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Effect of volume fraction on stability analysis of glass fibre reinforced composite plate

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Abstract. This paper deals with an experimental investigation to study the effect of fibre content on the stability of composite plates with various aspect ratios. Epoxy based glass fibre reinforced composite plates with aspect ratio varying from 0.4 to 1 and with volume fractions of 0.36, 0.4, 0.46, 0.49 and 0.55 are used for the investigation. From the study it is observed that for plate with aspect ratio of 0.5 and 0.4 there is no buckling and the plate got crushed at the middle. As the volume fraction increases the buckling load also increases to a limit and then began to reduce with further increase in fibre content. The optimum range of fibre content for maximum stability is found between 0.49 and 0.55. Polynomial expressions are developed for the study of buckling behaviour of composite plates with different volume fractions in terms of load and aspect ratio.

Keywords: buckling; composite plate; volume fraction; aspect ratio; polynomial equation.

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1. Introduction

Fibre-reinforced composites are used extensively in the form of relatively thin plate, and the load carrying capability of these composite plates against buckling has been intensively considered by researchers under various loading and boundary conditions.

There have been numerous studies on the buckling behaviour of fabric woven composite laminated structures (Roberts *et al* 1995, Balamurugan *et al* 1998, Ai Kah Soh *et al* 2000, Featherston and Watson 2005, Akhbari *et al* 2008, Kormaníková and Mamuzic 2008, Aymerich and Serra 2008) which find widespread applications in many engineering fields namely aerospace, biomedical, civil, and marine and mechanical engineering because of their ease of handling, good mechanical properties and low fabrication cost. They also possess excellent damage tolerance and impact resistance. The buckling behaviour of glass-epoxy plates has been investigated by Buket Okutan Baba and Aysun Baltaci (2007) numerically and experimentally and they focussed on the influence of boundary conditions, cut-out and length/

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thickness ratio on the buckling response of symmetrically laminated composite plates. Pein and Zahari (2007) conducted an experimental study on woven glass epoxy composite plate with cut-outs to investigate the ultimate load of the woven fibre glass laminated plates under quasi–static compression load and compare the results corresponding to various orientation angles. An approximate analysis for buckling of rectangular orthotropic plate and symmetric angle ply plates with a central circular hole was presented by Michael P. Nemeth (1990). He investigated the influence of orthotropy, hole size and aspect ratio of the plate on the buckling load for simply supported and clamped boundary conditions and compared with the finite element analysis and experimental results. Fatai Olufemi Aramide *et al* (2008) studied the effect of volume fraction on the mechanical properties of polymer matrix composite and they observed that the ultimate tensile strength, modulus of elasticity and the extension to break of polyester resin matrix composite increases with increase in fibre volume fraction to a certain limit and then begin to reduce with further increase in fibre content. Shrivastava *et al* (1999) investigated the effect of aspect ratio on buckling of composite plates and observed that for plates with two sides simply supported and two sides free the buckling load decreases continuously with increasing aspect ratio and becomes almost negligible beyond an aspect ratio of 3, for plates less than 0.5 as aspect ratio, the plates fail by crushing and not by buckling. The effect of fibre weight fraction on the buckling parameter of laminated composite plates was investigated by Chaitalli Ray (2004). She evaluated the buckling parameter with eight noded isoparametric elements and observed that the rate of increment of buckling parameter for lower fibre weight fraction is more and gradually decreases with the increment of fibre weight fraction in the laminae.

Mohd Aidy Faizal *et al* (2006) investigated the effect of curing pressure and ply arrangement in the tensile property of hand-layup specimen made of E-glass / polyester composite and found that their characteristic effects are consistent, and the structural arrangements of the fibre lay-ups have shown to adversely affect the ductility behaviour of the GFRP composite. Kyung-Su Na and Ji-Hwan Kim (2006) conducted studies on volume fraction optimization of Functionally Graded Materials (FGMs) considering stress and critical temperature as the constraints. They also done the optimal designs of FGM panels for stress reduction and improving thermo-mechanical buckling behaviour. An experimental investigation to assess the stability of composite plates under varied volume fractions has not been reported so far and the present study focused on that aspect.

