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Seismic response of underwater concrete pipes conveying fluid covered with nano-fiber reinforced polymer layer

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ABSTRACT

This research deals with seismic response of underwater fluid-conveying concrete pipes during the earthquake in Kobe. The pipe is reinforced with nano-fiber reinforced polymer (NFRP) layer. The displacement filed of the structure is considered based on the sinusoidal shear deformation theory. Navier-Stokes equation is applied to estimate the force due to the inner fluid. Furthermore, the effect of the outer fluid is taken into consideration as an equivalent force. The governing equations are derived on the basis of energy method and using Hamilton's principle. Differential quadrature method (DQM) and Newmark method are applied to obtain the dynamic deflection of the system. The effect of parameters such as NFRP layer, volume percent and agglomeration of nano-fibers, boundary conditions, inner and outer fluids, thickness to radius and length to thickness ratios on the dynamic deflection of the structure is examined. The results show that with increasing the thickness to radius ratio and volume percent of nano fiber and using NFRP layer, the dynamic deflection decreases while considering the inner and outer fluids and agglomeration effect of nano fiber and increasing the length to thickness ratio, the dynamic deflection of the structure increases.

1. Introduction

The dynamic response of the structure during the earthquake is a subset of structural analysis which called seismic analysis and is favored by many researchers. Reinforcing the structures with NFRP layer is one of the new ways to improve the strength of structures with respect to earthquake load.

In the flied of seismic response in different structure, Youssf et al. [1] described experimental work conducted to explore the possible use of crumb rubber concrete (CRC) for structural columns subjected to earthquake load. Seismic application of an innovative control device called self-centering hybrid damper (SCHD) was investigated by Asgarian et al. [2]. Hu et al. [3] presented an experimental study on seismic responses of high strength steel frames. The in-plane seismic response of latticed arches is estimated by Xiang et al. [4]. Xu et al. [5] proposed a new strategy to conduct stochastic seismic response analysis of nonlinear structures with uncertain parameters. Zou et al. [6] employed a pseudo-static method to investigate seismic response of underground frame structures subjected to increasing excitations. Soleimani et al. [7] developed a seismic demand model to identify the significant uncertain parameters in the seismic response of the concrete bridges. Yazdandoust [8], Chacon et al. [9], Bi et al. [10], Du and Pan [11], Ohsaki et al. [12] and Zhou et al. [13] are the other researchers who investigated the seismic responses of various structures.

Some researchers retrofit the conventional structure to improve the dynamic behavior and performance of them. Sheik [14] studied performance of concrete structures retrofitted with fiber reinforced polymers (FRP). Research on columns has particularly focused on improving their seismic resistance by confining them with FRP. Wu et al. [15] proposed a numerical simulation on seismic retrofitting performance of reinforced concrete columns strengthened with FRP sheets. They used two-dimensional finite element analysis to study the seismic response of three reinforced concrete columns. For this purpose, they analyzed load-deformation responses and the progression of stress-strain at the inflection points and bottoms of the structure. Toutanji and Deng [16] presented the performance of concrete columns retrofitted with carbon, glass and aramid FRP composite sheets. They evaluated stress-strain behavior, stiffness, ultimate strength and ductility of the structure by obtaining axial load and axial and lateral strains. Binici and Mosalam [17] proposed an analytical model to examine the reinforced concrete columns retrofitted with FRP lamina. Barbato [18] presented an efficient two-dimensional frame finite element to estimate the load-carrying capacity of retrofitted concrete beams which strengthened with FRP strips and plates. Also, Rafiee [19] investigated the mechanical

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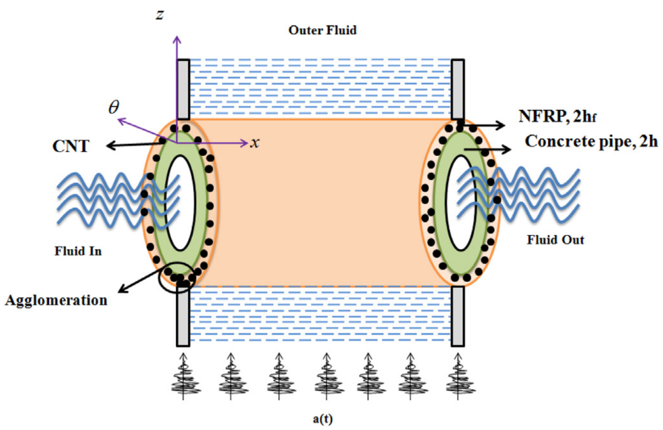

