Effect of vacuum bag pressure on the flexural properties of GFRP composite laminates

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ABSTRACT: A study of the influence of vacuum level on fibre fraction and flexural properties has been completed using burn-off and three-point bending tests. Surprisingly, neither the fibre volume fraction nor the flexural behaviour were seen to be dependent on vacuum level. Initial failure due to top ply delamination did not affect the very linear flexural stiffness response of the material. There was variation in material properties of different types of specimens, but no consistent correlation with material properties between the warp and weft directions was seen. It is thought that 'operator' (laminator) variation, both between and within panels, was more important than other factors for this study. Further work is needed to investigate the effects of vacuum level on larger panels, and to try to systematically quantify and investigate the effects of operator variation on the material properties.

1. INTRODUCTION

Composite materials have many advantages over more 'conventional' materials (e.g. steel, wood, aluminium), including the forming complex shapes, good environmental resistance and high specific material properties. However, a problem for many of the fibre reinforced polymer laminates typically used in maritime structures is their relatively low mechanical properties when subjected to out of plane loads, and flexural tests can be useful to investigate this aspect. Although flexural strength and stiffness are not basic material properties (rather arising from the combined effects of basic tensile, compressive and shear properties) flexural testing is common since specimen preparation and testing is relatively straight-forward, and importantly the loading replicates critical in-service loads in many situations.

One of the most fundamental quantities controlling the properties of fibre-reinforced composites is the fibre content. Stiffness, strength, and thermal conductivity, as well as other properties are strongly dependent on fibre volume fraction (FVF). An increase in fibre volume fraction usually improves mechanical properties, up to a limiting value where insufficient resin is available to support and/or protect the fibres. FVF is affected by both the fibre architecture (namely how closely the fibres can fit together) and the production method used to fabricate the laminates. Table 1 shows values of fibre weight and volume fractions for typical marine composites, where lower values of the ranges given correspond to hand lay-up, increasing for vacuum bagging, infusion, RTM, and prepreg laminates.

Table 1. Typical Fibre Volume Fraction (FVF) values

Type	W_f	V_f
CSM	0.2 – 0.4	0.1 – 0.25
WR, Cloth, Bi- Ax	0.45 – 0.65	0.3 – 0.5
UD	0.6 – 0.8	0.45 -0.65

Adapted from Sleight, 1986

Uleiwi (2007) studied the effect of fibre volume fraction on the flexural properties of the laminated composite. The results illustrated that tension stress decreases with the increase in fibre volume fraction of glass fibre of the lower layer while it increases with the increase of Kevlar volume fraction of the upper layer. As for compression stress, it increases with the increase in volume fraction of glass fibre of the lower layer while it decreases with the increase of volume fraction of Kevlar fibre of the upper layer.

Siva et. al. (2013) practiced four different fibre volumes in order to find the optimal fibre volume fraction. Flexural and impact tests were taken for mechanical properties. Result showed that, the trend in flexural properties increased as a function of increase in fibre volume fraction.

He and Gao (2015), investigated the effect of fibre content on the flexural property of continuous carbon fibre/epoxy composites. It was observed that the flexural strength and modulus of this material are enhanced with increasing FVF in the range of 50–70 vol. %. Results show that the carbon fibre/epoxy composites possess the largest fracture force and displacement when the FVF is 70 vol. %, which is mainly attributed to the effective stress transfer of fibres.

Izzati (2008), explained the effect of increasing FVF on the behaviour of flexural properties of woven composite. The results showed that the flexural properties were increased linearly due to the increasing of FVF until it reached a certain stage where the volume of the resin is no longer enough to cover the entire composite.

Nomenclature

ρ_m	matrix density
ρ_f	fibre density
ρ_c	composite density
W_2	weight of the residue
W_1	weight of the specimen
W_m	weight fraction of matrix
W_f	weight fraction of fibre
V_f	fibre volume fraction
b	width of beam tested
D	mid-span deflection
n	number of observations
L	support span length
d	depth of beam tested
ε_f	bending strain
σ_f	bending stress
E_B	tangent modulus of elasticity
g	random variable
X	value of a single observation
$\bar{X}$	arithmetic mean of the set of observations
P	load at a given point on the load-deflection curve
r	strain
m	the slope of the tangent to the initial straight- line portion of the load- deflection curve
μ	the mean value of E

Syed Azuan (2013), investigated the influence of different fibre volume loading (5%, 10%, 15%) and various vacuum pressures (5psi, 10psi, 15psi) on the flexural strength. Based on the result, it was found that the FVF of 5% and 15psi of vacuum pressures gave maximum value in flexural strength and flexural modulus. The results indicated that the decreasing the fibre volume and increasing the vacuum pressure had a better interfacial bonding between its fibre and matrix.

