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THE INFLUENCE OF FIBRE VOLUME FRACTIONS ON THE FLEXURAL BEHAVIOUR OF FRP REINFORCED TIMBER BEAMS

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Abstract: Research has been conducted to study the effects of fibre volume ratios on the strength and the stiffness of fiber-reinforced plastic (FRP) stringers. Since no literature has been found to evaluate the effects of fibre volume fractions on the structural behaviour of the FRP stringers, this paper is intended to fill this gap. The paper employed a finite element model to theoretically evaluate the structural behaviour of reinforced FRP Douglas fir Timber beams. A total of four FRP reinforced stringers were analyzed under three point bending. The beams were 4.8 m long and had a cross-section 150 mm wide by 330 mm deep. Several unidirectional fibre glass materials were mixed with Epoxy West System of 105 resin and 206 hardeners to manufacture various plates with various contents of fibre. The material properties used in the ANSYS program were obtained from ASTM FRP coupons testing. The results showed that the higher fibre volume ratio used in the manufactured FRP plates, the higher the stiffness of the beam. Also, there was no significant increase in the strength of the beams with increasing the fibre volume fractions.

1 INTRODUCTION

A complete replacement of dilapidated wooden bridges costs twice as much as getting them rehabilitated. The search for a reliable and cost-effective construction repair material with low maintenance to reinforce timber bridge beams has become more apparent in recent years. In this paper, glass fibre reinforced polymers (GFRP) materials are used to strengthen timber beams. Since there has been no specific research conducted on the effects of fibre volume fractions on the flexural strength and stiffness of timber beams, this paper is intended to fill this gap. The ANSYS finite element method was used to assess the percentage increase in strength and stiffness based on using various ingredients of fibre materials and fibre volume fractions used in manufacturing the FRP reinforcement plates.

1.1 Literature review

Some work related to strengthening timber was conducted by Taheri et al. (2009). They investigated the response of glued-laminated columns reinforced with GFRP. The authors performed a comprehensive experimental and computational investigation to describe the response of axially loaded glulam timber columns strengthened with GFRP. The study involved several parameters such as slenderness ratio, boundary conditions, and FRP reinforcement length. Yahyaei and Taheri (2011) studied the performance of GFRP reinforced glulam beams. They developed a non-linear finite element model to predict the creep response of the aramid fibre reinforced plastic (AFRP) reinforced timber beams based on the creep characteristics of the individual components. Alshurafa et al. (2012) conducted a linear NISA finite element model to predict the structural behaviour of the beam. The finite element results obtained from the model agreed well with their experimental testing results. Alhayek and Svecova (2012) investigated two groups of full scale salvaged creosote-treated Douglas fir timber beams reinforced with FRP plates. Ten stringers were reinforced with GFRP plates on the tension side (Group T) and another ten stringers reinforced with GFRP plates on the tension and compression side (Group TC). Their results revealed that the strength and stiffness of the stingers were increased by 36% and 3% for Group T and by 31% and 3.5% for Group TC, respectively. A post-tensioning mechanism for timber beams was developed by Alhayek and Svecova (2013) to investigate the effect of post-tensioning on their flexural strength and stiffness. Their results showed a significant increase in strength.

1.2 Objectives

The main objective of the article was to evaluate the structural response of timber beams reinforced with (GFRP) on the tension side. The aim is to study several GFRP manufactured reinforcement plates based on using several specific fiber volume fraction percentages, V_f, allowed in the manufactured composite plates to find their potential for providing improved strength and stiffness to beams when subjected to static loading.

2 EFFECT OF VARIOUS FIBRE VOLUME FRACTIONS

The finite element method was used to assess the effects of the fibre volume fraction V_f on the performance of GFRP reinforced beams. The main reinforcement of the fabricated GFRP plates consisted of matting with unidirectional fibre. The same properties of the unidirectional fibre constituents and the West System epoxy and hardener reported by Burachynsky (2006) were used in the analysis and are listed in Table 1.

Table 1 Constituents properties of unidirectional lamina (Burchynsky 2006)

Mechanical Property	E-Glass Fibre	West System Epoxy (105 resin/205 hardener)
Tensile modulus (GPa)	72.4	2.81
Tensile strength (GPa)	2.4	0.054
Poisson's ratio	0.27	0.3
Shear modulus (GPa)	30	1.38
Density (g/mm^3)	0.0025	0.0016

The common use of fibre volume fraction for unidirectional lamina ranges from 40% to 70%. Kaw (1997) recommends a range of possible fibre volume fractions for different reinforcement forms, as shown in Table 2.

