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Theoretical Study on the Effects of Various V_f on the Flexural Strength and Stiffness of non-Pre-stressed FRP Plates Reinforced Timber Beams

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Abstract: This study will present the findings of the computational investigations into fiber-reinforced plastic (FRP) reinforced timber bridge beams carried out at Prince Sultan University. The finite element program ANSYS was used to study the structural response of using various ingredients of fibre volume fraction in the reinforced FRP Douglas fir timber bridge beams. The beams were theoretically loaded under static loading condition. These beams had dimensions of $130 \times 330 \times 4500$ mm. The material reinforcement used was made from unidirectional fibre glass material made by Vector Ply Corporation mixed with Epoxy West System of 105 resin and 206 hardener. The material properties used in the ANSYS program were obtained from material testing. The influence of having various fibre volume fractions of the FRP plates on the strength and the stiffness of the timber bridge beams was evaluated. Discussions emanating from the computational investigation will provide interesting findings and will confirm the use of FRP as an effective and viable solution for strengthening and stiffening beams, without adding any appreciable weight to the structures.

Keywords: FEA; FRP; Beam; ANSYS; Bridge; Epoxy

I. Introduction

The search for a reliable and cost effective construction material with low maintenance to reinforce timber bridge beams has become more apparent in recent years. This research paper used fibre-reinforced polymers (FRP) materials to rehabilitate timber beam in tension. The paper involved ANSYS finite element analysis [2] that mainly focused on the ingredients of fibre used to manufacture the FRP plates. There was no specific research was conducted on the effects of fibre volume fractions of the flexural strength and stiffness of timber beams. Some literature related to strengthening timber was conducted by Taheri et al. [7]. They investigated the response of glued-laminated columns reinforced with GFRP. The authors performed a complimentary 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 [8] studied the performance of GFRP reinforced glulam beams. They developed a non-linear finite element model to predict the creep response of the AFRP reinforced timber beams based on the creep characteristics of the individual. Alshurafa et al. [6] conducted a linear NISA finite element model to predict the structural behavior of the beam. The finite element results obtained from the model agreed well with their experimental testing results. Alhayek and Svecova [1] tested a total of 20 salvaged creosote-treated Douglas fir timber stringers strengthened with glass fiber-reinforced polymer (GFRP) plates. The beams were reinforced using various GFRP configurations. The beams were tested to examine the effect of GFRP reinforcement on the stiffness increase of the beams. The beams were tested in three-point bending. They found that the strengthening using GFRP laminates, on average, increased the stiffness of the beams by 3.5%.

A. Objective

The main objective of this paper is to study the response of glass fiber-reinforced plastics (GFRP)-reinforced timber beams under using various glass fiber volume fractions (V_f), which can be considered cost-effective and innovative alternative to the current practice. The work contained a comprehensive computational investigation that focuses on the characterization of various V_f in the ingredient of FRP plates reinforced timber beams and their potential for providing improved strength, stiffness and ductility to structural wood when subjected to static loading.

II. Effect of Various Fibre Volume Fractions

This section presents information on the effect of V_f on the performance of the FRP plates reinforced timber beams as obtained from the finite element analysis. The main reinforcement of the fabricated FRP plates

consisted of matting with unidirectional fibre. The properties of the unidirectional fibre constituents and of the West System epoxy and hardener as reported by [3] are summarized in Table 1.

Table 1 Constituents properties of unidirectional lamina (Burchynsky [3])

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 [4] 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 [4])

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 V_f is calculated using the rule of mixtures as given by Equation 1. The longitudinal elastic modulus versus various V_f is shown in Figure 1.