The aim of this study was to carry out an initial exploratory investigation of the effects of production methods and the associated variables on the material properties of the laminates produced. Since this was an initial study, the effects of only one production method - associated production parameter combination was investigated here; the vacuum bag pressure used in the vacuum bagging method, and for the reasons discussed above, the flexural properties were first considered.

2. EXPERIMENTAL DETAILS

Specimens cut from three plates each fabricated under a different vacuum bag level were tested using a three-point flexural set-up.

Glass fibre reinforced orthophthalic polyester resin was used as representative of the materials used in the marine industry, where a roving/ mat reinforcement combination is often used to achieve a compromise between the ability to quickly build up laminate thickness and better material properties / lighter weight.

The exact laminate schedule was suggested by Estaleiros Navais de Peniche (ENP) engineers as representative of those used in the construction of robust work and fishing boats:

300 CSM, (800 WR / 300 CSM)$_3$, 300 CSM

where: 300, 600 & 800 are areal weights in gm^{-2}, CSM is Chopped Strand Mat, and WR is balanced Woven Roving.

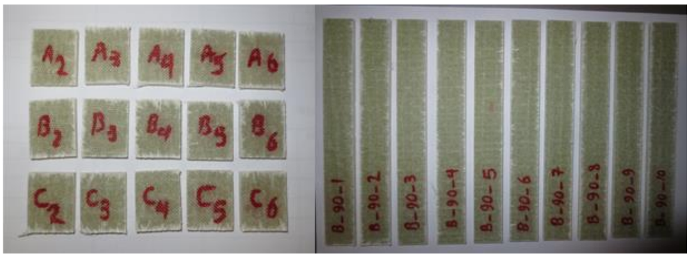
Vacuum bagging (i.e. vacuum assisted hand lay-up), as a production process typically used in the marine industry, was used in this study to fabricate the specimens. In this initial study the simply controlled parameter of vacuum level (i.e. level of vacuum, with 1 atmosphere being a full vacuum) was varied.

After consultation with ENP engineers, plates A, B and C were fabricated at vacuum levels of 0.2 bar (‘low’), 0.6 bar (‘normal’) and 0.9 bar (‘maximum practicably achievable’), respectively. Each panel was of dimensions 900 ×1100 mm panels were laminated using vacuum bagging method.

Three types of specimen were cut from each of the panels using a diamond-surrounded circular saw:

- Five 20×20× 4 mm burn-off specimens
- Ten 120× 20 × 4 mm flexural specimens (length aligned with warp fibres)
- Ten 120× 20 × 4 mm flexural specimens (length aligned with weft fibres)

Specimens cut giving the warp and weft directions aligned with the length of the specimens are indicated by ‘0’ and ‘90’ respectively. Examples of the untested specimens are shown in Fig. 1. Specimen width and thickness were then measured at four points along each specimen using electronic Vernier callipers before testing.



a) b)

Figure 1. Example specimens: a) Burn- off test, b) flexural test

2.1. Burn –off tests

In order to measure the fibre volume fraction (V_f) burn-off tests were carried out according to the standard ASTM D-2584 (02) ‘Ignition loss of cured reinforced resins’ (ASTM 2002). This ignition loss can be considered to be the resin content here since the laminates consisted of only glass fibres and the organic resin.

