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Smart and Robust Composite Tube Columns Frames for Offshore Sub-Structure Construction

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Abstract. Offshore industry has been welcoming to composite material for its saliences. Features such as corrosion and temperature resistance, construction cost reduction, and superb fatigue performance are some of the reasons for this choice. Steel tube-encased composite is an appropriate found composite replacement for traditional offshore construction. Regardless of all its advantages, they suffer from the interfacing problem between composite and steel layers; however, magnetostrictive nanofillers are proposed to increase the integration between the layers. Therefore, current effort is discussed the vibrational behavior of the proposed robust steel tube column as well as the actuation characteristics of the magnetostrictive nanofillers in encased composite. The result reveals that, the steel tube-encased composite columns exhibit greater stiffness in compare with traditional steel tube. Furthermore, magnetostrictive nanofillers have shown higher actuation capability of vibration at seismic mode.

Introduction

Composites have found extensive applications in the oil & gas industry since last two decades. Significant advances have been made in the areas of composite pipe work and fluid handling [1, 2]. The high cost to replace steel elements in retrofit applications and increased longevity in new construction are driving the use of composites, which withstand severe conditions as experienced in offshore environment [3, 4]. In the offshore oil and gas industry, the cost of manufacturing and erecting oil rigs could be reduced significantly if heavy metal column could be replaced with lighter ones made of composites. Composite column also could be used for:

1. Replace steel components to eliminate corrosion
2. Exhibit excellent fatigue performance, good resistance to temperature extremes and wear, especially in offshore industrial sectors.
3. Build lighter structures to increase platform performance.
4. Improved combat survivability.
5. Produce complex structural parts at reduced cost, especially in quantity
6. The tailorability of composites to suit specific applications has been one of its greater advantages such as imparting low thermal conductivity, low coefficient of thermal expansion, high axial strength and stiffness etc.

Therefore, offshore engineering center in Universiti Teknologi PETRONAS (OECU) has shifted attention to the development of composite structures of carbon and/or glasses fiber reinforced epoxy and steel for offshore jacket sub-structure construction with the aim of becoming a medium-scale contractor with leading-edge technology. Steel Tube-Encased Composite (STEC) column is developed essentially as weldable tubular structural element expected to be good replacement of traditionally steel tubes in offshore industrial facilities constructions. However, still the interfacing problem between composite and steel layers in STEC represent a challenge to be work out.

Therefore, a Nano-Hyprid-functionally graded composite (NHFG) proposed to increase the integration between the layers and grading the structural properties across tube thickness using magnetic nanoparticles as fillers. Furthermore, such functional composites could utilize the magnetostrictive properties to actuate the vibration inside the composite tubes. Several models have been found in the literature dealt with functional composite [5, 6]. Some of them could specialize to demonstrate the vibrational behavior of multilayered and functionally graded magnetostrictive composite. Albarody, et.al., [5] derived the exact solution for linearly constitutive properties, simply supported, functional composite shell subjected to static and dynamic loadings. The authors were investigated and analyzed the effects of the material properties, lay-ups of the constituent layers, and shell parameters under the free vibration behavior.

In this paper, a STEC columns filled with magnetic nanoparticles is modeled and the vibrational characteristic is discussed. Also, some of NHFG composite are examined.

Theoretical Formulation

Based on Hamilton's variational principle linked with Gibbs free energy functions, the steel tube-encased composite model is casted according to the first-order shear deformation shell theory. The exact solution is derived for linearly magnetostrictive constitutive properties, simply supported, and thick shell having rectangular plane-form. Expressed in the (meter–kilogram–second) system of units, the generation procedure of thick composite shell model, written in curvilinear coordinates and provides the much-needed materials in state of the smart or adaptive materials are as follows;

1. **Constitutive Relations:** In a system gather mechanical, magnetic, and thermal influences, the constitutive relations are expressed formally as:

$$S_{ij} = [\varsigma^{G,T}_{ijkl}\varepsilon_{ij} - \kappa^{T}_{pkl}\chi_p - \lambda^{G}_{kl}\tau], \tag{1}$$

