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Mechanical Behavior of GFRP Laminated Composite Pipe Subjected To Uniform Radial Patch Load

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Abstract. Cylindrical vessels are widely used for storage and transportation of fluids. Using composites shells can improve the corrosion resistance of the product and reduce weight therefore investigation of the mechanical behavior is important. For this purpose cylinders with 6, 12 and18-ply of GFRP , with symmetric ply sequence of $[90/0/90]_s$, $[90/0/90/0/90/0]_s$ and, $[90/0/90/0/90/0/90/0/90]_s$ with layer thickness 1.3 mm and mean radius 250 mm, are considered under uniform radial patch load. The analysis was based on the shell theory and classical mechanics of laminated composites. A code was written using MATLAB software to compute stress and deflection of the cylinder shell. In numerical simulation, each unidirectional composite ply is treated as an equivalent elastic and orthotropic panel. Analysis is focused on the area of cylinder where the patch load is applied. The results show that the analytical prediction compares well with numerical responses of previous literature. The procedure can be used to predict maximum stress and displacement in a multi-layer shell for various types of similar loading.

Introduction

Composite material is a structure which consists of two or more components of different materials that are mixed at a macroscopic level and are not soluble in each other. These different materials provide the composite singular mechanical properties. One of the advantages of the FRP composites is that their properties can be controlled effectively. In other words, desired directional property can be easily achieved by changing the material and manufacturing variables. Although composites have relatively poor resistance to impact loading, they have superior performance over metals in applications requiring high strength, high stiffness and low weight such as aircraft, sporting goods, automobiles, submarines, civil structures, robot components and electronic packaging industries.
One of the most common types of composites is GFRP (Glass Fiber Reinforced Polymer) which is made of resin matrix reinforced by fine glass fibers. Due to the improved strength, stiffness, flexibility, good thermal insulation, corrosion resistance and good fatigue life, GFRP composites have become very popular in many industries. The major problem of using these composites is the complexity of computing deformation and stress, especially in composite shells. This paper is focused on the laminated composite cylindrical shell subjected to patch loading. Fig. 1 is showing a pipeline installed on the ground and supported by curvature structure, to transfer liquid materials such as oil or water. The supports are designed to carry weights of pipeline and liquid. The reaction force feel by the curvature surface of supports is a good example of patch loading. The investigation reveals that the patch loads have a great effect on the stress states in the cylinder structure [1]. Many researchers have carried out studies numerically, experimentally and analytically to determine the stability and collapse behavior of GFRP cylinders subjected to bending and axial compression [2, 3, 4 and 5]. Earlier experimental studies have provided data on the strength of filament- wound GFRP thin-walled cylinder under combinations of internal pressure and axial loads [6-8]. In 1998, Tooth,

Banks and Rahman [9, 10 and 11] provided a series solution which predicts the behavior of a laminated cylindrical shell under different loads. In these studies a theoretical approach had been presented [9] to check the behavior of a horizontal laminated cylinder which was filled with liquid [10]. In the third paper [11] Tooth et al used the same approach to predict the behavior of the shell under a uniform radial patch load [11]. Although there were many studies conducted on composites cylinder, only a few were about mechanical behavior due to patch loading.

The aim of this study is to investigate the mechanical behavior of GFRP cylinder under the action of radial patch load. The cylinder is simply supported at the ends and the material is assumed to be linear and elastic. The cylinder is analyzed with three configurations, i.e. 6-ply, 12-ply and 18-ply of GFRP composite shell with symmetric ply sequences of $[90/0/90]_s$, $[90/0/90/0/90/0]_s$ and $[90/0/90/0/90/0/90/0\ /90]_s$. The thickness of each ply is assumed to be 1.3 mm. Fig. 2 shows the load location, and lamina sequence of the plies. Length of the cylinder (L) is 2500 mm (b=1250 mm), mean diameter (D) is 500 mm. The subtended angle of the load is assumed to be 30°, to give the area of the load equal to $13000mm^2$. A uniform load (P) of $1N/mm^2$ applied on the cylinder shell with the material properties of E_{11}=38.6e3 N/mm^2, E_{22}=8.27e3 N/mm^2, G_{12}=4.14e3 $N/mm^2$and $\nu_{12} = 0.26$.