In this paper the stability of glass fibre reinforced composite plate subjected to in-plane compressive load is presented. Experimental studies have been performed for the plates with various aspect ratio and fibre content. Variation in buckling load with respect to aspect ratio for plates with different volume fraction of fibres is analysed. Subsequently equations were developed to study the buckling behaviour of plates with various volume fractions in terms of load and aspect ratio. Using the results of these analyses, the optimum range of fibre content for the stability of glass fibre reinforced composite plates was found.

2. Experimental investigation

In the present study the composite plate is prepared using woven E-glass fiber as the reinforcement, Epoxy AY103 as the matrix and HY991 as the hardener. In addition to these a release film was used for easy removal of the specimen. The composite specimen is prepared by using vacuum bag moulding.

2.1 Testing and property evaluation

Various mechanical properties like tensile strength and hardness of the prepared specimen are evaluated to check the suitability of the specimen for the testing. A scanning electron microscopy analysis is also carried out to reveal the topology of the composite surface. Calculation of the volume fraction of the prepared specimen is done using the resin burn out method.

2.1.1 Tensile strength

The tensile strength of the prepared specimen is found out using the Tinius Olsen universal testing machine with a capacity of 25kt. It is tested as per ASTM D3039 standard. The specimen is axially loaded; the test specimens are placed between the two extremely stiff machine heads, of which the lower one was fixed during the test, and the upper head was moved upwards by a servo hydraulic mechanism. The results of the tensile test on the prepared specimen with various volume fractions are given in Table 1.

2.1.2 Shore D hardness test

The hardness test is conducted on Epoxy AY103 along with the Hardener HY991 to check whether the matrix has cured properly and is able to achieve the standard value of D80 at 23^{o}C. The specimen is cured for 16 hours and tested and was found to achieve a hardness value of D78.5.

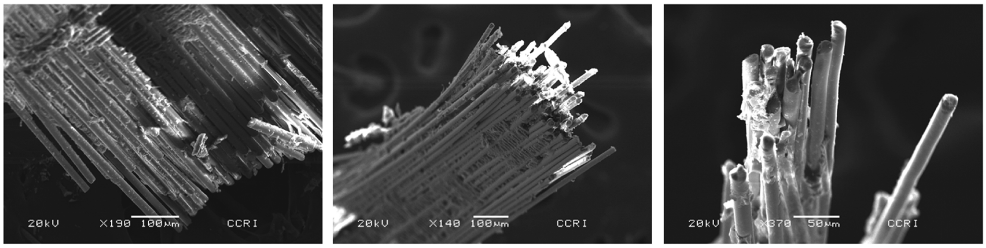
A scanning electron microscopy analysis is carried out to reveal the topology of the composite surface. Fig. 1 shows the scanning electron micrographs of the tensile fracture surfaces of the composites having volume fraction of 0.36, 0.46 and 0.49. From the figure it is observed that there is better fibre/matrix bonding in all cases as the fibre breakage can be seen in the fracture surface.

2.1.3 Calculation of volume fraction

The volume fraction is defined as the volume of fibre present in a cured composite and it was achieved by changing the fibre to matrix ratio by using the vacuum bag moulding process. In the present

Table 1 Results of tensile test

No.	Volume fraction	Young's modulus (GPa)
1	0.36	56.47
2	0.40	57.93
3	0.46	59.37
4	0.49	61.25
5	0.55	64.50



(a) (b) (c)

Fig. 1 Scanning electron micrographs of the tensile fracture surface of composites (a) at 36 % volume fraction (b) at 46% volume fraction and (c) at 49 % volume fraction investigation the volume fraction is found out by using the resin-burn off method (ASTM D2584) for which a sample of dimensions 25 mm × 25 mm × 3 mm is cut from the completely cured composite and is placed in a silicon crucible and kept in the muffle furnace. Before initiating the burning process the initial weights of specimen as well as the crucible is noted .The temperature for burning the specimen is kept above 550°C so that the resin in the sample gets burned off completely. The specimen along with the crucible is cooled off and the weight is taken and further calculations are done based on the equations [1].

$$M_f = \frac{w_f}{w_c};\ M_f = \frac{\rho_f}{\rho_c}V_f$$

$$M_m = \frac{w_m}{w_c};\ M_f + M_m = 1,\ M_m = \frac{\rho_m}{\rho_c}V_m$$

$$V_f = \frac{M_f/\rho_f}{M_f/\rho_f + (1 - M_f)/\rho_m} \tag{1}$$

where M_f = mass fraction of fibre, M_m = mass fraction of matrix, V_f = volume fraction of fibre and V_m = volume fraction of matrix. Volume fractions of 0.36, 0.40, 0.46, 0.49 and 0.55 are achieved in the present study.