2. **Kinematic Relations:** According to the FOSD shell theory, the following representation of the 3D displacement and magnetic potentials is postulated:

$$u(\alpha,\beta,\zeta,t) = u_o(\alpha,\beta,t) + \zeta\psi_\alpha(\alpha,\beta,t), \qquad v(\alpha,\beta,\zeta,t) = v_o(\alpha,\beta,t) + \zeta\psi_\beta(\alpha,\beta,t),$$

$$w(\alpha,\beta,\zeta,t) = w_o(\alpha,\beta,t), \quad \text{and} \quad \vartheta(\alpha,\beta,\zeta,t) = -\big(\vartheta_o(\alpha,\beta,t) + \zeta\vartheta_1(\alpha,\beta,t)\big), \tag{2}$$

where u_o, v_o, and w_o are referred to as the mid-surface displacement functions, and ψ_α and ψ_β are the midsurface rotation functions of the shell, and ϑ is the magnetic potential function. The strains at any point in the shell can be written in terms of mid-surface strains and curvature changes as:

$$\begin{aligned} \varepsilon_\alpha &= (\varepsilon_{o\alpha} + \zeta\varepsilon_{1\alpha}), \quad & \varepsilon_{\alpha\beta} &= (\varepsilon_{o\alpha\beta} + \zeta\varepsilon_{1\alpha\beta}), \quad & \varepsilon_{\alpha\zeta} &= (\varepsilon_{o\alpha\zeta} + \zeta\,\psi_\alpha/R_\alpha), \\ \varepsilon_\beta &= (\varepsilon_{o\beta} + \zeta\varepsilon_{1\beta}), \quad & \varepsilon_{\beta\alpha} &= (\varepsilon_{o\beta\alpha} + \zeta\varepsilon_{1\beta\alpha}), \quad & \varepsilon_{\beta\zeta} &= (\varepsilon_{o\beta\zeta} + \zeta\,\psi_\beta/R_\beta). \end{aligned} \tag{3}$$

However, the mid-surface strains as well as the curvature and twist changes are extended by Codazzi-Gauss geometric relations, as [6]. The distributions of magnetic fields at any point in the composite shell are assumed as:

$$\chi_\alpha = (\chi_{o\alpha} + \zeta\chi_{1\alpha}), \qquad \chi_\beta = (\chi_{o\beta} + \zeta\chi_{1\beta}). \tag{4}$$

and the magnetic field changes are

$$\chi_{o\alpha} = -\frac{1}{A}\frac{\partial\vartheta_o}{\partial\alpha}, \quad \chi_{1\alpha} = -\frac{1}{A}\frac{\partial\vartheta_1}{\partial\alpha}, \quad \chi_{o\beta} = -\frac{1}{B}\frac{\partial\vartheta_o}{\partial\beta}, \quad \chi_{1\beta} = -\frac{1}{B}\frac{\partial\vartheta_1}{\partial\beta}. \tag{5}$$

3. **Kinetic Relations:** The elastic, electric, and magnetic force and moment resultants are obtained by integrating the constitutive relations (1) over the shell thickness as below:

$$\{N_n\ ,\ M_n\} = \int_{-\frac{h}{2}}^{\frac{h}{2}} (1,\zeta)\{S_{ij}\}\gamma_n d\zeta + \{N_n^T,\ M_n^T\}, \quad (6)$$

where $\gamma_n = (1 + \zeta/R_n)$, the subscripts n denote either of α, β or αβ, and h is the shell thickness. In order to gain a numerical stability and pursue a possible integration of Eq. (6) in absence of thermal forces, the term $(1 + \zeta/R_n)$ should be expanded in a geometric series as in [7, 8].