Fig. 1. Schematic view of the underwater fluid-conveying concrete pipe wrapped with NFRP layers.

behavior of glass-fiber reinforced thermosetting-resin (GFRP) pipes.

To the best of authors' knowledge, seismic analysis of underwater fluid-conveying concrete pipes reinforced with NFRP layer cannot be found in literature. The displacement filed of the structure is considered based on the sinusoidal shear deformation theory. Navier-Stokes equation is employed to estimate the force due to the inner fluid. Furthermore, the effect of the outer fluid is considered as an equivalent force. The governing equations are derived on the basis of energy method and using Hamilton's principle. DQM and Newmark method are applied to obtain the dynamic deflection of the system. The effects of various parameters such as NFRP layer, volume percent and agglomeration of nano-fibers, boundary conditions, inner and outer fluids, thickness to radius and length to thickness ratios on the dynamic deflection of the structure are investigated.

2. Mathematical formulation

2.1. Geometry of problem

As illustrated in Fig. 1, an underwater fluid-conveying concrete pipe wrapped with NFRP layers is considered. The length of the structure is L, thickness of concrete pipe is h, the thickness of the NFRP is h_f and the radius of the concrete pipe is R. It is assumed that the structure is subjected to seismic load. The coordinate system is considered in the middle surface of the concrete pipe where the x-, θ- and z- axis are in axial, circumferential and transverse directions, respectively.

2.2. Displacement field and constitutive relation

In the SSDT, the displacement field can be considered as a sinusoidal function which is the same of deflection of the structure. However, this theory leads to accurate results with lowe degree of freedom. The displacement field of the structure in confront with lateral and in-plane forces is considered based on the sinusoidal shear deformation theory (SSDT) which can be expressed as [20]:

$$u_1(x,\theta,z,t) = u(x,\theta,t) - z\frac{\partial w_b(x,\theta,t)}{\partial x} - f\frac{\partial w_s(x,\theta,t)}{\partial x}, \tag{1}$$

$$u_2(x,\theta,z,t) = v(x,\theta,t) - z\frac{\partial w_b(x,\theta,t)}{R\partial \theta} - f\frac{\partial w_s(x,\theta,t)}{R\partial \theta}, \tag{2}$$

$$u_3(x,\theta,z,t) = w_b(x,\theta,t) + w_s(x,\theta,t), \tag{3}$$

in which u_1, u_2 and u_3 are general displacements in x-, θ- and z- directions, respectively; u, v and w are mid-plane displacements in x-, θ- and z- directions, respectively; $f = z - \frac{h}{\pi}\sin\frac{\pi z}{h}$; $w_b(x,\theta,t)$ and $w_s(x,\theta,t)$ denote the bending and shear components of transverse displacement. So, the nonlinear kinematic relations can be obtained as bellows

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

$$\varepsilon_{\theta\theta} = \frac{\partial v}{R\partial\theta} + \frac{w_b}{R} + \frac{w_s}{R} + \frac{1}{2}\left(\frac{\partial w_b}{R\partial\theta}\right)^2 + \frac{1}{2}\left(\frac{\partial w_s}{R\partial\theta}\right)^2 - z\frac{\partial^2 w_b}{R^2\partial\theta^2} - f\frac{\partial^2 w_b}{R^2\partial\theta^2}, \tag{4b}$$

$$\gamma_{\theta z} = p\frac{\partial w_s}{R\partial\theta} - \frac{v}{R}, \tag{4c}$$

$$\gamma_{xz} = p\frac{\partial w_s}{\partial x}, \tag{4d}$$

$$\gamma_{x\theta} = \frac{\partial u}{R\partial\theta} + \frac{\partial v}{\partial x} + \left(\frac{\partial w_b}{\partial x} + \frac{\partial w_s}{\partial x}\right)\left(\frac{\partial w_b}{R\partial\theta} + \frac{\partial w_s}{R\partial\theta}\right) - 2z\frac{\partial^2 w_b}{R\partial x\partial\theta} - 2f\frac{\partial^2 w_s}{R\partial x\partial\theta}, \tag{4e}$$

where $p = \cos\frac{\pi z}{h}$.