Fig. 1. Pipeline installed on the ground

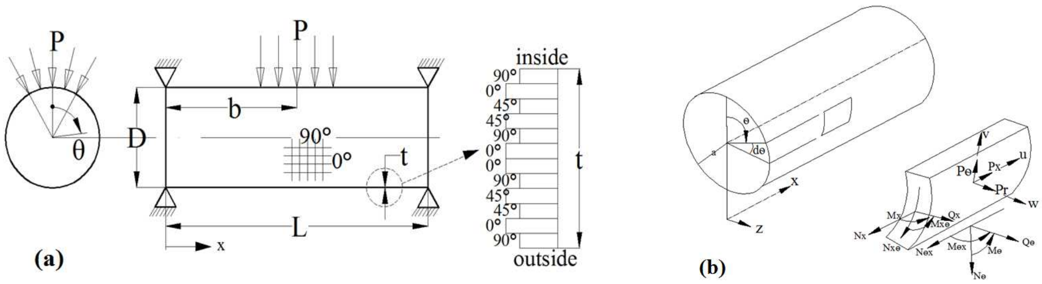

Fig. 2. (a) Multi-layered GFRP cylindrical shell subjected to radial patch loading, (b) Stress resultants

Equilibrium Equation of Cylindrical Shell

The following equilibrium equations are reproduced for a thin-walled circular cylinder based on the shell theory:

$$\frac{a\,\partial N_x}{\partial x} + \frac{\partial N_{\theta x}}{\partial \theta} + ap_x = 0 \quad (1)$$

$$\frac{a\ \partial N_\theta}{\partial \theta} + \frac{a^2\,\partial N_{x\theta}}{\partial x} - \frac{\partial M_\theta}{\partial \theta} - \frac{a\ \partial M_{x\theta}}{\partial x} + a^2 p_\theta = 0 \quad (2)$$

$$\frac{\partial^2 M_\theta}{\partial \theta^2} + \frac{a\,\partial}{\partial x}\frac{\partial}{\partial \theta} M_{x\theta} + \frac{a\,\partial}{\partial x}\frac{\partial}{\partial \theta} M_{\theta x} + a^2 \frac{\partial^2 M_x}{\partial x^2} + aN_\theta - a^2 p_r = 0 \quad (3)$$

$$aN_{x\theta} - aN_{\theta x} + M_{\theta x} = 0 \quad (4)$$

Governing equation for composite cylinder

The strain values $\varepsilon_x, \varepsilon_\theta, \varepsilon_{x\theta}$ are defined in terms of u, v and w for small strains compatibility [13]. They are defined as follows:

$$\varepsilon_x = \frac{\partial u}{\partial x} = \frac{\partial u_0}{\partial x} - z\frac{\partial^2 w_0}{\partial x^2} \tag{5}$$

$$\varepsilon_y = \frac{\partial v}{\partial y} = \frac{\partial v_0}{\partial y} - z\frac{\partial^2 w_0}{\partial y^2} \tag{6}$$

$$\gamma_{xy} = \frac{\partial u}{\partial y} + \frac{\partial u}{\partial x} = \frac{\partial u_0}{\partial y} + \frac{\partial v_0}{\partial x} - 2z\frac{\partial^2 w_0}{\partial x \partial y} \tag{7}$$

u, v, w can be expressed in terms of double Fourier series thus:

$$w = \sum_{n=0}^{\infty}\sum_{m=1}^{\infty} w_{n,m} \cos n\theta \sin {}^{\lambda x}/_{a} \tag{8}$$

$$u = \sum_{n=0}^{\infty}\sum_{m=0}^{\infty} u_{n,m} \cos n\theta \sin {}^{\lambda x}/_{a} \tag{9}$$

$$v = \sum_{n=1}^{\infty}\sum_{m=1}^{\infty} v_{n,m} \sin n\theta \sin {}^{\lambda x}/_{a} \qquad \lambda = m\pi a/L \tag{10}$$

Stress resultants

u, v and w are then used to obtain the stress resultants as it is shown in fig. 2(b),

$$N_x = \frac{1}{a}\sum_{n=0}^{\infty}\sum_{m=1}^{\infty} Z1_{n,m} \cos n\theta \sin {}^{\lambda x}/_{a} \tag{11}$$

$$N_\theta = \frac{1}{a}\sum_{n=0}^{\infty}\sum_{m=1}^{\infty} Z2_{n,m} \cos n\theta \sin {}^{\lambda x}/_{a} \tag{12}$$

$$Z1_{n,m} = -A_{11}\lambda u_{n,m} + \frac{1}{a^2}D_{11}\lambda^2 w_{n,m} + A_{12}(nv_{n,m} + w_{n,m}) \tag{13}$$

$$Z2_{n,m} = -A_{12}\lambda u_{n,m} + A_{22}\left(nv_{n,m} + w_{n,m}\right) + \frac{1}{a^2}D_{22}w_{n,m}(1 - n^2) \tag{14}$$

The terms A, B and D, form the stiffness matrix of the mentioned composite. The MATLAB software is used to solve the equations and to obtain stress and displacement.

Results and Discussion

To validate the theanalytical solution, boundary conditions and material properties which were used by Tooth, Banks and Rahman, are used here. Shell displacements in radial direction with 0, 50 and l00% fibers (is this fibre volume content) along the x-axis , were compared well with litrautre results (Fig. 3).

