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A Composite Steel Plate Shear Walls for Offshore Constructions

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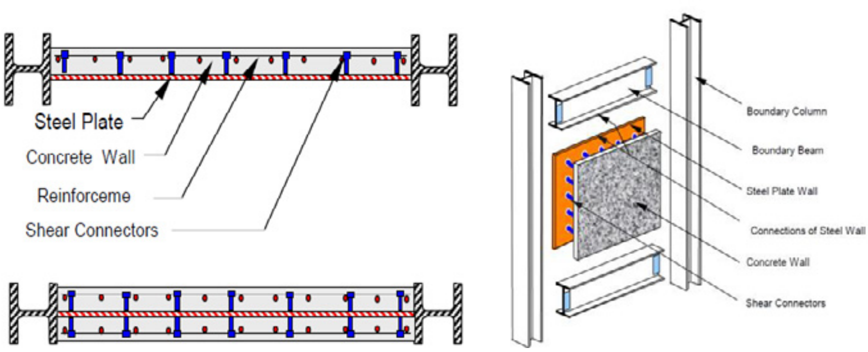
Abstract. A new-type of weldable composite steel plate shear wall, which consists of a steel plate sandwiched by either of two or one composite panels at each side or at one side, has been proposed. An analytical model for such shear wall – via shell model is derived and the vibrational modes are discussed. Truss reinforcement is used to increase the integration between the steel and composite layers and the cross sectional properties were graded by magnetic nanoparticles fillers. The thickness shear modes at the composite wall appear higher than those of thickness stretch modes, but they are varied in a very orderly manner with respect to the vibrational mode. Also, some of characteristics are examined.

1 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 [1-3]. The high cost to replace steel element in retrofit applications and increased longevity in new construction are driving the use of composites, which withstand severe conditions as experienced in offshore environment [1, 2, 4]. In the offshore oil and gas industry, the cost of manufacturing and erecting oil rigs could be reduced significantly if heavy metal plate and shell could be replaced with lighter ones made of weldable composites.

Figure 1. Composite steel plate shear walls.



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Therefore, offshore engineering center in Universiti Teknologi PETRONAS (OECU) has shifted attention to the development of weldable composite steel plate shear walls for offshore construction with the aim of becoming a medium-scale contractor with leading-edge technology and to:

1. Develop wall with the same shear capacity, most likely larger shear stiffness, smaller thickness and less weight increasing platform performance.
2. Replace steel components to eliminate corrosion and to increase the combat survivability.
3. Improve fatigue performance, good resistance to temperature extremes and wear.
4. Impart the structural wall a low thermal conductivity, low coefficient of thermal expansion, high axial strength and stiffness etc.
5. Produce large structural parts at reduced cost, especially in offshore industrial sectors.

However, the tailorability of composites to suit a steel plate represents a challenge to be work out. Therefore, truss reinforcement is proposed to increase the integration between the steel and composite layers (see Fig. 2). As well as, a magnetic nanoparticles fillers is used to grade the structural properties across the wall thickness. Such functional composites could utilize the magnetostrictive properties to control the vibration inside the shear walls.

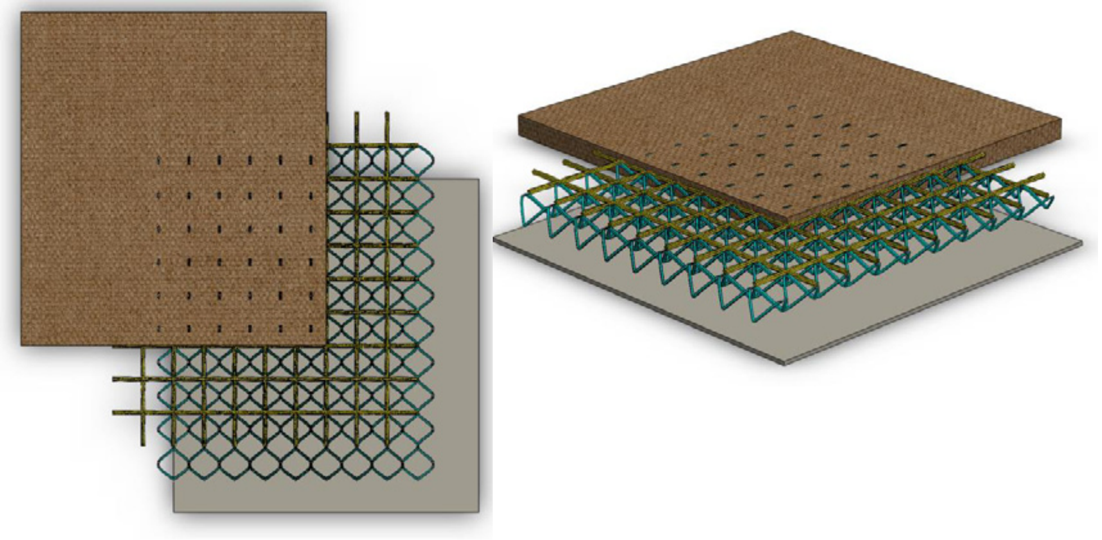

Figure 2. The propose composite steel plate shear walls with truss reinforcement.

