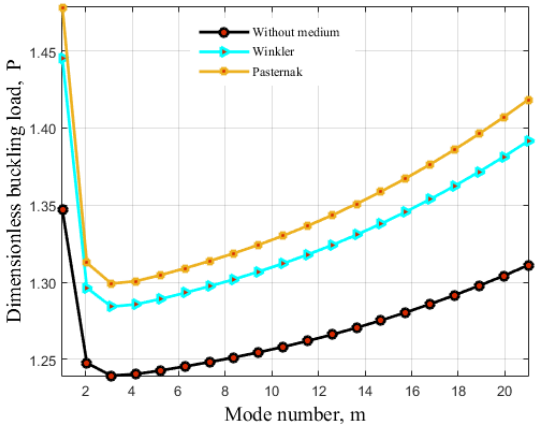

Fig. 4 The effect offoundation on the dimensionless buckling load

Fig. 5 shows the effect of the boundary condition on buckling load, which varies as a function of the longitudinal mode number. From this plot, it can be noticed that boundary conditions have vastly changed the buckling characteristic of the system. The column with clamped boundary conditions at both ends bears the highest buckling load among the other cases because the CC boundary condition provides maximum stiffness. Also, the column with fixed-simple boundary conditions shows a higher buckling load than the column with simple-simple boundary conditions.

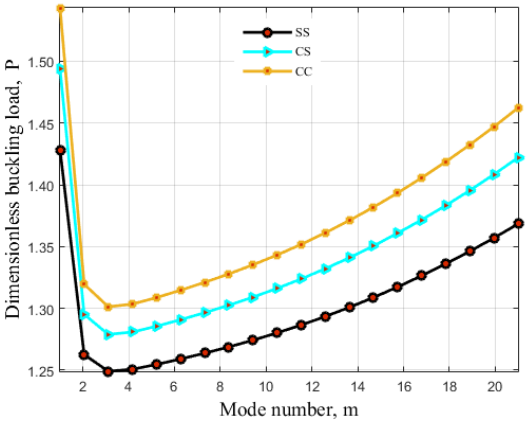

Fig. 5The effect of boundary condition on the dimensionless buckling load

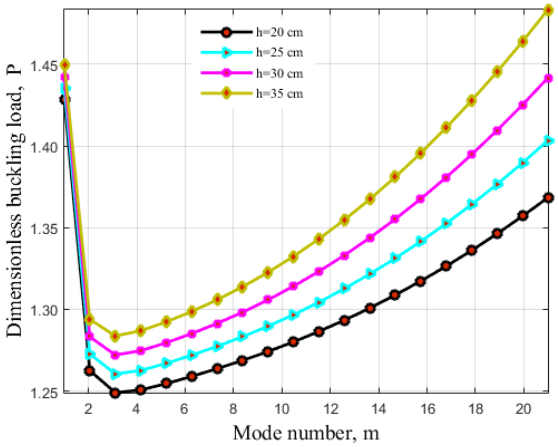

Fig. 6 The effect of thickness on the dimensionless buckling load

Fig. 6 shows the variation of buckling load with thickness. The buckling load increases with an increase in thickness. This is because a higher thickness increases structural stiffness that, on the other hand, increases the ability of the structure to resist buckling. The relationship between thickness and buckling load is important in that it shows how great stability during compressive loading can be achieved using a column by just increasing the thickness. The above trend underlines the high

relevance of geometric parameters-thickness among others-to optimization in buckling performance in structural elements.

IV. CONCLUSION

The theme of this study is buckling behavior of ZnO nanoparticle-reinforced embedded concrete columns under an electric field. First, the foundation model is developed with vertical springs and shear constants, which is mathematically represented by ESDT. Then, the coupled governing equations are derived using the equations of strain-displacement, the energy method, and Hamilton's principle. The buckling load is then determined by DQM and the effects of various parameters such as ZnO nanoparticle volume fraction, external voltage, and foundation properties are analyzed on buckling behavior. From the obtained results, it has been seen that the critical buckling load occurs at approximately the third longitudinal mode. In the process of increasing the volume percentage of ZnO nanoparticles, buckling load increases accordingly. In sum, the buckling load increases with the presence of a foundation, and boundary conditions are very important in order to determine column stability.

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