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

Where:

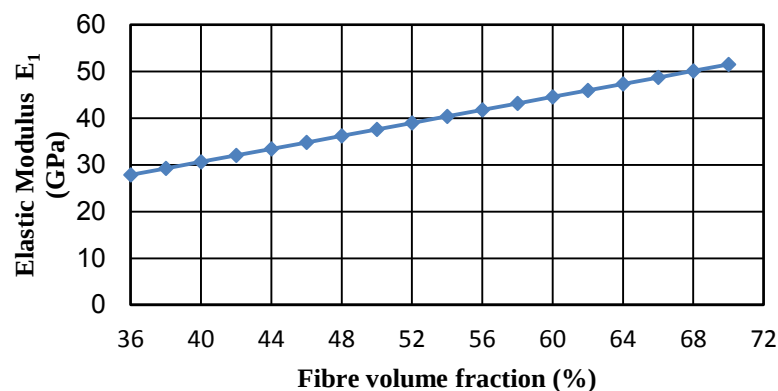
E_1 : Modulus of elasticity of the composite, in the direction of the fibre

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



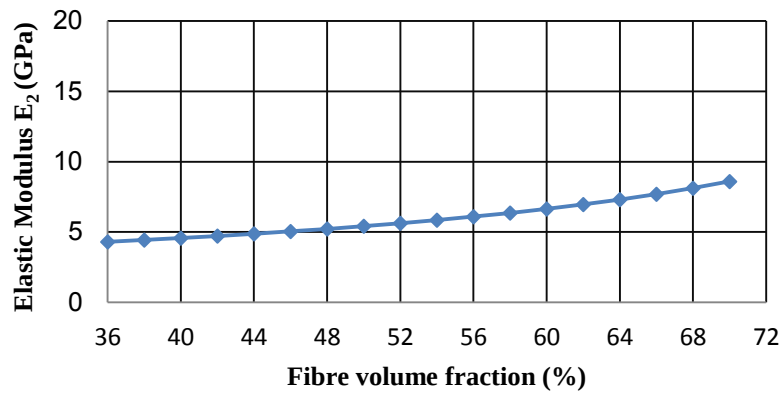
The modulus of elasticity in the direction perpendicular to the fibres was determined by the inverse rule of mixtures as given in equation 2. The transverse modulus of elasticity was plotted against various V_f as shown in Figure 2.

$$\frac{1}{E_2} = \frac{V_f}{E_f} + \frac{(1 - V_f)}{E_m} \quad (2)$$

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 equation 3 and was plotted at different V_f as shown in Figure 3.

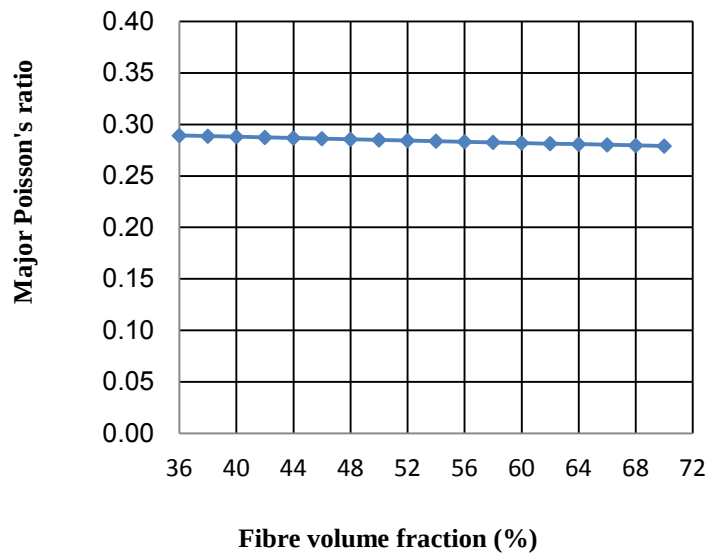
$$v_{12} = v_f V_f + v_m V_m \quad (3)$$

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 attained using the inverse rule of mixtures using equation 4. The in-plane shear modulus using the inverse rule of mixtures formula is shown as a function of V_f in Fig. 4.

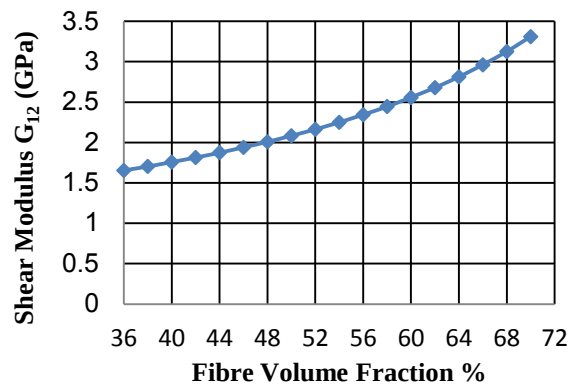
$$\frac{1}{G_{12}} = \frac{V_f}{G_f} + \frac{V_m}{G_m} \quad (4)$$