Table 2 Recommended use of fibre volume fraction (Kaw 1997)

Type of reinforcement	Range of fibre volume fraction	Common value of fibre volume fraction (%)
Unidirectional	50-70	65
Woven	35-55	45
Random	10-30	20

The tensile modulus of elasticity in the fibre direction versus various values V_f was calculated using the rule of mixtures as given by Eq. 1. The longitudinal elastic modulus versus various V_f values is plotted in Figure 1.

$$E_1 = E_f V_f + (1 - V_f) E_m \quad [1]$$

Where:

E_1 : Modulus of elasticity of the composite, in the direction of the fibre

E_f : Modulus of elasticity of the fibre

V_f : Fibre volume fraction

E_m: Modulus of elasticity of the Matrix

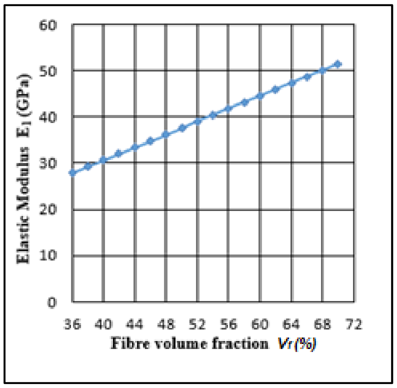

Figure 1: Elastic modulus E_1 at various fibre volume fractions

The modulus of elasticity in the direction perpendicular to the fibres was determined by the inverse rule of mixtures as given in Eq. 2. The transverse modulus of elasticity is plotted against various V_f values in Figure 2.

[2] $$\frac{1}{E2} = \frac{Vf}{Ef} + \frac{(1-Vf)}{Em}$$

Where:

E_2 : Modulus of elasticity of the composite perpendicular to the fibre

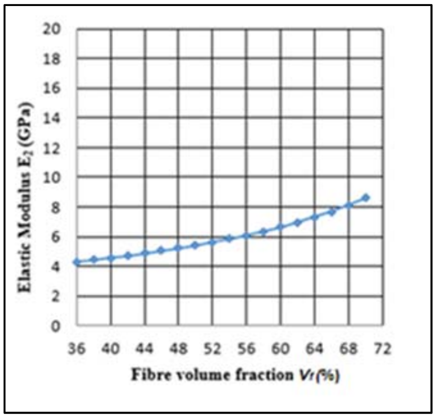

Figure 2 Elastic modulus E_2 at various fibre volume fractions

The major Poisson's ratio was calculated as a function of V_f using Eq. 3 and was plotted at different V_f values in Figure 3.

[3] $$v_{12} = v_f V_f + v_f V_m$$

Where:

v_f : Poisson's ratio of fibre

v_m : Poisson's ratio of matrix

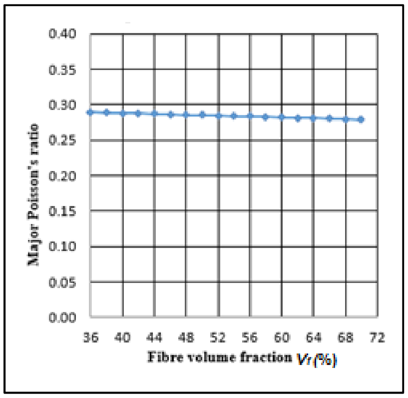

Figure 3: Major Poisson's ratio at various fibre volume fractions

The in-plane shear modulus, G_{12}, was calculated using the inverse rule of mixtures with Eq. 4 and is plotted as a function of V_f in Figure 4.

[4] $$\frac{1}{G_{12}} = \frac{V_f}{G_f} + \frac{V_m}{G_m}$$

Where:

G_f (shear modulus of fibre) = $\frac{E_f}{2(1+V_f)}$

G_m(shear modulus of matrix) = $\frac{E_m}{2(1+V_m)}$

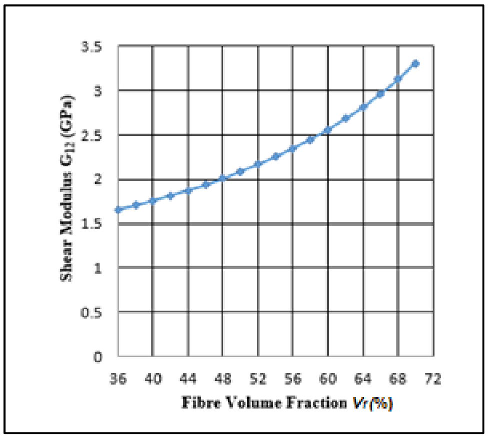

Figure 4 Shear modulus (in-plane) at several fibre volume fractions

The composite density is calculated using Eq. 5 and is plotted in Figure 5 as a function of V_f.