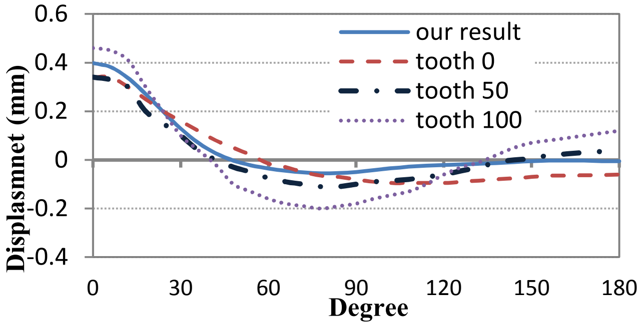

Fig. 3. Comparison of displacements in radial direction

In all analyses the maximum shell displacement in the radial direction occurs at $\theta = 0°$. Increasing of θ results in the decrease of displacement. In the Fig. 4A, the maximum radial displacement corresponds to the top of the cylinder where $\theta = 0$ degrees. As θ is increased, the amount of displacement in the radial direction decreases, and far from the patch loading location, displacements decrease to zero. In the cylinder which consists of 6 layers the maximum displacement is around 3.2mm while in the cylinder with 12 layers maximum displacement is 1.2 mm and in the cylinder with 18 layers the maximum of displacement decreases to 0.5mm. Fig. 4B shows that the displacement in circumferential direction is maximum at θ equal to30°.

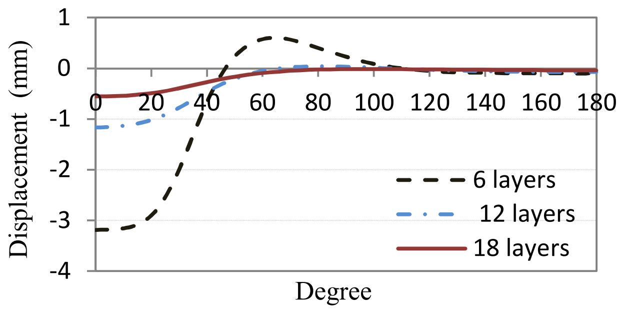

Fig. 4A. Shell displacement in radial direction

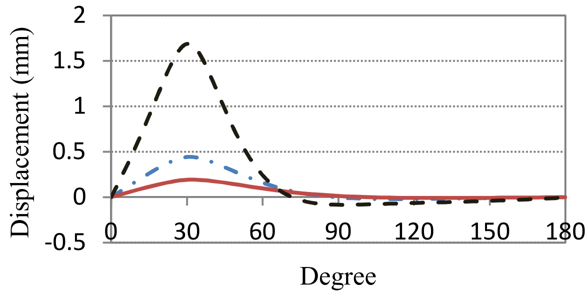

Fig. 4B. Shell displacement in circumferential direction

From Fig. 4C, the maximum stress resultant (Nx) occurs in the cylinder with 6 layers. It is observed that the cylinders experience a similar trend of Nx stress reversal. The stress is tensile from $\theta = 0°$ to around $\theta = 30°$ and compressive from around $\theta = 30°$ to $\theta = 180°$, as illustrated in Fig. 4C.

Fig. 4D shows the tensile stress resultant in the circumferential direction (N_θ). The maximum stress occurs at $\theta = 0°$. For all cylinders the stress resultants in circumferential direction fall to zero at $\theta = 30°$.

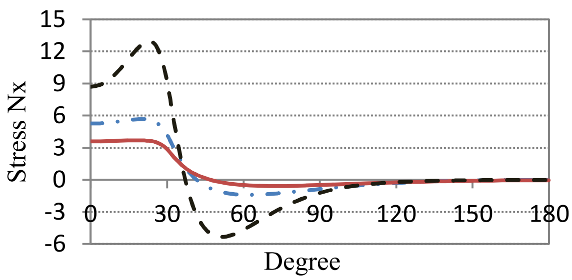

Fig. 4C. Stress resultant in axial direction (Nx)

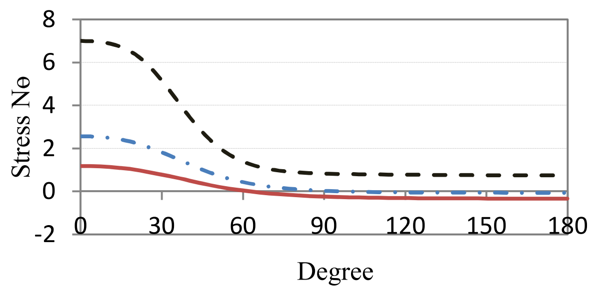

Fig. 4D. Stress resultant in circumferential direction (Nө)

Conclusion

In this study the mechanical behavior of GFRP composite cylinder subjected to radial patch loading was investigated by using an analytical solution. The results of this study indicate that the maximum displacement in radial direction and the maximum stress resultant in the circumferential directions occurred at the center of the patch loading area, while the maximum stress resultant in the axial direction occurred at around $\theta = 30°$ where the cylinder experienced both tensile and Compressive stresses.

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