Where:

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

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

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



The composite density was obtained from equation 5 using [5]. The composite density is plotted in Fig. 5 as a function of V_f .

$$\text{Density of composite} = \rho_f \frac{V_f}{W_f} \quad (5)$$

Where:

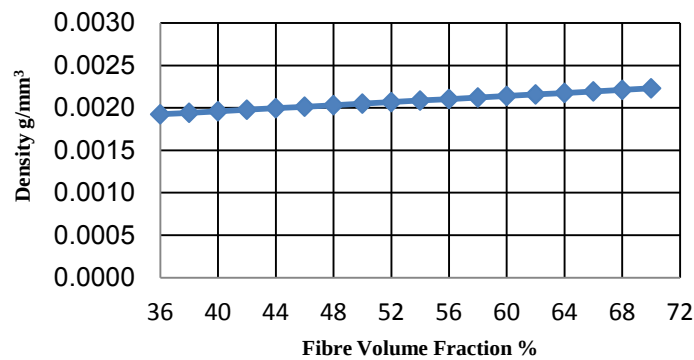
W_f : Weight of fibre fraction, defined as:

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

ρ_f : Density of fibre

ρ_m : Density of matrix

Figure 5 Composite density as a function of fibre volume fraction



The mechanical properties at various V_f obtained using various equations are listed in Table 4

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
ν_{12}	0.288	0.284	0.282	0.280
ρ (g / mm ³)	0.0020	0.0021	0.0022	0.0022

The mechanical properties of the various V_f given in Table 3 were used in the ANSYS finite element program to analyze the FRP Reinforced timber beams.

III. Finite Element Analysis

ANSYS finite element was used to analyze the reinforced FRP timber beams using various constituents of V_f . The center beam deflections and the calculated stiffness obtained from analyzing the FRP reinforced beam under 40%, 50%, 60% and 65% of fiber volume fractions are given in Table 5. The deflected shape of the beam using V_f of 65% is shown in Figure 6. As given in Table 5, the timber beam reinforced with FRP having V_f of 65% showed an increase in stiffness by 3.46% compared to the beam reinforced with FRP having V_f of 40%. The increase in strength when using V_f of 65% to V_f compared to 40% was only 1.7%

Figure 6: Deflected beam shape under 143kN using $V_f=65\%$

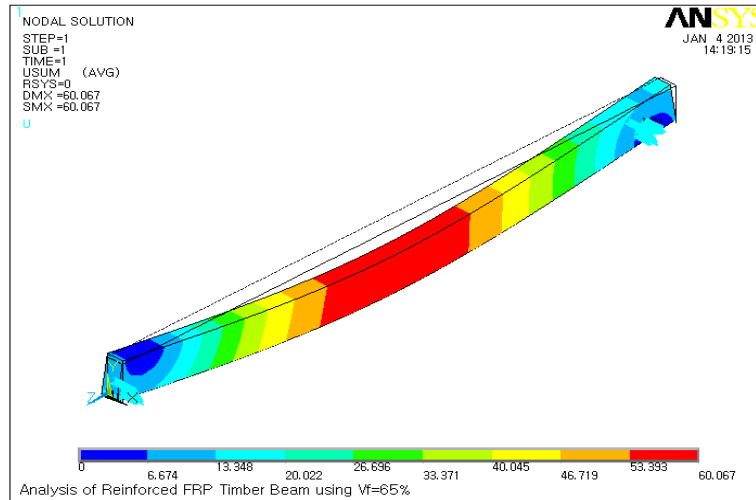


Figure 5: Beam deflections and stiffness under 143kN

V_f (%)	Deflection (mm)	Stiffness in MPa (E+12)
40	62.14	4.37
50	61.08	4.44
60	60.36	4.50
65	60.06	4.52

IV. Conclusions

A finite element ANSYS program was established to analyse a timber bridge beam using various fibre volume fractions. The stiffness and strength of the beam when using V_f of 65% was increased by 3.46% and 1.7%, respectively compared to using V_f of 40%.

V. References

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