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Evaluation of structural responses of natural fibre reinforced composite plates and pressure vessels

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Abstract . The present work discusses the bending, buckling and free vibration of natural fibre reinforced composite (NFC) plates initially. Numerical formulation is done based on higher order shear deformation theory and programming in Matlab environment is performed. The results for NFC plates are presented for several parametric variations. Finally, as an application of NFC panels, the cylindrical pressure vessel structure is analysed by considering flax-epoxy as inner laminate layers in combination with carbon-epoxy as outer laminate layers. The deformation and stress values are presented for various load conditions on the NFC pressure vessel.

1. Introduction

The rapid growth in applications of natural fibre reinforced polymer composites (NFC) are due to their relative high strength, corrosion and fatigue resistance, low specific weight, biodegradability, relatively good mechanical properties as compared to synthetic fibers [1, 2]. Natural fibres offer multiple benefits over their synthetic counterparts as reductions in weight and cost. Also they offer improved recyclability. Layth et al. [3] conducted a survey on NFCs and presented different surface treatments for natural fibres, changes in mechanical, thermal properties of natural fibres when subjected to various chemical treatments. They also mentioned several applications of using NFC. May-Pat et al. [4] revealed that the mechanical properties of natural fibre polymer composite depend on region of fibre surface and properties of constituents. Thomas et al. [5] discussed the dynamic behaviour of aloevera fibre reinforced composites employing FEM and experimental techniques and suggested the significance of usage of NFCs. Flax fibres have been increasingly employed as reinforcement in NFC. The mechanical properties of the natural fibres and the thermosetting resin were compared and compiled by Mussig and Hughes [6]. They observed that flax has the best properties than other natural fibres by analysing strength and stiffness. So, flax can be chosen as a natural fibre to build any eco-friendly structure. Ticoalu et al. [7] studied that in recent times the practice of employing flax fibre has increased for automobile interior, bicycle frame, table, tennis racket, building structure, etc. Hyunbum and Lee [8] observed that flax fibre has enhanced vibration absorption behaviour and is also easier to procure and less costly than other natural fibres. The ever



increasing application of NFCs also motivates researchers to investigate the shell type structures also made of NFC. The surface and chemical properties of flax can be improved by treating with enzymes [9].

The ever increasing application of NFCs also motivates researchers to investigate the aircraft fuselage made of NFC. Static analysis of fuselage plays a very important role in the structural design of aircraft. Abbishek et al. [10] carried out a fatigue analysis as well as design optimization of aluminium fuselage using ANSYS. They observed that compared to aluminium alloy the structural steel has better fatigue properties but with an added weight penalty. Han-Gi et al. [11] analyzed composite aircraft fuselage which can be efficiently developed where the stacking sequence for frame and skin are designed as [90/45/-45]_s and [45/90/-45/0/45/0/-45]_s respectively. Failure conditions of fuselage have been checked for torsional load, bending moment, shear load cases. Thus it is noted from detailed literature survey that the study on plates and cylindrical structures made of NFC is highly relevant.

This paper aims to present initially the structural responses obtained by analytical method for NFC plates. Then as an application, the present work analyses a pressure vessel made of flax fibre reinforced composites.

2. Methodology

The methodology adopted for the numerical formulation of present work is described in this section. The displacement field relation is as in Eq. (1) and is formed of the translational and rotational displacements $(u_0, v_0, w_0, \phi_x, \phi_y)$.

$$\begin{bmatrix} u \\ v \\ w \end{bmatrix} = \begin{bmatrix} u_0 \\ v_0 \\ w_0 \end{bmatrix} + z \begin{bmatrix} \phi_x \\ \phi_y \\ 0 \end{bmatrix} - c_1 z^3 \begin{bmatrix} \phi_x + \frac{\partial w_0}{\partial x} \\ \phi_y + \frac{\partial w_0}{\partial y} \\ 0 \end{bmatrix} \quad (1)$$