2.2 Experimental study

The experiment is conducted using universal testing machine and a fixture is fabricated to hold the specimen. The fixture is made up of mild steel plates with a clamping length of 25 mm at the top, 25 mm in the bottom and a top attachment of 30 mm diameter. The plate is kept on the fixture (Fig. 2) with two sides as clamped and two sides as free such that the compressive loads are applied in the plane of the plate at two opposite clamped ends.

The specimen used for testing is based on the compression after impact standard of dimensions

Fig. 2 Plate in the assembled position

Fig. 3 Different stages in buckling test

150 mm × 100 mm × 3 mm. The entire arrangement is assembled in the universal testing machine of 400 kN capacity and the plates are loaded at a constant speed of 5 mm/min.. A deflection meter is mounted at the centre of the specimen to observe the lateral deflection and all specimens are loaded slowly up to failure. Deflections corresponding to each load are noted down from deflection meter. The different stages during the testing of specimen are shown in the Fig. 3.

3. Results and discussion

In the present study composite plates with varying volume fractions are tested under varying plate aspect ratios. Keeping the width and thickness of the specimen fixed at 150 mm and 2.8 mm, the height is varied to obtain aspect ratio values of 0.4, 0.5, 0.667 and 1. Composite plate of 300 mm × 300 mm is prepared using vacuum bag method and specimens of required dimensions are cut from the plate. Burn out tests is carried out to obtain the fibre volume fraction in the specimens and volume fractions of 0.36, 0.40, 0.46, 0.49 and 0.55 are obtained from the test. The specimens are kept in the fabricated fixture for assessing the buckling strength and tested using universal testing machine.

For plate with aspect ratio of 0.5 and 0.4 there is no buckling phenomenon as the plate got crushed at the middle and hence only the crushing load is noted and the results are shown in Fig. 4 for different volume fraction of fibre.

In case of plates with aspect ratio of 0.667 and 1 graphs are plotted between load and deflection for various volume fraction of fibre and are presented in Figs. 5 and 6. From the figures it can be seen that as load increases the deflection also increases.