Constitutive relation of the concrete pipe is considered as:

$$\begin{Bmatrix}\sigma_{xx}\\ \sigma_{\theta\theta}\\ \sigma_{\theta z}\\ \sigma_{zx}\\ \sigma_{x\theta}\end{Bmatrix} = \begin{bmatrix} Q_{11} & Q_{12} & 0 & 0 & 0\\ Q_{21} & Q_{22} & 0 & 0 & 0\\ 0 & 0 & Q_{44} & 0 & 0\\ 0 & 0 & 0 & Q_{55} & 0\\ 0 & 0 & 0 & 0 & Q_{66}\end{bmatrix}\begin{Bmatrix}\varepsilon_{xx}\\ \varepsilon_{\theta\theta}\\ \gamma_{\theta z}\\ \gamma_{xz}\\ \gamma_{x\theta}\end{Bmatrix}, \tag{5}$$

in which Q_{ij} are elastic constants of concrete. Moreover, constitutive relations related to NFRP layers are written as:

$$\begin{Bmatrix}\sigma_{xx}\\ \sigma_{\theta\theta}\\ \sigma_{\theta z}\\ \sigma_{zx}\\ \sigma_{x\theta}\end{Bmatrix}^f = \begin{bmatrix} C_{11} & C_{12} & 0 & 0 & 0\\ C_{21} & C_{22} & 0 & 0 & 0\\ 0 & 0 & C_{44} & 0 & 0\\ 0 & 0 & 0 & C_{55} & 0\\ 0 & 0 & 0 & 0 & C_{66}\end{bmatrix}\begin{Bmatrix}\varepsilon_{xx}\\ \varepsilon_{\theta\theta}\\ \gamma_{\theta z}\\ \gamma_{xz}\\ \gamma_{x\theta}\end{Bmatrix}, \tag{6}$$

where C_{ij} denote elastic constants of NFRP layer and may be evaluated using Mori-Tanaka approach which is defined in the next section.

2.3. Mori-Tanaka approach and agglomeration effects

In this section, the effective material properties of the concrete column reinforced by SiO2 nanoparticles is developed using Mori-Tanaka approach [21] which is simple and accurate even at high volume percent of inclusions. According to this approach, the matrix material is assumed to be isotropic and elastic, with the Young's modulus E_m and the Poisson's ratio υ_m. Therefore, constitutive relations for a layer of the composite with the principal axes parallel to the r,θ and z directions can be considered as [21]:

$$\begin{Bmatrix}\sigma_{11}\\ \sigma_{22}\\ \sigma_{33}\\ \sigma_{23}\\ \sigma_{13}\\ \sigma_{12}\end{Bmatrix} = \begin{bmatrix} k+m & l & k-m & 0 & 0 & 0\\ l & n & l & 0 & 0 & 0\\ k-m & l & k+m & 0 & 0 & 0\\ 0 & 0 & 0 & p & 0 & 0\\ 0 & 0 & 0 & 0 & m & 0\\ 0 & 0 & 0 & 0 & 0 & p\end{bmatrix}\begin{Bmatrix}\varepsilon_{11}\\ \varepsilon_{22}\\ \varepsilon_{33}\\ \gamma_{23}\\ \gamma_{13}\\ \gamma_{12}\end{Bmatrix} \tag{7}$$

where σ_{ij}, ε_{ij}, γ_{ij}, k, m, n, l, p indicate the stress components, the strain components and the stiffness coefficients, respectively. Based on the Mori-Tanaka approach, the stiffness coefficients can be calculated by [21]: