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Instability Analysis of a Woven Fibre Composite Plate

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Abstract*: *The instability behaviour of a woven fibre composite plate in respect of its free vibration and buckling analysis has been presented in this paper. The woven fibre composite plate has been prepared by hand layup with bidirectional woven glass fibres in epoxy matrix. The mechanical properties of the woven fibre composite plate have been characterised experimentally and a finite element investigation has been done for the instability analysis. Modal response of the plate and the critical buckling load leading to instability of the plate to varying parameters are studied and numerical results have been presented.

Keywords* : *woven fibre composite, instability analysis, finite element method, buckling, free vibration

I. INTRODUCTION

Normally, structures comprising of composite materials are now-a-days being utilized in various fields of engineering applications demanding light weight structures. In recent years, laminated composite structures are being used in various sectors of engineering applications considering their superior strength, durability and hygrothermal resistivity. Due to their low weight to stiffness ratio and high fatigue strength, thin laminated composite structures have almost replaced their metallic counterpart satisfying the requirements of a large number of structural applications. In addition to the advantages of high strength (as well as high stiffness) and light weight, structural properties of the laminated composite structures can be tailor made by changing the lamina sequence, effectively designing the number of piles and proper selection of the materials of the composite structure. In the present days, laminated composite structures with bidirectional woven fibers are gaining importance as they can be characterized by balanced in-plane properties with higher resistance to fracture and impact. These light weght composite structures however are prone to undergo large amplitude vibration and buckling due to in-plane loading leading to structural instability. Hence the analysis pertaining to the stability of such composite structure with respect to buckling and free vibration plays a significant role for their proper characterisation for future applications. Lot of research work has been carried out by many pioneers to study the static and dynamic behaviour of composite plates and are available in literature. However, researches pertaining to woven fibre composite plates are very limited. Panda et al. [1] carried out an experimental as well as numerical investigation for the free vibration analysis of woven glass fibre reinforced composite plates with delamination under hygrothermal environment. The delamination and the hygrothermal parameters are seen to have great influence on the vibration characteristics the plate. Rajesh and Pitchaimani [2] carried out an experimental investigation to study the characteristics free vibration of natural fibre fabric polymer composite beam and also the buckling behaviour corresponding to axial in-plane compressive load. With increasing number of fabric layers the buckling load is found to increase. Also strength corresponding to buckling is seen to be influenced by the weaving pattern of the fabric. For woven fibre composite doubly curved panels with delaminated strip, the natural frequency of free vibration is found to reduce with increase of moisture by Panda et al. [3] who carried out a finite element investigation to study the effects of damp environment on the natural frequencies of vibration. An experimental investigation was carried out by Chavan and Joshi [4] to study the effect of boundary condition on the free vibration response of woven fibre composite plates. Testing for a three point bending and tensile strength were performed on woven fibre composite laminated cross ply plates by Sahoo et al. [5] to address their behaviour in flexure corresponding to different parametric variations. Later on, a free vibration study for woven fibre laminated composite plates for varying geometrical parameters was carried out by Mishra and Sahu [6] experimentally. On the other hand, an experimental study for the free vibration behaviour to determine the natural frequency of woven fibre composite plates with delamination was carried out by Muhannad Al-Waily [7] and came to a conclusion that there is a reduction in the stiffness and natural frequency of such plates with delamination. Ratha M.K. [8] carried out a numerical study of laminated composite angular plates wherein the effect of moisture and temperature on the buckling and free vibration behaviour of the woven fibre composite plates are studied taking into account of material and geometrical parameters. Dynamic instability of woven fibre laminated composite plates increases with the increase in moisture content and temperature [9].

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Mohan Kumar et al. [10] carried out buckling analysis of woven fibre composite plates considering the effect of fibre orientation, aspect ratio etc. using finite element method. Considering dynamic loads for the failure analysis of woven fabric composite plates Dambal and Sharma [11] developed a finite element transient analysis using ANSYS for different boundary criteria.

Validation of the experimental results on free vibration of bi-woven Glass/Epoxy composite plates was carried out by Dhanduvari et al. [12] using finite element analysis in ANSYS. From the fore going discussions it is obvious that the instability analysis of woven glass fibre-epoxy laminated composite plates are not fully explored and still needs greater investigations. Keeping in view of this, the present work is aimed at carrying out a finite element analysis of woven fibre composite plates using ANSYS. The plates are cast through hand layup and tested for their material properties. These properties are then used to perform the buckling and free vibration analysis of the woven fibre composite laminated plates. Effects of different parametric variations have been considered for analysis and numerical results are presented.

II. EXPERIMENTAL SETUP

For the instability analysis with respect to buckling and free vibration of the laminated plates using finite element method, it is necessary to know its material properties. To determine the properties of the woven fibre composite plate experimentally, the plate was cast and its mechanical properties were tested using a universal testing machine by uni-axial tension test. Standard methodology has been adopted for casting of the laminated composite plate, wherein equal proportion by weight of fibre and matrix has been taken. Major ingredient materials used in the process of fabrication are: E-Glass woven fibre (bi-directional), epoxy resin as matrix, a hardening agent which also acts as catalyst. The amount of hardening agent is to be taken as 1/10th of the weight of the matrix. Also, a releasing agent is required. Here, polyvinyl chloride has been adopted as the releasing agent. Different layers of the woven fibres are laid in proper sequence using hand layup methodology. Contact moulding process has been adopted for the laying up of the plies [6]. After the plates being cast, they are allowed to get hardened for a minimum period of 48 hours so that they can be used for subsequent work for cutting into proper shape and desired dimensions before testing. A typical casting process is shown in fig.1.

Fig. 1 Fabrication of the woven fibre composite plate (a) Casting of plate, (b) Releasing of entrapped air, (c) plate after 24-hours of curing.

After 24 hours of curing, the specimen was cut into sizes having length of 200 mm, width 25.5 mm and 5mm thick. The mechanical properties were determined in a simple tension test using a UTM of 100 KN capacity. The elastic modulii of the plate specimen were determined for a 8-layered laminate by conducting tensile tests on specimens along 0^0, 45^0 and 90^0 respectively for the longitudinal direction, 45^0 and transverse directions to determine the parameters E_x, E_{45}, E_{90} and μ_{xy}.
The material constants of the woven fibre composite plate corresponding to the experimental results are presented in Table-1. The following equation [13] was used to determine the in-plane modulus of rigidity, G_{xy}.

$$G_{xy} = \frac{1}{\frac{4}{E_{45}} - \frac{1}{E_x} - \frac{1}{E_y} + \frac{2\mu_{xy}}{E_x}} \qquad (1)$$

Table- I: Material properties of the woven fibre composite plate

Number of layers of laminates	Elastic Properties					
	E_x (MPa)	E_y (MPa)	E_{45} (MPa)	G_{xy} (MPa)	μ_{xy}	ρ Kg/m^3
8	7750	7750	7140	2890	0.17	1500

III. FINITE ELEMENT MODELLING

To carry out the free vibration and buckling analysis of the woven fibre laminated composite plate to characterize its instability behavior, a finite element model of the woven fibre composite plate is developed in ANSYS. SHELL281 element has been employed for modelling the plate.
For thin structures and structures having moderate thickness SHELL 281 element is quite efficient. It is a 8-noded element and has six degrees of freedom, three translations, u_x, u_y and u_z and three rotations θ_x, θ_y and θ_z . The element is appropriate for linear as well as non-linear analysis and has the capability of modelling composites with layup options.

A typical model of the plate for the analysis is depicted in Fig. 2.

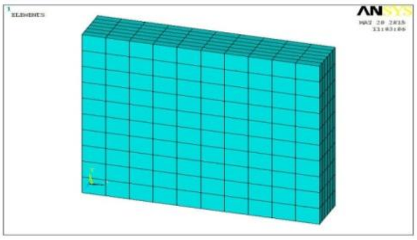

Fig. 2. A typical Finite Element model of a woven fibre composite laminated plate

A. Validation of the Model

The finite element model developed in ANSYS was first validated for its accuracy comparing the results obtained by the model with previous literatures [14, 15]. For this, the dimensions, the material properties and the lamina sequence of the plate are considered to be same as those in the references [14, 15]. The comparisons are shown in Table-II and Fig.3.

Table-II Comparison of results of present study with those of the reference.

Parameters	*Ref*	*Present Study*
Non-dimensional buckling load	35.27 [5]	35.92
Natural frequency	41.347 [15]	41.292

B. Buckling Analysis

With the accuracy of the present ANSYS model being validated, the study here is focused on static stability for buckling behaviour of woven fabric composite plates. The rectangular laminated composite plate having dimensions given in Table-3 are considered for evaluating the critical buckling load using Eigen-buckling analysis in the ANSYS APDL environment. The plate is considered to be simply supported on all four edges to evaluate the critical buckling load. Effects of various geometric parameters on the buckling strength of the plate have been investigated and the results are presented. The material properties of the plate were considered as those obtained experimentally. The critical buckling loads are converted into non-dimensional form using the equation

$$\bar{\lambda} = \frac{\lambda_{cr} a^2}{E_y h^3} \quad (2)$$

Where $\bar{\lambda}$ = non-dimensional buckling load

λ_{cr} = critical buckling load for the plate

a = larger dimension of the plate

E_y = Transverse Modulus of Elasticity, and

h = thickness of the plate.

- **Effect of Number of Layers and fibre orientation angle of Laminate**

The number of layers of plies and the fibre orientation angle have great influence on the critical buckling load of the laminated plate. To characterise these effects, in this section, investigations have been carried out to find the critical buckling load for the plate corresponding to three different layers, namely 8 and 12 numbers of layers of plies for fibre orientation angles of 15^0, 30^0 etc. upto 90^0. The dimensions of the plates considered are as given in Table-3.For each case, the plate is considered to be simply supported on all four edges.

Table-III Dimensions of plate for analysis

No. of layers	Size of plate	Thickness of plate
8	0.255m x 0.255m	0.0033m
12	0.255m x 0.255m	0.0053 m

The variation of critical buckling load with different fibre orientation angle for 8-layer and 12-layer laminates have been represented in Fig.4 for simply supported boundary conditions.

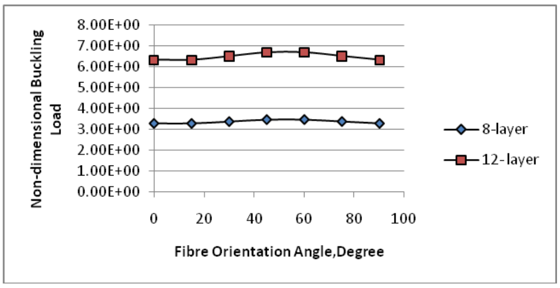

Fig.4 Non-dimensional buckling load for 8 and 12 layers of plate for different fibre orientation angle.

From the Fig., it is observed that with the increasing number of layers, the buckling strength is more increasing the stability of the plate, being maximum corresponding to a fibre orientation angle of 50^0.

- **Effect of laminae sequence**

This section provides the investigation on the effect of laminae sequence on the buckling loads for symmetric cross-ply and anti-symmetric angle ply laminates. In laminated composite plates, the lamina sequence influences the buckling strength greatly. Symmetric and anti-symmetric behaviour of the plate plays a great role in influencing the buckling of such plates. Hence symmetric cross-ply and anti-symmetric angle ply laminates are considered in the present analysis to evaluate their critical buckling loads. The size of the plate considered is (0.255×0.255) m and the thickness of the plate is 0.00333m. The critical buckling load for $0^0/90^0$, $0^0/90^0/90^0/0^0$ and $-45^0/45^0/-45^0/45^0$ laminates are shown in Table-IV.

Table- IV Critical buckling loads (Non-dimensional) for symmetric cross-ply and Anti-symmetric angle ply laminated plates.

Ply orientation	Critical buckling loads
$0^0/90^0$	0.0515
$0^0/90^0/90^0/0^0$	0.4120
$-45^0/45^0/-45^0/45^0$	0.4350

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It is observed from the results that the efficiency corresponding to critical buckling load is more in case of anti-symmetric angle ply laminated plate as compared to symmetric cross ply laminated plate of same dimensions and material properties.

- **Effect of Aspect Ratio**

Aspect ratio greatly influences the buckling behaviour of woven fibre composite laminated plates. The behaviour of a plate is similar to a column for large aspect ratio, where as if the aspect ratio is less than a particular value, the plate does not fail in buckling.

To study the effect of aspect ratio on the buckling strength of the plate, investigations have been carried out in this section to evaluate the critical buckling load for different values of a/b ratio where a and b are respectively the long and short side of the plate. The critical buckling load for varying aspect ratio is presented in Table- V.

With decreasing of aspect ratio an increasing trend of buckling load is found to be occurring.

Table-V Variation of (Non-dimensional) critical buckling load for varying a/b ratio.

Aspect Ratio (a/b)	Critical Buckling Load
1	0.4120
0.9	0.5150
0.8	0.6780
0.7	0.9600
0.6	1.490
0.5	1.950

C. Free Vibration Analysis

This section presents the parametric variation of the free vibration response of woven fibre composite plates. The modal analysis of the plate was considered and the results corresponding to the natural frequency of the plate are presented.

The material properties of the woven fibre composite plates are considered as per experimental results. The natural frequency of the plate are converted into non-dimensional form using the equation

$$\bar{\omega} = \frac{\omega a^2}{h}\sqrt{\frac{\rho}{E_y}} \qquad (3)$$

where

$\bar{\omega}$ = non-dimensional frequency

ω = plate natural frequency

a = larger dimension of the plate

E_y = Transverse Modulus of Elasticity,

h = thickness of the plate.