4. **Variational Principle:** The variational energy method via the Hamiltonian axiom has been used by [9, 10] for coupling of the energy phenomena and to derive a consistent set of equations of motion coupled with the free charge equation. In summary, the total energy of a shell element can be defined as:

$$\delta \int_{t_o}^{t_1} (K - P)\, dt = 0, \quad (7)$$

where P is the total potential energy induced in the system given by:

$$P = \iiint_V \left[\varsigma_{ijkl}^{G,T}\varepsilon_{ij} - \kappa_{pkl}^{T}\chi_p - \lambda_{kl}^{G}\tau\right] dV \ - \iint_{\Omega_o} \left(t(S_i, G_{l,}) + W(S_i, G_{l,})\right), \quad (8)$$

where $Q(S_i, G_l, T)$ is the thermodynamic potential. $t(S_i, G_{l,})$ and $W(S_i, G_l)$ are the tractions and the work done by body force, and magnetic charge, respectively. The kinetic energy is given as:

$$K = \frac{I}{2}\iint_{\Omega_o}\int_{-\frac{h}{2}}^{\frac{h}{2}} \left((\dot{u}_o^2 + \dot{v}_o^2 + \dot{w}_o^2) + \zeta^2(\dot{\psi}_\alpha^2 + \dot{\psi}_\beta^2) + 2\zeta(\dot{u}_o^2\dot{\psi}_\alpha^2 + \dot{v}_o^2\dot{\psi}_\beta^2)\right)\gamma_\alpha\gamma_\beta\, AB d\zeta dA. \quad (9)$$

The traction is

$$t(S_i, G_l) = \left(\tilde{S}_{nn}\delta u_n + \tilde{S}_{nt}\delta v_t + \tilde{S}_{n\zeta}\delta w_r\right) + \left(\tilde{G}_{nn}\delta\vartheta + \tilde{G}_{nt}\delta\vartheta\right) \quad (10)$$

and the external work is

$$W(S_i, G_l) = \left(F_\alpha^S u_o + F_\beta^S v_o + F_n^S w_o + C_\alpha^S \psi_\alpha + C_\beta^S \psi_\beta\right) - \left(F^G \vartheta_o + C^G \vartheta_1\right), \quad (11)$$

where F_α^S, F_β^S, and F_n^S are the distributed forces in α, β and ζ directions, respectively, while C_α^S and C_β^S are the distributed couples about the middle surface of the shell. F^G and C^G are the distributed forces and couples due to the magnetic charge. Hence, the temperature, τ is a known function of position and enter the formulation only through the constitutive equations. Substituting Eqs. (1, 10, and 11) into Eq. (8) and equating the resulting equation with Eq. (9), yields after expanding the terms:

$$\delta \int_{t_o}^{t_1} \iint_{\Omega_o} \begin{pmatrix} \frac{\bar{I}_1}{2}(\dot{u}_o^2 + \dot{v}_o^2 + \dot{w}_o^2) + \frac{\bar{I}_3}{2}(\dot{\psi}_\alpha^2 + \dot{\psi}_\beta^2) \\ +\bar{I}_2(\dot{u}_o^2\dot{\psi}_\alpha^2 + \dot{v}_o^2\dot{\psi}_\beta^2) \end{pmatrix} AB dA dt - \int_{t_o}^{t_1} \iiint_V (\varsigma_{ij}\varepsilon - \kappa_{ij}\chi - \lambda_i\tau\delta\varepsilon)\, dV dt$$

$$+\int_{t_o}^{t_1} \iint_{\Omega_o} \left(\tilde{S}_{nn}\delta u_n + \tilde{S}_{nt}\delta v_t + \tilde{S}_{n\zeta}\delta w_r + \tilde{G}_{nn}\delta\vartheta + \tilde{G}_{nt}\delta\vartheta\right) AB dA dt$$

$$+\int_{t_o}^{t_1} \iint_{\Omega_o} \left(F_\alpha^S u_o + F_\beta^S v_o + F_n^S w_o + C_\alpha^S \psi_\alpha + C_\beta^S \psi_\beta - F^G \vartheta_o - C^G \vartheta_1\right) AB dA dt = 0. \quad (12)$$