The mass of the composite specimen (W_1) and the mass of the specimen and containing crucible together were determined to the nearest 1.0 mg and the specimen and crucible heated in a muffle furnace at 400 °C for 4 hours and then at 565 °C for 2 hours, or until all of the resin material was burnt away. The crucible and the residual glass fibre was then removed from the furnace, cooled to room temperature in a desiccator and then weighed to allow the mass of the residue (W_2) to be calculated. Five specimens for each of panels A, B and C were tested. Fig. 2 shows the furnace and residual fibres after burning.

a b

Figure 2. a) Specimens after burning, b) Furnace

The weight fractions of the matrix (i.e. the ignition loss) and of the fibres were calculated using:

$$W_m = (W_1 - W_2)\,/\,W_1$$
$$W_f = W_2\,/\,W_1 \qquad (1)$$

The following equations were then used to obtain the fibre volume fraction:

$$\rho_c = 1/(W_f/\rho_f + W_m/\rho_m) \qquad (2)$$
$$V_f = \frac{\rho_c}{\rho_f} \times W_f$$

(3)

2.2. Flexural tests

Flexural tests were performed with a calibrated servo-hydraulic mechanical test rig equipped with a 500 kg load cell and infinite resolution displacement transducer according to ASTM D-790 (03) ‘Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials’ (ASTM 2003). A three-point loaded simply supported beam test set-up was used with the loading nose midway between the supports (Fig. 3).

A support-to-depth ratio of 30 was chosen such that failures occurred in the outer fibres of the specimens due only to the bending moment, giving a support length of 120 mm. Loading and support nose radii were both 20 mm. The load was applied to the specimen at a crosshead rate of 0.05 mm/s and load-deflection measurements recorded. Total beam deflection, D, on the centreline was measured, and tests were terminated shortly after breakage occurred.

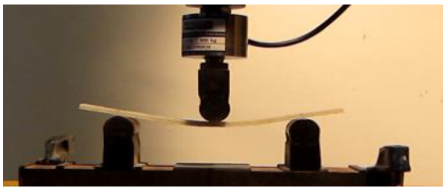


Figure 3. Flexural test set-up

The bending strain ε_f and bending stress σ_f were calculated from Eqs. (4) and (5), respectively:

$$\varepsilon_f = \frac{6Dd}{L^2} \qquad (4)$$

$$\sigma_f = (3PL/2bd^2)[1 + 6(D/L)^2 - 4(d/L)(D/L)] \qquad (5)$$

Eq. (5) was used since the support span-to-depth ratio was greater than 16, giving rise to deflections in excess of 10% of the support span (ASTM 2003).

The tangent modulus of elasticity, the Young’s modulus, was calculated according to the Standard (ASTM, 2003) by drawing a tangent to the steepest initial straight-line portion of the load-deflection curve and then applying Eq. (6):

$$E_B = \frac{L^3 m}{4bd^3} \qquad (6)$$

3. ‘RESULTS AND DISCUSSION

3.1 Burn-off test results

The average fibre weight and volume fraction results from the ignition loss tests for each panel, along with their respective standard deviations, are given in Table 2.

Table 2. Burn-off test results

Type	W_f	c. o .v	V_f	c. o. v
Panel A (0.2 bar)	0.597	0.008	0.417	0.011
Panel B (0.6 bar)	0.602	0.012	0.425	0.017
Panel C (0.9 bar)	0.606	0.014	0.425	0.020

Table 2 shows that despite the slightly lower fibre content of plate A (by less than 2%) there are no significant differences between the FVFs of the three plates. Hence, it appears that the vacuum pressure of 0.2 bar used to fabricate plate A was sufficient to extract as much resin as possible, and that the lower vacuum pressures of 0.6 and 0.9 bar used for plates B and C respectively did not result in any extra resin extraction. However, it must be noted that these results concern very small flat plates and that the same may not be true for larger structural scale components.

3.2 Flexural test results

The average dimensions of the flexural specimens cut from plates A, B and C, along with their respective coefficients of variation are given in Table 3.

Table 3. Average Specimen Dimensions

	Width (mm)	CV	Thickness (mm)	CV
A0	20.24	0.0018	3.82	0.032
A90	20.29	0.0023	3.85	0.011
B0	20.28	0.0031	3.76	0.037
B90	20.29	0.0031	3.99	0.032
C0	20.11	0.0064	3.98	0.024
C90	20.26	0.0032	3.62	0.036

Table 3 shows that there is very little variation in specimen width, either between plates or warp and weft, or within each type of specimen.

Table 3 also shows that the variability of specimen thickness within each type of specimen is low and similar for each type, except for the weft specimens from plate A which have less variation than for other specimen types. However, there are significant differences in the average thicknesses of the different specimen types, although there seems to be no clear correlation with either vacuum level or warp/weft direction; thickness values range between 3.62 mm for C90 specimens to approximately 4 mm for B90 and C0 specimens.

