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Seismic response of underwater fluid-conveying concrete pipes reinforced with SiO_2 nanoparticles and fiber reinforced polymer (FRP) layer

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ABSTRACT

This study aims at investigating the seismic response of the fluid-conveying concrete pipes reinforced with SiO_2 nanoparticles and fiber reinforced polymer (FRP) layer. The earthquake acceleration is consistent with the earthquake occurred in Tabas. It is assumed that the structure is subjected to external forces which exerted by inner and outer fluids. The force due to the inner fluid is evaluated using Navier-Stokes equation. Also, Mori-Tanaka model is employed to take into account the agglomeration effect of SiO_2 nanoparticles. The mathematical model of the structure is developed based on the first order shear deformation theory (FSDT) and the governing equations are derived using energy method and Hamilton's principle. Finally, the problem is solved employing differential quadrature method (DQM) and Newmark method and the effect of different parameters like SiO2 nanoparticles agglomeration and volume percent, inner and outer fluids, various boundary conditions and geometric parameters on the dynamic deflection of the structure is studied. The results indicate that with increasing the thickness to radius ratio and volume fraction of SiO2 nanoparticles and also employing the NFRP layer, the dynamic deflection of the structure decreases while considering the effect of inner and outer fluids and agglomeration of SiO2 nanoparticles and increasing the length to thickness ratio increases the dynamic deflection of the structure.

1. Introduction

Underwater pipelines can be used to carry oil, gas and water. The structure is often shielded against external corrosion by coatings such as epoxy, concrete or fiberglass. In addition, the concrete coating is also useful to compensate for the pipeline's negative buoyancy when it carries lower density substances. The underwater pipelines are exposed to seismic loads and however, the reinforce of these structure is very important. In this work, the SiO_2 nanoparticles and FRP layer are used for reinforcement of the underwater pipe subjected to earthquake load.

The earthquakes in different parts of the world reveal the necessity of the seismic analysis of the structures which have a higher chance to be damaged and fractured. Therefore, many researchers investigate the seismic response of the various structures. For instance, Cai et al. [1] probed the seismic response of short circular reinforced concrete columns. They assumed that the structure is subjected to combined constant axial compression and lateral cyclic load. Chacon et al. [2] examined the seismic response of the reinforced concrete free-plan structures. The seismic behavior of steel reinforced Ultra high strength concrete column and reinforced concrete beam connection is studied by Changwang et al. [3]. They discussed the influences of applied axial load ratio and volumetric stirrup on the strength degradation, ductility and rigidity degradation. Also, Chen et al. [4] investigated the seismic response of the Zipingpu concrete face rockfill dam employing finite element method (FEM). Experimental investigation of crumb rubber concrete columns (CRC) subjected to seismic loading is presented by Youssf et al. [5]. The pipelines are one of the most significant structures which affected by seismic waves dramatically. Bi et al. [6] analyzed the stochastic seismic response of buried onshore and offshore pipelines. Zhang et al. [7] developed nonlinear equations of three-dimensional motion to study dynamic behavior of straight fluid-conveying pipes with general boundary conditions. Also, He et al. [8] proposed a theoretical investigation of an elastic and slender fluid-conveying pipe. Kjolsing and Todd [9] studied damping of a fluid-conveying pipe surrounded by a viscous annulus fluid. They used a hydrodynamic forcing function to simulate the annulus fluid and solved the problem using the spectral element method. Li and Hu [10] evaluated critical flow velocity of fluid-conveying magneto-electro-elastic pipe. They assumed the structure resting on Winkler elastic foundation. They developed mathematical formulation based on Timoshenko beam theory and derive the

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governing equations using Hamilton's principle. They examined the effects of elastic foundation, shear deformation and applied magnetic and voltage potentials on the critical flow velocity. Hesseini and Bahaadini [11], Luczko et al. [12] and Rafiee [13] are the other researchers who examined the behavior of pipes under different conditions. Binici et al. [14] and Wu et al. [15] retrofitted the concrete columns to improve the mechanical properties of them. Furthermore, Toutanji and Deng [16] investigated the performance of retrofitted concrete columns wrapped with carbon, glass and aramid fiber reinforced polymer (FRP) composite sheets. Sheikh [17] applied FRF to strengthen and repair the damaged structures. Also, Parvin and Brighton [18] provided a review of some of the advances in the area of FRP-strengthening of concrete columns under different loading conditions. Stochastic seismic response analysis of buried onshore and offshore pipelines was studied by Bi et al. [19]. Yazdandoust [20] presented seismic response of the soil-nailed walls in terms of the distribution of shear modulus *(G)* and damping ratio *(D)* in soil-nailed mass.

In the above mentioned works, seismic response of the pipes is studied experimental or theoretically without considering nanoparticles and FRP as reinforcement of the structure. To the best of authors' knowledge, this paper is the first to present a mathematical model for the seismic response of the fluid-conveying concrete pipes reinforced with SiO_2 nanoparticles and FRP layer. It is assumed that the structure is subjected to external forces which applied by inner and outer fluids. The force due to the inner fluid is estimated using Navier-Stokes equation. Furthermore, Eshelby-Mori-Tanaka model is employed to consider the agglomeration effect of SiO_2 nanoparticles. The mathematical formulation of the structure is developed based on the first order shear deformation theory (FSDT) and the governing equations are derived using energy method and Hamilton's principle. Differential quadrature method (DQM) and Newmark method are employed to solve the problem and the influence of various parameters like SiO2 nanoparticles agglomeration and volume percent, inner and outer fluids, various boundary conditions and geometric parameters on the dynamic deflection of the structure is studied.

2. Theoretical model

2.1. Stress-strain relations

The constitutive equations correspond to FRP layers are considered as:

$$\begin{Bmatrix}\sigma_{xx}\\ \sigma_{\theta\theta}\\ \sigma_{\theta z}\\ \sigma_{zx}\\ \sigma_{x\theta}\end{Bmatrix}^{f}=\begin{bmatrix}C_{11}&C_{12}&0&0&0\\ C_{21}&C_{22}&0&0&0\\ 0&0&C_{44}&0&0\\ 0&0&0&C_{55}&0\\ 0&0&0&0&C_{66}\end{bmatrix}\begin{Bmatrix}\varepsilon_{xx}\\ \varepsilon_{\theta\theta}\\ \gamma_{\theta z}\\ \gamma_{xz}\\ \gamma_{x\theta}\end{Bmatrix}, \tag{1}$$

where C_{ij} denote elastic constants of FRP layer. Based on Mori-Tanaka method, the constitutive equation of the concrete pipe reinforced by SiO_2 nanoparticles is taken into account as follows [21]

$$\begin{Bmatrix}\sigma_{xx}\\ \sigma_{\theta\theta}\\ \sigma_{\theta z}\\ \sigma_{zx}\\ \sigma_{x\theta}\end{Bmatrix}=\begin{bmatrix}\underbrace{Q_{11}}_{k+m}&\underbrace{Q_{12}}_{l}&0&0&0\\ \underbrace{Q_{21}}_{l}&\underbrace{Q_{22}}_{n}&0&0&0\\ 0&0&\underbrace{Q_{44}}_{p}&0&0\\ 0&0&0&\underbrace{Q_{55}}_{m}&0\\ 0&0&0&0&\underbrace{Q_{66}}_{p}\end{bmatrix}\begin{Bmatrix}\varepsilon_{xx}\\ \varepsilon_{\theta\theta}\\ \gamma_{\theta z}\\ \gamma_{xz}\\ \gamma_{x\theta}\end{Bmatrix}, \tag{2}$$

in which k, m, n, l, p represent the stiffness coefficients of the structure which are reported in Appendix A.

According to the experimental results, the assumption of uniform distribution of nanoparticles in the matrix material is not exact and the most of nanoparticles are bent and concentrated in some regions of the matrix. These regions with centralized nanoparticles are considered in spherical shapes, and are named as "inclusions" which have different elastic properties from the surrounding regions of the material. The total volume V_r of nanoparticles can be considered as below [22]

$$V_r=V_r^{inclusion}+V_r^{m} \tag{3}$$

in which $V_r^{inclusion}$ and V_r^{m} denote the volumes of nanoparticles distributed in the spherical inclusions and in the matrix material, respectively. The agglomeration of nanoparticles can be considered by introducing two parameters ξ and ζ which can be defined as follows

$$\xi=\frac{V_{inclusion}}{V}, \tag{4}$$

$$\zeta=\frac{V_r^{inclusion}}{V_r}. \tag{5}$$

Moreover, the average volume fraction c_r of nanoparticles in the composite is considered as:

$$c_r=\frac{V_r}{V}. \tag{6}$$

Assuming the completely random orientations of nanoparticles, the elastic modulus (E) and poison's ratio (υ) of the equivalent composite layer can be calculated as

$$E=\frac{9KG}{3K+G}\quad, \tag{7}$$

$$\upsilon=\frac{3K-2G}{6K+2G}. \tag{8}$$

where the effective bulk modulus (K) and effective shear modulus (G) are written in Appendix B.

2.2. Geometry of problem

Fig. 1 illustrates an underwater fluid-conveying concrete pipe reinforced with SiO_2 nanoparticles and integrated by FRP layers. As shown in Fig. 1, the structure is under seismic loading condition.

2.3. First order shear deformation theory (FSDT)

Recently, FSDT and other higher order theories have been used for different structure. Hebali et al. [23] used a new quasi-three-dimensional (3D) hyperbolic shear deformation theory for the bending and free vibration analysis of functionally graded plates. A simple and refined trigonometric higher-order beam theory was developed by Bourada et al. [24] for bending and vibration of functionally graded beams. In another work by Bouderba et al. [25], a new class of FSDT

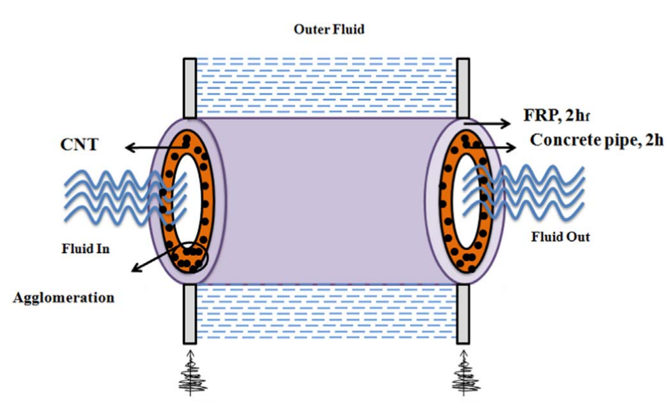

Fig. 1. Geometry of an underwater fluid-conveying concrete pipe reinforced with SiO2 nanoparticles and integrated with FRP layers.