Replacing the constitutive terms in Eq. (12) by the kinetic relations (6), then integrating the displacement gradients by parts to obtain only the virtual displacements, we can set the coefficients of δu_o, δv_o, δw_o, $\delta\psi_\alpha$, $\delta\psi_\beta$, $\delta\vartheta_0$ and $\delta\vartheta_1$ to zero, individually. The equations of motion and the charge equilibrium equation for isothermal case are

$$\frac{\partial}{\partial\alpha} BN_\alpha + \frac{\partial}{\partial\beta} AN_{\beta\alpha} + \frac{\partial A}{\partial\beta} N_{\alpha\beta} - \frac{\partial B}{\partial\alpha} N_\beta + \frac{AB}{R_\alpha} Q_\alpha + \frac{AB}{R_{\alpha\beta}} Q_\beta + ABF_\alpha = AB\left(\bar{I}_1 \frac{\partial^2 u_o}{\partial t^2} + \bar{I}_2 \frac{\partial^2 \psi_\alpha}{\partial t^2}\right),$$

$$\frac{\partial}{\partial\beta}AN_{\beta} + \frac{\partial}{\partial\alpha}BN_{\alpha\beta} + \frac{\partial B}{\partial\alpha}N_{\beta\alpha} - \frac{\partial A}{\partial\beta}N_{\alpha} + \frac{AB}{R_{\alpha\beta}}Q_{\alpha} + \frac{AB}{R_{\beta}}Q_{\beta} + ABF_{\beta} = AB\left(\bar{I}_1\frac{\partial^2 v_o}{\partial t^2} + \bar{I}_2\frac{\partial^2 \psi_{\beta}}{\partial t^2}\right),$$

$$-AB\left(\frac{N_{\alpha}}{R_{\alpha}} + \frac{N_{\beta}}{R_{\beta}} + \frac{N_{\alpha\beta}+N_{\beta\alpha}}{R_{\alpha\beta}}\right) + \frac{\partial}{\partial\alpha}BQ_{\alpha} + \frac{\partial}{\partial\beta}AQ_{\beta} + ABF_{n} = AB\left(\bar{I}_1\frac{\partial^2 w_o}{\partial t^2}\right),$$

$$\frac{\partial}{\partial\alpha}BM_{\alpha} + \frac{\partial}{\partial\beta}AM_{\beta\alpha} + \frac{\partial A}{\partial\beta}M_{\alpha\beta} - \frac{\partial B}{\partial\alpha}M_{\beta} - ABQ_{\alpha} + \frac{AB}{R_{\alpha}}P_{\alpha} + ABC_{\alpha} = AB\left(\bar{I}_2\frac{\partial^2 u_o}{\partial t^2} + \bar{I}_3\frac{\partial^2 \psi_{\alpha}}{\partial t^2}\right)$$

$$\frac{\partial}{\partial\beta}AM_{\beta} + \frac{\partial}{\partial\alpha}BM_{\alpha\beta} + \frac{\partial B}{\partial\alpha}M_{\beta\alpha} - \frac{\partial A}{\partial\beta}M_{\alpha} - ABQ_{\beta} + \frac{AB}{R_{\beta}}P_{\beta} + ABC_{\beta} = AB\left(\bar{I}_2\frac{\partial^2 u_o}{\partial t^2} + \bar{I}_3\frac{\partial^2 \psi_{\beta}}{\partial t^2}\right). \quad (13)$$

here $\bar{I}_1$, $\bar{I}_2$, and $\bar{I}_3$ are the inertia terms defined as:

$$\bar{I}_j = \left[I_j + I_{j+1}\left(\frac{R_{\alpha} + R_{\beta}}{R_{\alpha}R_{\beta}}\right) + \frac{I_{j+2}}{R_{\alpha}R_{\beta}}\right]_{j=1,2,3}, \; [I_1, I_2, I_3, I_4, I_5] = \sum_{k=1}^{N}\int_{h_{k-1}}^{h_k} I^k\,(1, \zeta, \zeta^2, \zeta^3, \zeta^4, \zeta^5)d\zeta,$$

where I^k is the mass density of the k^{th} layer of the shell per unit mid-surface area. Eqs. (13) can be written in a matrix form as $\left(K_{ij} + \partial^2/\partial t^2\, M_{ij}\right)\{\Delta\} = \{F - F^T\}$, where K and M are stiffness and mass matrices, respectively, and F^T is the thermal forces. Thus, the forced method will apply satisfying SS boundary conditions and admit specially-orthotropic rectangular laminates, to determine the governing equations that satisfied everywhere in the domain of the shell.