This indicates that the thickness values are more influenced by ‘operator’ (i.e. laminator) variation, both within (across) and between panels, than by the level of vacuum parameter studied here. This inference is reinforced by the facts that significant thickness differences between warp and weft aligned specimens were seen for plates A & B, that these differences are not in the same sense, and that the direction in which the specimens were cut out should have had no effect on thickness.

Figure 4 shows typical stress-strain plots for each type of test. These plots were used to determine the flexural strength and the Young’s modulus of elasticity, which are given Table 4.

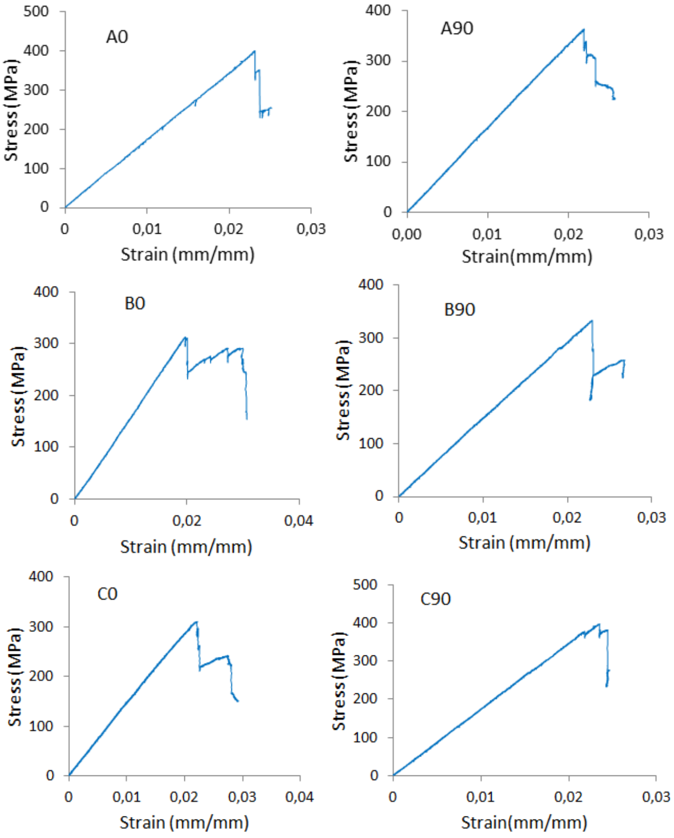


Figure 4. Stress-strain plots

Table 4. Flexural test results

Property	**A0**	**B0**	**C0**
E (GPa)	16.5	17.1	14.5
CV	0.07	0.07	0.03
First Audible Crack (MPa)	322	297	244
CV	0,14	0,07	0,06
Maximum stress (MPa)	353	364	280
CV	0.11	0.15	0.12
Property	**A90**	**B90**	**C90**
E (GPa)	15.8	14.7	17.2
CV	0.06	0.07	0.09
First Audible Crack (MPa)	314	301	321
CV	0,13	0,11	0,09
Maximum stress (MPa)	343	318	372
CV	0.07	0.09	0.12

As the tests progressed an audible crack was heard at a relatively low load, very soon after which a delamination or buckling of the top ply at the loading roller was observed. The stresses at which these cracks, thought to be the initiation of the delamination, were heard are also given in Table 4.

However, no visible effect on the stress-strain responses at this delamination was seen (Fig. 5).

As the load was increased this delamination spread outwards along the length of the specimen, and further delamination progressively occurred between successive plies from the top surface.

Finally, as the delamination compromised the structural integrity of the specimens, catastrophic failure occurred, which included tensile failure of the bottom ply, and was accompanied by a sharp reduction in the load (Fig.5).

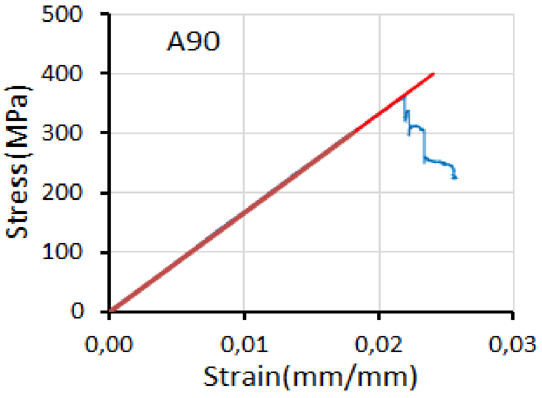


Figure 5. Stress-strain Linearity

Table 4 shows that there are no clear correlations between any of the responses and properties and the vacuum bagging pressure. As discussed above concerning specimen thickness, this is thought to be because operator variability, both within and between panels, is far more important than vacuum level for the fabrication of these small panels.