Where $c_1 = 4/3h^2$

Here, h refers to the laminate thickness. The governing equations are derived employing $\int_{t_1}^{t_2} \delta L dt = 0$, $L = K - (U + V)$, where L , K , U , V denotes Lagrangian, kinetic energy, strain energy, and potential energy respectively.

$$K = \int_{-h/2}^{h/2} \int \rho \left\{ \left(\frac{\partial u}{\partial t} \right)^2 + \left(\frac{\partial v}{\partial t} \right)^2 + \left(\frac{\partial w}{\partial t} \right)^2 \right\} dz dA \quad (2)$$

$$U = \frac{1}{2} \int_{-h/2}^{h/2} \int (\sigma_{xx} \epsilon_{xx} + \sigma_{yy} \epsilon_{yy} + \tau_{xy} \gamma_{xy} + \tau_{yz} \gamma_{yz} + \tau_{xz} \gamma_{xz}) dz dA \quad \text{and} \quad V = \int q w dA \quad (3)$$

The bending equation $[K]\{\Delta\}=\{F\}$, (where $[K]$, $\{\Delta\}$, $\{F\}$ denotes the stiffness matrix, displacement vector and the load vector respectively), is obtained by following the general mathematical formulation steps as done for laminated composite plates [12]. Subsequently, geometric stiffness matrix $[K_G]$ linked with the membrane forces is calculated and the critical buckling load is evaluated by solving the linear eigenvalue problem $([K]+\lambda_{cr}[K_G])\{\Delta\}=\{0\}$.

For free vibration, a harmonic solution as in Eq. (4) is assumed:

$$U_{mn}(t) = U_{mn}^0 e^{i\omega t}, V_{mn}(t) = V_{mn}^0 e^{i\omega t}, W_{mn}(t) = W_{mn}^0 e^{i\omega t}, X_{mn}(t) = X_{mn}^0 e^{i\omega t}, Y_{mn}(t) = Y_{mn}^0 e^{i\omega t} \quad (4)$$

Where $i = \sqrt{-1}$ and ω is the frequency of the free vibration. The eigenvalue problem (as in Eq. (5)) for analysis of free vibration can be obtained [12] by applying Eq. (4) in the governing equation.

$$([K] - \omega^2[M]) \{\Delta\} = 0 \quad (5)$$

The natural frequency is estimated from Eq. (5) and noted the fundamental frequency values [12]. The above mathematical formulation is coded in Matlab software for NFC panel.

3. Results and discussions

Consider a square plate of three layers (0/90/0) made of flax fibre reinforced in epoxy matrix. The material properties for flax epoxy are considered as: $E_{11} = 10.8$ GPa, $E_{22} = E_{33} = 0.4$ GPa, $\mu_{12} = \mu_{13} = 0.4$, $\mu_{23} = 0.4$, $G_{12} = G_{13} = 0.74$ GPa, $G_{23} = 0.74$ GPa, $\rho = 1250$ kg/m³. The side to thickness ratio varies from 10 to 100 and analysis was performed of sinusoidal and uniformly distributed loads (SSL and UDL). The maximum deflections observed for above cases are presented in Fig 1. The results were presented in nondimensional form using the nondimensional equations in [12]. Nondimensional central deflection of NFC plate decreases as side-to-thickness ratio (a/h) increases. Nature of variation is similar to the variation of behaviour of composites made of synthetic fibres [12]. Then the critical buckling loads were calculated (as in Fig 2) for a square plate of three layers (0/90/0) made of flax fibre reinforced in epoxy matrix. The side to thickness ratio was varied from 10 to 100 and analysis was performed for uniaxial and biaxial loads. The vibration analysis was performed for the same structure with SSL loading. Natural frequencies were calculated for plates with side to thickness ratio varying from 10 to 100 (as in Fig 3).

Three layered angle ply laminates ($\theta/-\theta/\theta$) made of flax fibre reinforced in epoxy matrix were considered next. The SSL loading condition was taken and side to thickness ratio was taken as 10. The ply angles (θ) were varied from 10 to 90 and calculated the nondimensional centre deflection of NFC plates as presented in Fig 4. The analysis was repeated for moderate thick and thin plates, i.e., for the side-to thickness ratios of 50 and 100 respectively as in Fig. 4. Similarly the critical buckling loads for three layered angle ply laminates with ply angle varied from 10 to 90 were calculated. The results are presented in Fig 5. Finally, the natural frequencies were estimated for three layered angle ply NFC laminates with ply angle varied from 10 to 90 as in Fig 6. The results present the numerical value of maximum deflections, buckling loads and natural frequencies for various cases. Also it is noted that flax epoxy with (45/-45/45) orientation has better performance.

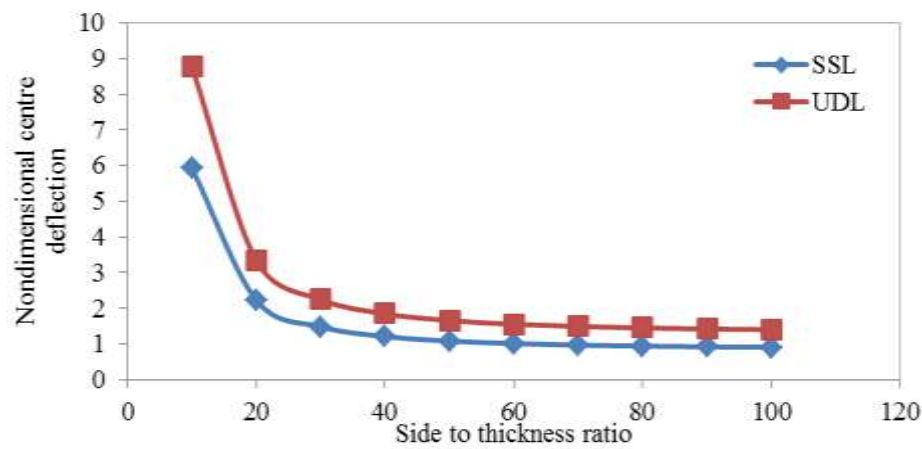


Figure 1. Nondimensional central deflection of NFC plate subjected to UDL and SSL for various a/h ratios

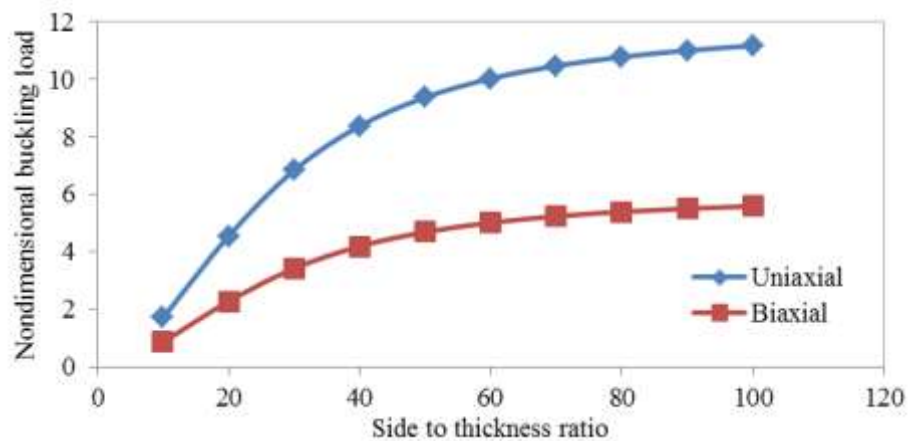


Figure 2. Nondimensional buckling loads of NFC plate subjected to uniaxial and biaxial loads for various a/h ratios