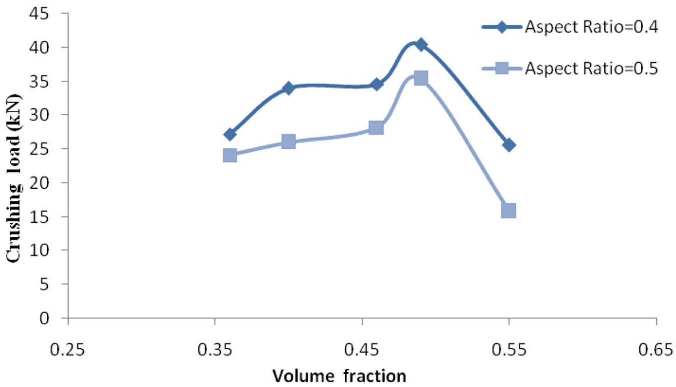


Fig. 4 Crushing load vs volume fraction

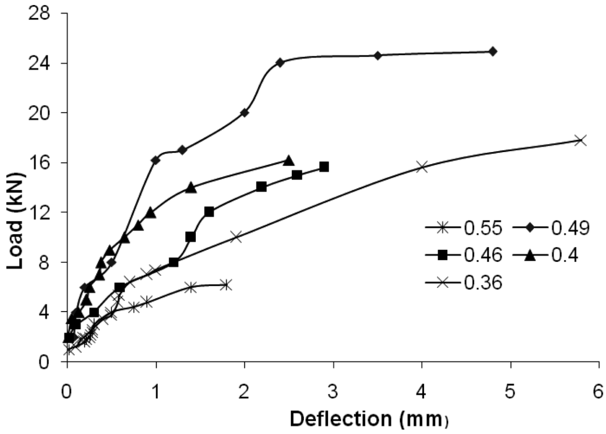


Fig. 5 Load vs deflection for aspect ratio 0.667

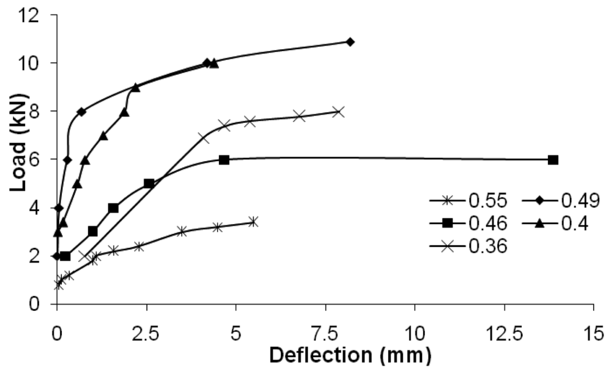


Fig. 6 Load vs deflection for aspect ratio 1

Figs. 7 to 11 present the graphical representation of the buckling load corresponding to various aspect ratios for different volume fractions. In all cases the variation in load with respect to aspect ratio

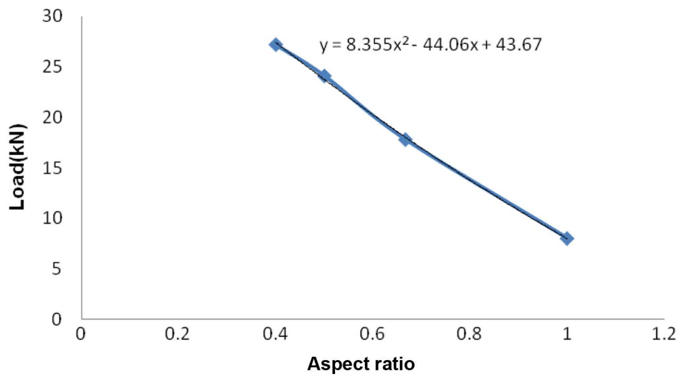


Fig. 7 Variation of buckling load with aspect ratio for volume fraction-36%

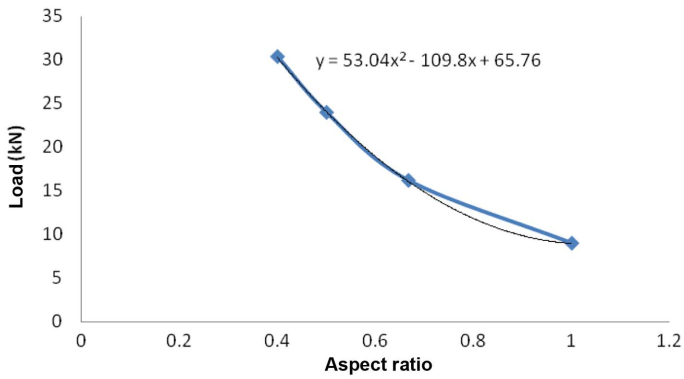


Fig. 8 Variation of buckling load with aspect ratio for volume fraction-40%

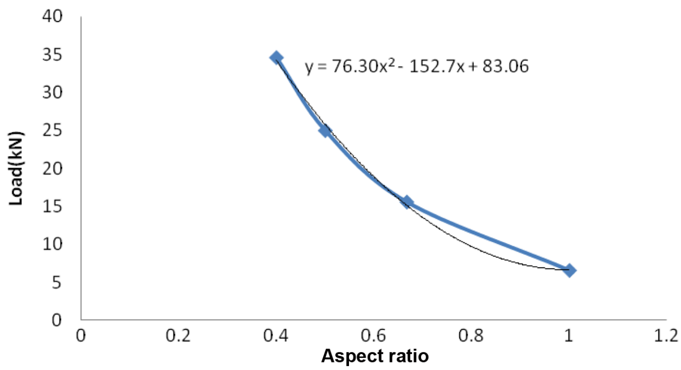


Fig. 9 Variation of buckling load with aspect ratio for volume fraction-46%

corresponding to different volume fractions is represented by polynomial equations, where x represents the aspect ratio and y, the corresponding load. These equations can be used for finding buckling load corresponding to various aspect ratios for different volume of fibre content.