According to Tables 3 and 4, there is a correlation between specimen thickness and Young's modulus, as shown in Fig. 6. This is despite the fact that Eq. (6) shows that stiffness should already be independent of thickness. Perhaps this is because thinner specimens have slightly less crimp in the woven fibres, which could have arisen from the compressing action of the vacuum bag, and / or from variations in the pressure applied during hand lamination (it must be remembered that 'vacuum bagging' consists of hand lay-up followed by the application of a vacuum consolidation process).

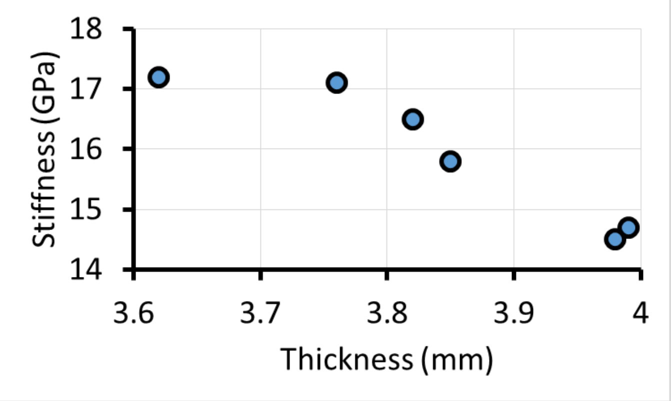


Figure 6. Specimen thickness – Stiffness correlation

The absolute values of material properties are not their only aspect of interest to a designer; their variability or uncertainty may well be just as, or even more, important (Sutherland & Guedes Soares, 1997). Eq. (6) shows that Young's modulus (E) is calculated from the slope of the force-deflection curve (m), and both the specimen width (b) and thickness (d). The contribution of the variability of each of these parameters to the uncertainty in the calculated stiffness is investigated via the first order second moment method using Eqs. (7) and (8), and the results of this analysis reported in Table 5.

$$Var[E]_X = \left(\frac{\partial g}{\partial X}\right)^2 Var[X]\,,\ X{=}m{,}d{,}b \qquad (7)$$

$$CV_X = \frac{\sqrt{Var[E]_X}}{\mu} \qquad (8)$$

Table 5. Contributions to stiffness standard deviation and coefficient of variance due to specimen width, and thickness, and stress-strain slope.

	A0	B0	C0	A90	B90	C90
E	16.5	17.1	14.5	15.8	14.7	17.2
CV_b	0.001	0.003	0.007	0.002	0.003	0.003
CV_d	0.090	0.109	0.087	0.030	0.094	0.104
CV_m	0.054	0.069	0.094	0.069	0.055	0.058

Table 5 shows that generally the variability in thickness is the largest contributor to that in stiffness, but not in the cases of C0 and A90. Table 5 also shows that the variability in the slope of the stress-strain plot has a significant effect, but that that due to specimen width is negligible.

4. CONCLUSIONS

An initial study of the influence of the vacuum bagging production process parameter vacuum level has been completed. Burn-off and three-point bending tests have been carried out to ascertain the effect of vacuum level on the fibre fraction and hence the flexural material properties. Three levels of vacuum level, corresponding to 'low', 'normal' and 'maximum practicably achievable' were used to fabricate three separate panels.

Surprisingly, the fibre volume fraction was not seen to be dependent on vacuum level, perhaps because of the very small size of the test panels studied here.

Failure of the flexural specimens was initially a top ply delamination, which progressed and finally lead to catastrophic collapse, including bottom ply tensile failure. The initial delamination of the top ply did not affect the very linear flexural stiffness response of the material.

There was variation between material properties of different types of specimens, but no consistent correlation with material properties between the warp and weft directions was seen. This is thought to be because 'operator' (laminator) variation, both between and within panels, was more important.

Further work is needed to investigate if the fibre fraction of larger panels are also insensitive to the range of vacuum level considered here, and to try to systematically quantify and investigate the effects of operator variation on the material properties.

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