ρ = density of the plate material

- **Effect of fibre orientation angle for different boundary condition**

The natural frequency of the woven fibre composite plate for varying lamination angle for a 8-layer plate for different boundary conditions have been represented in Table-VII corresponding to first, second and third mode.

- **Effect of layup sequence**

To investigate the effect of layup sequence on the natural frequency of the woven fibre composite plate, three types of layup sequences [(0/90), (0/90/90/0), (-45/45/-45/45)] have been considered. The results corresponding to different boundary conditions are represented in Table-VIII.

- **Effect of Aspect Ratio**

To study the effect of aspect ratio on the natural frequency of the plates, six different types of aspect ratios for laminated composite plates are considered i.e. for b/a values (0.5,0.6,0.7,0.8,0.9 and 1).

All plates are considered to be composed of four layers with a stacking sequence of $[(0/90)_4]$. The natural frequencies for free vibration are found for clamped edges, cantilever and simply supported boundary condition. The results are presented in Table-IX.

Table-VII Variation of non-dimensional frequency with lamination angle for different boundary conditions.

Fibre orientation angle (Degree)	Clamped-Free			Clamped			Simply Supported		
	Mode-1	Mode-2	Mode-3	Mode-1	Mode-2	Mode-3	Mode-1	Mode-2	Mode-3
0	1035.074	2536.484	6434.848	10517.33	21538.78	21538.78	1418.715	7217.156	7217.156
15	1026.527	2563.432	6379.864	10509.16	21506.66	21506.66	1428.406	7191.569	7213.89
30	1010.957	2618.254	6269.35	10492.83	21442.42	21442.42	1447.95	7164.349	7186.125
45	1003.39	2646.236	6213.821	10489.57	21403.76	21403.76	1457.803	7162.171	7162.171
60	1010.957	2618.254	6269.35	10492.83	21442.42	21442.42	1447.95	7164.349	7186.125
75	1028.541	2578.839	6619.401	10863.03	23722.38	23722.38	1428.406	7191.569	7213.89
90	1034.53	2536.484	6434.848	10517.33	21538.78	21538.78	1418.715	7217.156	7217.156

Table-VIII Variation of non-dimensional frequency with layup sequence for different boundary conditions.

Layup sequence	Clamped-Free			Clamped			Simply Supported		
	Mode-1	Mode-2	Mode-3	Mode-1	Mode-2	Mode-3	Mode-1	Mode-2	Mode-3
(0/90)	258.7549	636.2443	1610.672	2728.387	5723.858	5723.858	354.7333	1805.623	1805.623

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(0/90/90/0)	517.401	1271.182	3220.201	5307.389	10950.67	10950.67	709.4665	3610.592	3610.592
(-45/45/45/-45)	501.8855	1326.439	3109.905	5291.819	10889.7	10889.7	728.9562	3583.263	3583.263

Table-IX Variation of non-dimensional frequency with aspect ratio for different boundary conditions.

Aspect ratio	Clamped-Free			Clamped			Simply Supported		
	Mode-1	Mode-2	Mode-3	Mode-1	Mode-2	Mode-3	Mode-1	Mode-2	Mode-3
0.5	515.8767	2211.367	3227.822	14472.42	18812.4	26947.42	1791.251	4630.641	10454.72
0.6	516.3122	1898.498	3228.966	10584.84	15335.3	23867.19	1348.27	4210.688	9438.322
0.7	516.6388	1675.075	3229.456	8303.241	13384.16	20164.7	1082.165	3960.099	7022.26
0.8	516.911	1507.29	3229.02	6876.36	12207.7	15896.04	910.1881	3798.793	5454.378
0.9	517.1832	1376.306	3226.951	5941.619	11455.88	12997.63	792.8691	3688.878	4379.399
1	517.401	1271.182	3220.201	5307.389	10950.67	10950.67	709.4665	3610.592	6390.207

D. Conclusion

The present study is carried out to predict the buckling and free vibration behaviour of woven glass fibre reinforced laminated composite plates. The material properties are determined experimentally and the critical buckling loads of plates are found corresponding to these material properties with simply supported boundary conditions using finite element simulation modelling in ANSYS for varying parametric variations. However, to study the effect of parametric variation on the natural frequency of the plate, three different boundary conditions have been considered. It is seen that the natural frequency for Clamped plate is highest and for Clamped-Free plate it is the lowest. Similarly, the increase in aspect ratio shows an increasing trend of natural frequency of the plate. The present study will give an insight into the stability of woven fibre laminated composite plates for their future design.

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