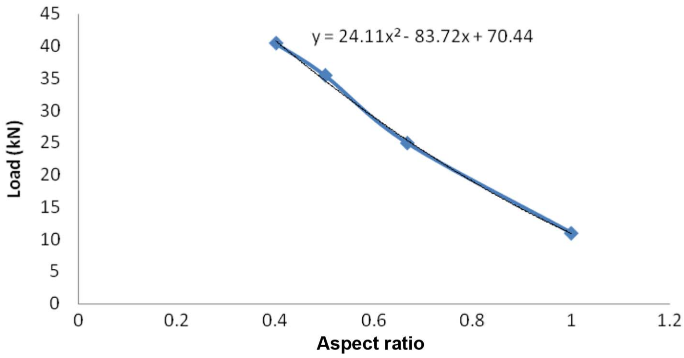


Fig. 10 Variation of buckling load with aspect ratio for volume fraction-49%

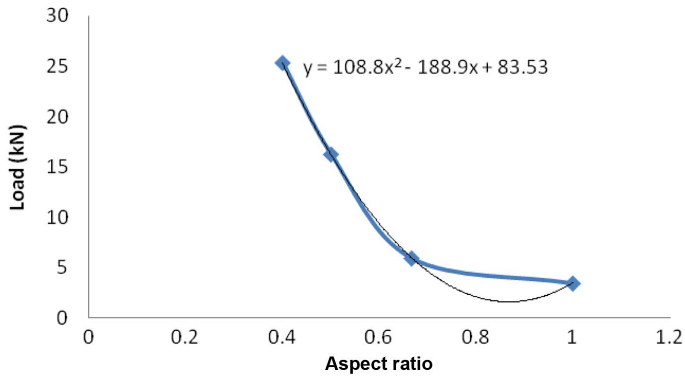


Fig. 11 Variation of buckling load with aspect ratio for volume fraction 55%

4. Comparison of results

A comparative study is made to assess the buckling strength of composite plates made of different volume fractions under various aspect ratios and the results are shown graphically in Fig. 12. The behaviour of neat epoxy resin is also presented in the Fig.12.

From Fig. 12 it is observed that the buckling load decreases continuously with increasing aspect ratio for all volume fractions, the rate of decrease is not uniform. Maximum load is observed for plate with volume fraction of 0.49 and it is observed that for a further increase in volume fraction of 0.55 there is a decrease in load.

The increase in strength of composite plate of various aspect ratios due to the addition of fiber (reinforcement) in various amounts (volume fraction) is studied with reference to plate made of epoxy (without reinforcement) and the results are shown in Table 2 and graphically presented in Fig. 13.

From Table 2 it is found that for plates with aspect ratio 1 and 0.667 the percentage increase in load is in the range of 80%~85% due to the addition of fibre content. As the aspect ratio decreases there is a decrease in the percentage increase buckling load. From Fig. 13 it is observed that from volume fractions of 0.36 to 0.49 there is an increase in buckling load (percentage) and after that it is found to decrease. The optimum range of volume fraction for attaining the maximum percentage increase in buckling load

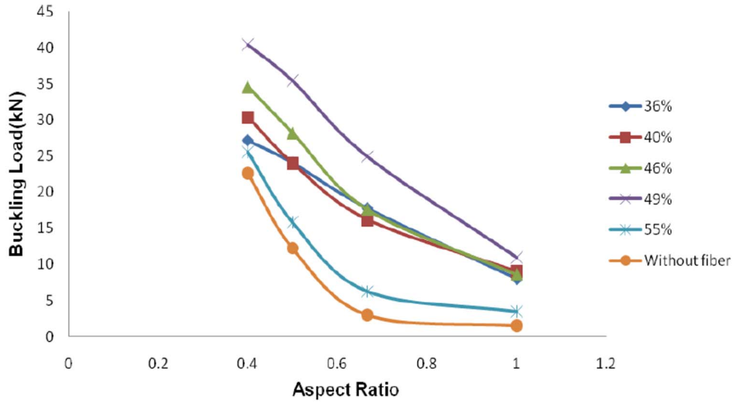


Fig. 12 Variation of Buckling load with aspect ratio for various volume fractions