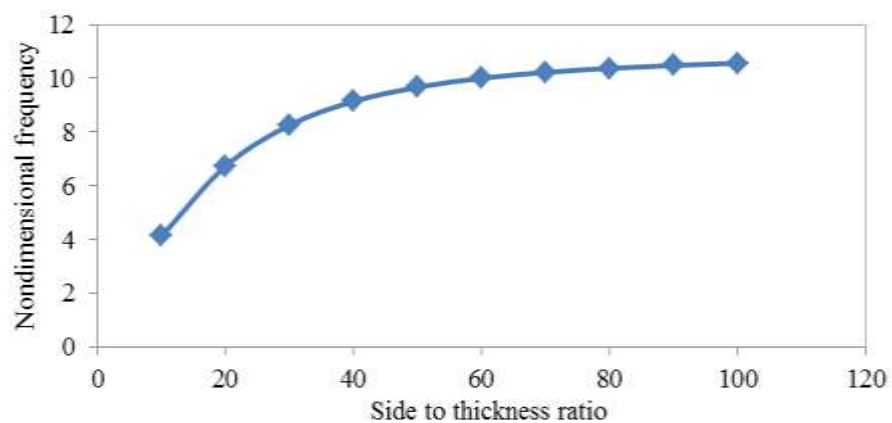


Figure 3. Nondimensional frequency of NFC plate for various a/h ratios

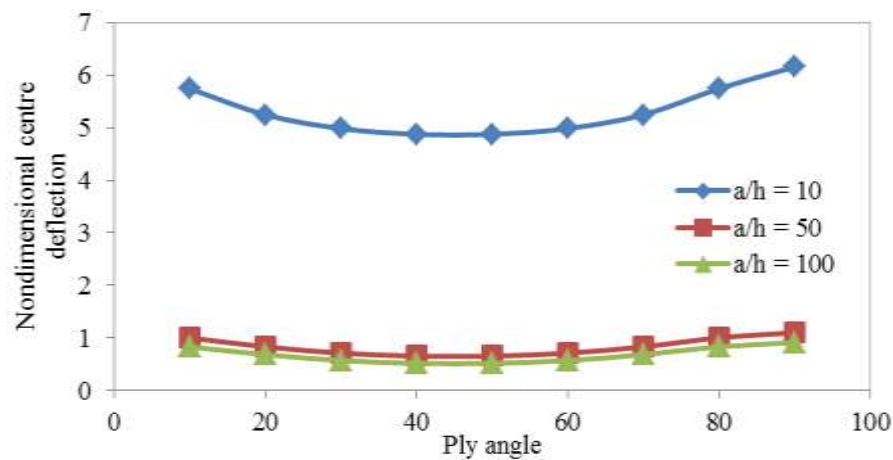


Figure 4. Nondimensional central deflection of three layered angle ply NFC plate for various ply angles

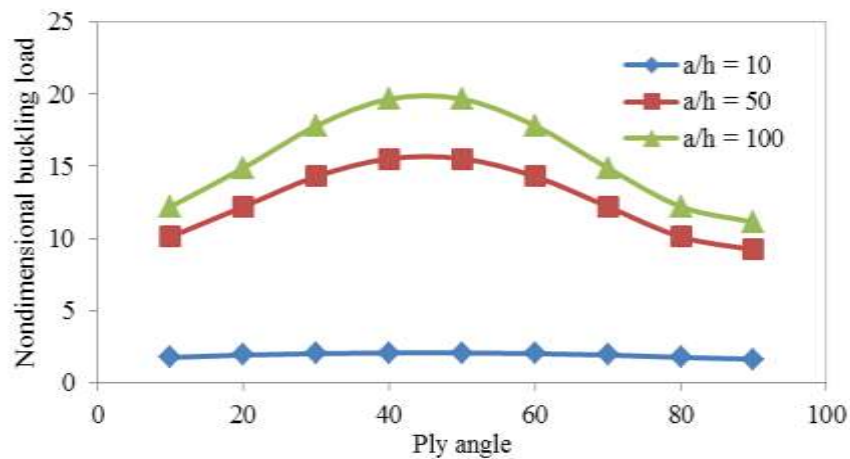


Figure 5. Nondimensional buckling load of three layered angle ply NFC plate for various ply angles