Thus far, the accurate treatment of thermal, magnetic and elastic energies that are taken into account in this smart composite shell that encased a steel tube column, expect yields rather sophisticated equations interlink the magnetic inductions and stress resultants.

Parametric Analysis

As deepwater structures for the future developments are expected to be floating structures. Structural systems that can adapt to the environment automatically offer new vistas for designers and lead to novel efficient developments. An offshore structure that form from the proposed steel tube-encased composite is defined smart due to the actuation capability of the magnetostrictive materials that integrated into structural.

The challenging part of the offshore structural adaption is that the structure is subjected to highly uncertain environmental forces. Thus, the effects of the material properties, and lay-ups of the constituent layers of the encased composite and the steel tube parameters on the vibration behavior are required to be dissected. In Fig. 1, a $CoFe_2O_4$ Nano particle material is scrutinized and the mechanical properties of the encased shell are found to be varied in a very orderly manner across the tube thickness. The STEC tubes that encased with shell made of composite filled with $CoFe_2O_4$ appear with higher stiffness as compared to traditional steel tube and exhibit possible actuations when a magnetic field propagate along the tube.

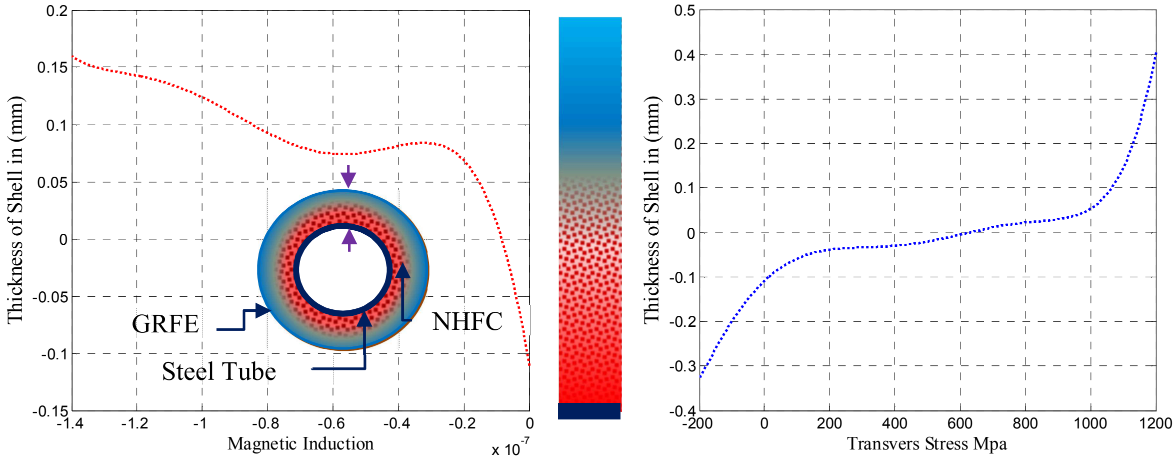

Fig 1. The transvers stresses and magnetic induction across the composite tube thickness, at unity load. GRFE properties are (E_1/ E_2=15, G_{12}/ E_2=0.5, G_{13}/ E_2=0.5, υ_{12}=0.3, a/b=1, a/h=10, and the lamination scheme is $(0/09)_S$), while $CoFe_2O_4$ properties and the grading material properties model can be found in [5].

Conclusions

The evolutionary process of development of adaptive steel tube-encased composite for tubular constructions has opened up new vistas for the several interdisciplinary applications. The benefits of these composite tubes are expected to be enormous. The concept of a structure with capability of automatically responding to the environment by change in the self-configuration, or by changing the interface with the environment is one which offers the potential of extremely attractive advantages in the design, development and operation of offshore structures. The STEC columns comprising magnetostrictive materials have been modeled and scrutinized. The present model may serve as a reference in developing a prototype of STEC columns for further experimentations.

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