Density of composite

$$[5] \quad \rho = \frac{V_f}{W_f}$$

Where:

W_f: Weight of fibre fraction, defined as:

$$W_f = \frac{\rho_f V_f}{\rho_f V_f + \rho_m (1 - V_f)}$$

ρ_f: Density of fibre

ρ_m: Density of matrix

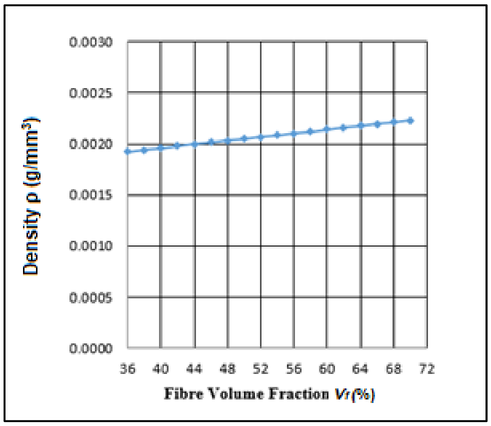

Figure 5 Composite density ρ as a function of fibre volume fraction

The mechanical properties at various V_f values are summarized in Table 3 and these values are used in the ANSYS finite element program to analyze the GFRP reinforced timber beams.

Table 3 Mechanical properties under various fibre volume fractions

Property	V_f=40%	V_f=50%	V_f=60%	V_f=65%
$E_1 (GPa)$	30.65	38.88	44.56	47.35
$E_2 (GPa)$	4.56	5.60	6.71	7.70
$G_{12} (GPa)$	1.76	2.16	2.56	2.85
v_{12}	0.288	0.284	0.282	0.280
$\rho (g/mm^3)$	0.0020	0.0021	0.0022	0.0022

3 FINITE ELEMENT ANALYSIS

An ANSYS finite element model was developed to analyze several GFRP reinforced timber beams using various constituents of V_f. The modulus of elasticity of the beam, 10615.7 MPa, was taken from data published by Alhayek and Svecova (2012). Two GFRP plates of 40 mm x 5 mm x 4.5m were embedded along the created grooves of the bottom surface of the beam. The dimensions of the beams were 330 mm deep x 150 mm wide x 4.8 m long. The GFRP reinforced beams were analyzed for a point load of 143KN.

The finite element program established contained 53200 nodes and 48951 elements. ANSYS Link8 element was chosen to model the GFRP plate. This element is a two-dimensional spar element. The element type used in the analysis of timber beam was Solid45. This element is used for the 3-D modeling of solid structures. The deflection at the mid beam along with the calculated stiffness obtained from analyzing the GFRP reinforced beam under several $\boldsymbol{V_f}$ of 40%, 50%, 60% and 65% were extracted from the analysis and were listed in Table 4. The deflected shape of the beam using $\boldsymbol{V_f}$ of 65% can be shown in Figure 6. As listed in Table 4, the timber beam reinforced with GFRP having $\boldsymbol{V_f}$ of 65% showed an increase in stiffness by only 3.5% compared to the beam reinforced with GFRP having $\boldsymbol{V_f}$ of 40%. The increase in strength when using $\boldsymbol{V_f}$ of 65% compared to 40% was only 1.7%.

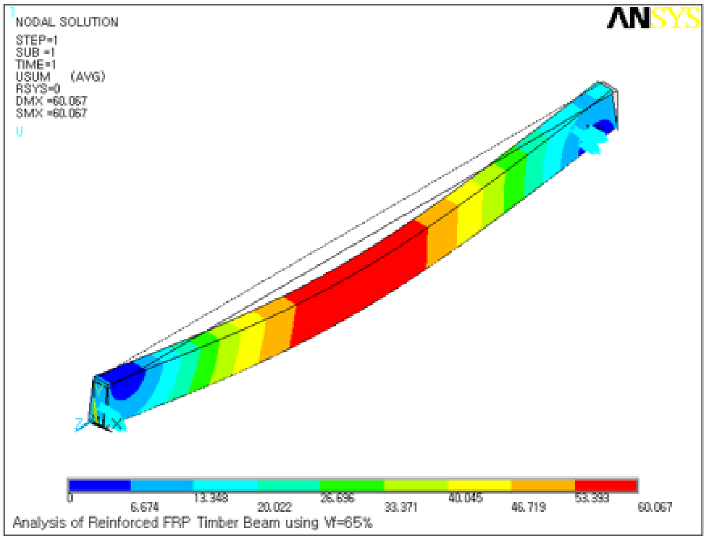

Figure 6: Deflected beam under 143kN with V_f =65%

Table 4: Beam deflections and stiffness under 143kN

V_f(%)	Deflection (mm)	Stiffness x (E^{12}) MPa
40	62.1	4.37
50	61.1	4.44
60	60.4	4.50
65	60.1	4.52

4 CONCLUSIONS

A finite element ANSYS program was developed to analyze timber beams. The reinforced beams using several fibre volume fractions along the bottom surface were all analyzed. The finite element method was effectively used to characterize the response of GFRP-reinforced timber beams in an economical manner. The stiffness and the strength of the beams when using V_f of 65% was increased by 3.5% and 1.7%, respectively compared to the beams using the V_f of 40%.From the numerical results, it is concluded that the volume ratio of fibres, V_f ,does not have a significant effect on the stiffness and strength of GFRP reinforced timber beams

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