Table 2 Percentage increase in load due to various volume fractions

L/b \ V_f	0.36	0.40	0.46	0.49	0.55
1	81.25	85.00	82.56	86.24	55.88
0.667	83.15	81.48	82.95	87.95	51.61
0.5	49.38	53.08	56.74	65.54	22.78
0.4	16.91	25.66	34.68	44.06	11.72

L / b represents the aspect ratio of the plate and V_f represents the volume fraction

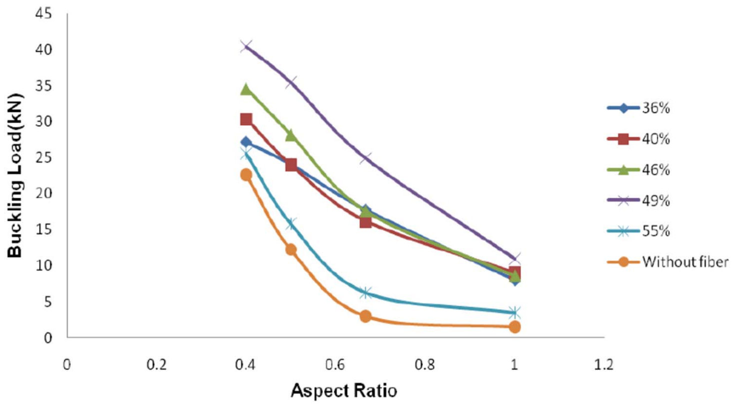


Fig. 13 Increase in load vs volume fraction for various aspect ratios

is found to be 0.49 to 0.55.

Table 3 presents the polynomial equations developed and the corresponding R-squared value based on the experimental investigation to assess the buckling load corresponding to various aspect ratio for different volume fractions. These equations can be used for the stability analysis of GFRP composite plates of different aspect ratio and volume fractions, thus avoiding the large time required for the manufacturing and testing of these types of materials.

Table 3 Equation for different volume fractions

No.	Volume fraction (%)	Polynomial equation*	R-squared value
1	36	$y = 8.355x^2 - 44.06x + 43.67$	0.999
2	40	$y = 53.04\ x^2 - 109.8x + 65.76$	0.998
3	46	$y = 76.30\ x^2 - 152.7x + 83.06$	0.997
4	49	$y = 24.11\ x^2 - 83.72x + 70.44$	0.991
5	55	$y = 108.8\ x^2 - 188.9x + 83.53$	1.0

*y = buckling load, x = aspect ratio.

5. Conclusions

The effect of volume fraction of fibre on the stability of glass fibre reinforced composite plates with various aspect ratios has been investigated experimentally. The experimental investigation was conducted on plates with two sides clamped and two sides free.

The composite plate made using Glass–Epoxy was fabricated with the help of vacuum bag moulding by varying the volume fractions of the fibre. By keeping the width and thickness of the specimen as constant, the aspect ratio of plate is also varied. The loading was done by giving a uniform compressive load along the clamped edges of the plate and the buckling behaviour was observed. The buckling behaviour was studied by noting the deflection calculated from corresponding load versus deflection curve.

The increase in strength of composite plate of various aspect ratios due to the addition of fibre (reinforcement) in various amounts (volume fraction) is studied with reference to plate made of epoxy (without reinforcement) and the results are compared. From the results it was found that for plates with aspect ratio 1 and 0.667 the percentage increase in load is in the range of 80%-85% due to the addition of fibre content. As the aspect ratio decreases there is a decrease in the percentage increase in buckling load due to the addition of fibre. It is also observed that for volume fractions of 0.36 to 0.49 there is a percentage increase in buckling load and after that it is found to decrease. The optimum range of volume fraction for attaining the maximum percentage increase in buckling load is found to be between 0.49 to 0.55. Polynomial equations have been developed to assess the buckling load of composite plates with various aspect ratios for different volume fractions.

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