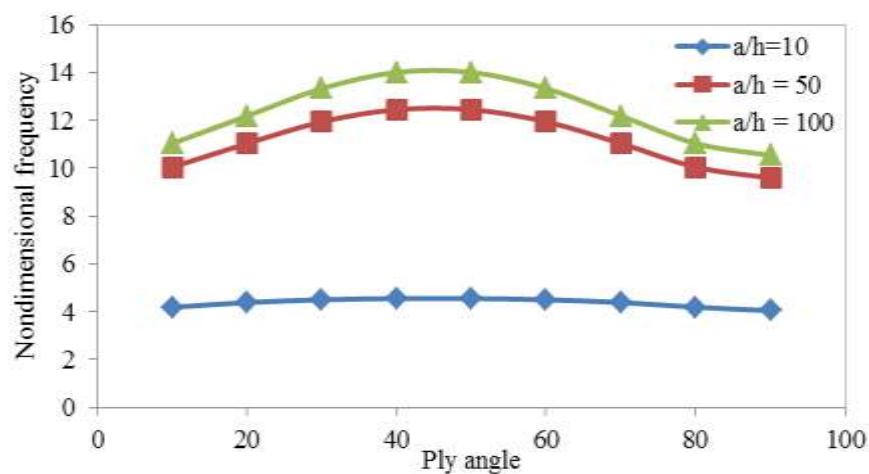


Figure 6. Nondimensional frequency of three layered angle ply NFC plate for various ply angles

Finally, pressure vessel structures made of carbon epoxy alone and pressure vessel structure made of carbon epoxy outer layers and flax epoxy inner layers are analysed and the results are compared. Both pressure vessels were of same size and support conditions, but with only material difference as discussed above. Analysis of fuselage panel has been presented as an application of NFC panels. Sample cases of modelling and post processing results are shown in Fig 7. Length of the structure was considered as 15 m for the analysis. Geometric model is created in the Solidworks software where skin, bulkheads, longerons, stringers are drawn individually and later assembled together. The thickness considered for various parts are: Skin - 0.005 m, Longerons - 0.250 m, Stringers - 0.125 m, Bulkhead - 0.150 m. The geometric model of the fuselage is created in Solidworks and then imported to ANSYS for meshing and analysis. For smooth transition of meshing between different parts, meshing is done with proper smoothening level and apt element size. The meshed model has 37000 nodes and 35000 elements. Carbon epoxy is used for top and bottom layers of structure to avoid the absorption of moisture content from atmosphere. The material properties of Carbon epoxy is considered as: $E_{11} = 121$ GPa, $E_{22} = E_{33} = 8.6$ GPa, $\mu_{12} = \mu_{13} = 0.27$, $\mu_{23} = 0.4$, $G_{12} = G_{13} = 4.7$ GPa, $G_{23} = 3.1$ GPa, $\rho = 1490$ kg/m³. The stacking sequence for the skin was [45/90/-45/0/45/0/-45]_s and the stacking sequence for longerons, stringers, bulkhead was [90/45/-45]_s. The ends are defined to be fixed supports and internal pressure is applied. Internal pressure of 7 psi, 8 psi, 9 psi, 10 psi, 11 psi (corresponding values in SI units are 48263.3 N/m², 55158.1 N/m², 62052.8 N/m², 68947.6 N/m², 75842.3 N/m² respectively) are applied. The results of static analysis are summarized in Table 1 for two types of fuselage structure and for loading 7 to 11 psi. The total deformation and equivalent stresses are presented.