Several models 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*., [7] derived the exact solution for linearly constitutive properties, simply supported, functional composite shell subjected to static and dynamic loadings. The authors 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 composite steel plate shear walls filled with magnetic nanoparticles is modeled and the vibrational characteristic is discussed. Also, some of vibrational modes are examined.

2 Theoretical Formulation

2.1 Constitutive Relations

In a system gather mechanical, magnetic, and thermal influences, the constitutive relations are expressed formally as [7-10]:

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

2.2 Kinematic Relations

According to the FOSD shell theory, the following representation of the 3D displacement and magnetic potentials is postulated [11-14]:

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

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

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:

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

However, the mid-surface strains as well as the curvature and twist changes are extended by Codazzi-Gauss geometric relations, as [15, 16]. The distributions of magnetic fields at any point in the composite shell are assumed as:

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

and the magnetic field changes are

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

2.3 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:

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

where $\gamma_n = (1 + \zeta/R_n)$, the subscripts n denote either of α, β or $\alpha\beta$, 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 [11, 12].

2.4 Variational Principle

The variational energy method via the Hamiltonian axiom has been used by [17, 18] 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(*6, 14*):

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

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

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

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(*5*):

$$K = \frac{I}{2}\iint_{\Omega_o}\int_{-\frac{h}{2}}^{\frac{h}{2}}\Big((\dot u_o^2 + \dot v_o^2 + \dot w_o^2) + \zeta^2\big(\dot\psi_\alpha^2 + \dot\psi_\beta^2\big) + 2\zeta\big(\dot u_o^2\dot\psi_\alpha^2 + \dot v_o^2\dot\psi_\beta^2\big)\Big)\,\gamma_\alpha\gamma_\beta\,AB d\zeta dA. \quad (9)$$

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

and external work:

$$W(S_i, G_l) = (F^S_\alpha u_o + F^S_\beta v_o + F^S_n w_o + C^S_\alpha \psi_\alpha + C^S_\beta \psi_\beta) - (F^G \vartheta_o + C^G \vartheta_1), \quad (11)$$

where F^S_α, F^S_β, and F^S_n are the distributed forces in α, β and ζ directions, respectively, while C^S_α and C^S_β 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, (*19-22*). Substituting Eqs. (1, 10, and 11) into Eq. (8) and equating the resulting equation with Eq. (9), yields after expanding the terms:

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

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

$$+ \int_{t_o}^{t_1} \iint_{\Omega_o} (F^S_\alpha u_o + F^S_\beta v_o + F^S_n w_o + C^S_\alpha\psi_\alpha + C^S_\beta\psi_\beta - F^G\vartheta_o - C^G\vartheta_1)\, ABdAdt = 0. \quad (12)$$

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 δuo, δvo, δwo, δψα, δψβ, δϑ0 and δϑ1 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[13, 23]:

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

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

$$(K_{ij} + \partial^2/\partial t^2\, M_{ij})\{\Delta\} = \{F - F^T\},$$

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 [24-26].

Parametric Analysis

In Table 1, the vibration mode scrutinized and as expected, the magnetostrictive material has a magnificent shear mode. The thickness shear modes appear higher than those of thickness stretch, but they are varied in a very orderly manner with respect to the vibrational mode.

Table 1. Non-dimensionalized frequencies of the hyperbolic paraboloidal shallow shell.

Mode†	Vibration mode							
	1	2	3	4	5	6	7	8
Thickness-Stretch	1.8346	2.7393	3.5118	4.0856	4.5378	4.9372	5.3201	5.7027
Thickness-Shear	4.6098	6.8830	8.8241	10.265	11.4019	12.405	13.367	14.329

†Thickness Stretch: $\Omega = \omega a^2\sqrt{\rho/\varsigma_{11}h^2}$, Thickness Shear: $\Omega = \omega a^2\sqrt{\rho/\varsigma_{44}h^2}$, and $\left(N = 1, {}^{a}/_{h} = 0.1,\ a/R = 0.5,\quad a/b = 1\right)$.

Conclusions

This paper discusses an economical composite steel plate shear walls developed essentially in response to the need of non-metallic replacement in offshore constructions. The said shear wall introduces some critical issues in the design, such as; perfect for corroded environment and stable at seismic event. Some comments regarding this shear walls behavior and design are worth noting:

1. At seismic effect, the thickness-stretch vibration mode shows slightly increase unlike thickness-shear mode. We expect that could be solved by grading the material properties across wall thickness at more precession using ferrite nanoparticle minimizing the dislocation effect between the steel phase and composite phase.
2. The magnetic nanoparticle could control the vibration induced into structure by applying magnetic field utilizing the so called piezo-stiffening effect.
3. However, the said shear wall still has steel plate embedded inside offering welding solution during construction.

The present results may serve as a reference in developing a prototype of this new composite shear wall for further experimentations that indeed is needed to identify the true behavior regarding the strain demand on the compression side in flexure, the compression capacity, and the flexural stiffness.

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