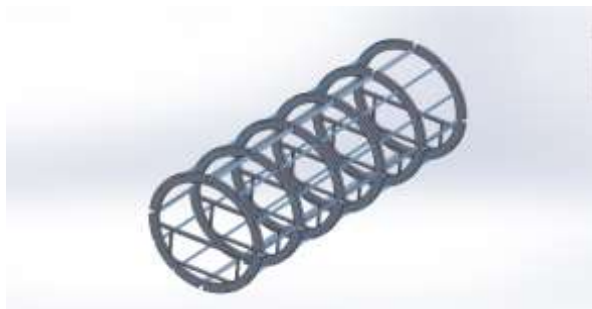


Figure 7a. Modelling of bulkhead, longerons, stringers

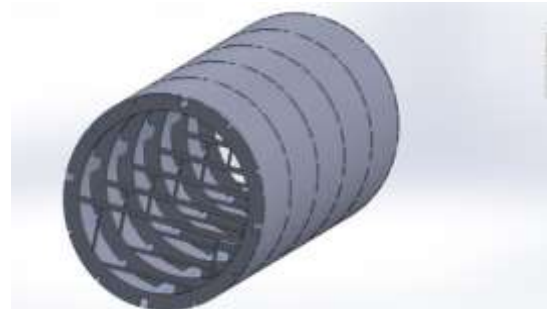


Figure 7b. Assembly with skin

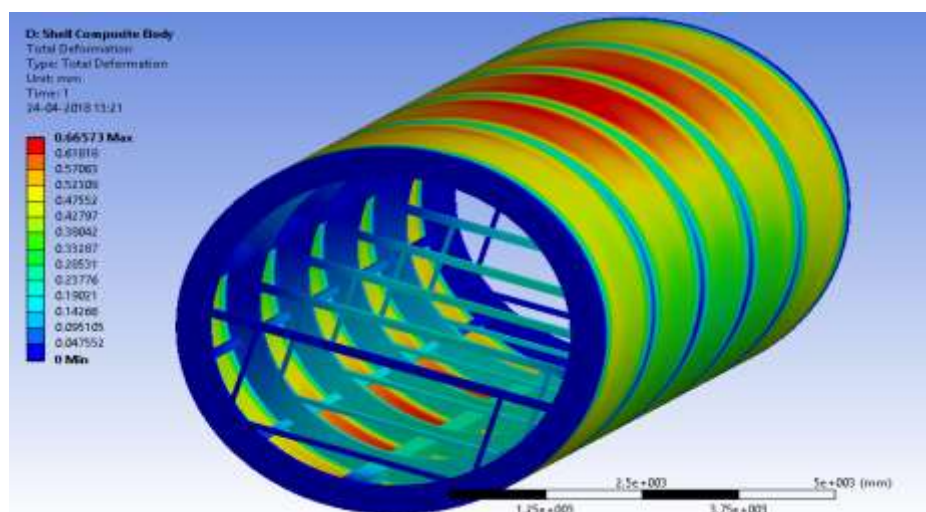


Figure 7c. Evaluation of maximum displacement of fuselage structure made of carbon epoxy outer layers and flax epoxy inner layers for 7 psi internal pressure

Table 1. Static analysis of pressure vessel structures made with carbon epoxy and with NFC inner layers along with carbon epoxy outer layers

Differential Pressure (Pa)	Maximum Deformation (mm)		Maximum Equivalent Stress (MPa)		Maximum Shear Stress (MPa)	
	Carbon epoxy	NFC	Carbon epoxy	NFC	Carbon epoxy	NFC
48263.3 (7 psi)	0.48	0.66	16.91	20.45	8.57	10.37
55158.1 (8 psi)	0.55	0.76	19.30	23.43	9.78	11.88
62052.8 (9 psi)	0.62	0.85	21.76	26.42	11.03	13.40
68947.6 (10 psi)	0.68	0.94	23.86	28.97	12.10	14.69
75842.3 (11 psi)	0.76	1.04	26.32	31.96	13.34	16.21

The maximum equivalent stress for the pressure vessel structure made of flax is well below the maximum strength of the material as presented in Table 1. Thus this study presents the reasonable strength and other mechanical properties of NFC and thereby signifies the usage of NFC in possible applications.

4. Conclusion

A detailed study on bending, buckling, and vibration responses of NFC has been presented in this paper. Mathematical formulation as well as programming in Matlab software was carried out and got the detailed results for bending, buckling and vibration analysis of NFC plate structure. The deformation values, buckling loads and natural frequencies are presented for NFC plate structure for several parametric variations. Finally, the analysis of pressure vessel structure made of carbon epoxy alone and pressure vessel structure made of carbon epoxy outer layers and flax epoxy inner layers is presented and the results are compared. It has been observed that the maximum equivalent stress for the fuselage made of flax is well below the maximum strength of the material. Thus the present study signifies the feasibility of employing natural fibres which helps in a sustainable development.

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