# PERFORMANCE EVALUATION OF FRP REINFORCED PARA WOOD GLUED LAMINATED BEAMS

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# ABSTRACT

Glued laminated (glulam) timber, one of various engineered wood products (EWP), has been widely accepted as structural, as well as non-structural member of choices in civil engineering infrastructure applications. During recent years, fiber reinforced polymer (FRP) has been introduced to be applied as external reinforcement for glulam timber beams due to its many advantages over conventional engineering material reinforcement. The use of Para-rubber wood (PW) planks in glulam beams has been intensely under attention over the past decades. However, the use of FRP materials for reinforcement and PW as a raw wood material for glulam timber are still very limited; prior studies are scarcely available and/or have not yet shed sufficient light, especially on structural performances and behaviors. The main objective of this research is thus to evaluate the structural performance, strength, stiffness properties and the behavior of FRP reinforced PW glulam beams under a variety of bending test conditions. In the study, analytical methodologies have been proposed to determine the maximum load (moment) capacity, reduction factor of flexural rigidity and deformation factor. The experimental and analytical results derived are expected to contribute to a further knowledge and understanding of structural performance and behavior of this promising composite material.

KEYWORDS: Fiber reinforced polymer (FRP), Para rubber wood, laminate, beam, bending.

# **INTRODUCTION**

Timber, one of the longest-serving traditional engineering materials, has been widely applied in construction. In general, timber possesses a high strength to weight ratio, good insulating properties, and good durability when properly treated. Also, it is capable of good load transferring in both tension and compression (Porteous and Kermani 2007). Timber can also easily be shaped, reshaped and joined using various types of connections and connectors. However, timber acquired naturally does have its limitation. At present, engineered wood products (EWPs) have been developed to overcome some of major limits in available timber dimension and natural

defect found in sawn wood. Typically, EWPs are formed by mechanical manipulation together with chemical bonding which is applied to the original sawn wood or plank to enhance better efficiency in structural performances and mechanical properties. Glued laminated (glulam) timber, one type of a variety of engineered wood timbers, can provide high quality and uniform products in any shape, size, and form. Glulam is fabricated from dried thin wood planks bonded together into laminates with grains of the laminate arranged parallel to the longitudinal axis of the member (Porteous and Kermani 2007).

In recent years, fiber reinforced polymer (FRP) materials have been used for external reinforcement of glulam timber beams (Plevris and Triantafillou 1992; Fiorelli and Dias 2006; Dempsey and Scott 2006). However, the use of FRP materials for reinforcement is still very much limited due to the relatively high cost and rather complicated fabrication processes (Lopez and Xu 2002). For civil engineering infrastructure applications, glulam panels reinforced with hybrid FRP had been experimentally and analytically evaluated for bridge deck construction (Lopez and Xu 2002). Several computational models of glulam timber beams have been developed and reported in a number of researches (Lindenberg 2000; Romani and Blab 2001; Lopez and Xu 2002; Fiorelli and Dias 2003, 2006). A semi-probabilistic model based on the Monte Carlo approach to determine the strength and stiffness of glulam beams was developed by Lindenberg (2000). A simple beam analyzed linearly and non-linearly based on a moment-curvature model had been proposed to respectively compute structural properties and to predict ultimate load (Lopez and Xu 2002). Design models for moment of rupture had been developed and compared with experimental results (Romani and Blab 2001; Fiorelli and Dias 2003, 2006). Furthermore, various approaches to improve post elastic responses of glulam timber beams under bending had been experimentally investigated by Tomasi et al. (2009).

Certain past studies (Beng 2004; Ngamcharoen et al. 2007) presented the use of PW planks in glulam beams which had been intensely under attention over the past years. Currently, the plantation area for Para-rubber tree (*Hevea brasiliensis*), cultivated in more than 30 countries particularly in South East Asia and China, has been rapidly expanding. Para-rubber wood is very well suited as a raw material for various wood products such as wood based panel, plywood, particleboard, medium density fiberboard (MDF), and oriented strand board (OSB). However most PW has been utilized in industries concerning furniture, furniture components and wood panels. Their applications in civil engineering infrastructures still have not been widely investigated and accepted due to the lack of data and understanding in structural performance and responses. Past researches on PW glulam structural members are scarcely available and/or are not yet too well understood. In addition, structural performances and behaviors of structural FRP reinforced PW glulam beams are also not yet comprehensively studied and established still.

To overcome this concern, further researches are deemed necessary to evaluate the performance and behavior of FRP reinforced PW glulam members. Based principally on experimental and analytical investigations, the primary objectives of this research focus on structural properties and responses of FRP reinforced PW glulam beams under various bending test conditions. Moreover, analytical methodologies have been proposed to predict the moment capacity, reduction factor, and ductility. Results from this research are anticipated to contribute to a further knowledge and understanding of the structural performance and behaviors of FRP reinforced PW glulam beams prior to actual practical utilization.

## MATERIAL AND METHODS

#### **Beam specimens**

This section describes in details the glued laminated beams used in the study. Beam specimens had been prepared using Para-rubber wood (Hevea brasiliensis) species. Presently, available sawn sections of PW are limited in size and in quality. Thus PW glulam timber has been developed to offer an alternative and/or to replace the use of original sawn PW timber. In the study, PW glulam beams were experimentally investigated under flexure and shear through various beam bending tests. Beam specimens with nominal cross-section of 7.5 x 16 cm and 300 cm in length were created. These had been produced from small sections of PW thin planks called laminates. In a small section, planks are joined together using finger joints at the seam. The PW laminates were then bonded with phenol resorcinol adhesive. In this study, all PW glulam beams are horizontally glued laminated timber, i.e. having the height of the beam cross-section perpendicular to the glue-line planes. Thirty six PW glulam beams had been fabricated in this study. The PW glulam timbers were fabricated with four laminations and with two different laminated lay-ups, P1 and P2, as shown in Fig. 1. To produce different combinations of the beam test specimens, two-thirds of the beams had been reinforced with glass fiber reinforced polymer (GFRP) on the surface(s). Of the thirty six beams, twelve had been reinforced with GFRP on the bottom surface - equally in 2 different patterns (P1B and P2B), twelve with GFRP on both the bottom and the top surface - also equally in the similar 2 different patterns (P1BT and P2BT), and the remaining twelve without any GFRP reinforcement but still equally in the same 2 different patterns (P1 and P2). A manual lay-up process was used to administer GFRP reinforcement on the top and the bottom surfaces of the PW glulam beams. The beam dimension, length, joint pattern and type of reinforcement are summarized in Tab. 1, and depicted in Fig. 1.



Fig. 1: Types of Para-wood glued laminated beams.



Fig. 2: Schematic of test set-ups.

No. specimens	Cross section (cm)		Length	Joint	Reinforcement			Beam
	Width	Height	(cm)	pattern	Туре	Surface		notation
						Bottom	Тор	
6	7.5	16	300	1	-	-	-	P1
6	7.5	16	300	2	-	-	-	P2
6	7.5	16	300	1	G (0°/90°)	В	-	P1B
6	7.5	16	300	2	G (0°/90°)	В	-	P2B
6	7.5	16	300	1	G (0°/90°)	В	Т	P1BT
6	7.5	16	300	2	G (0°/90°)	В	Т	P2BT

Tab. 1: Summary of beam dimensions, joint pattern and type of reinforcement.

#### Test set-ups

The PW glulam beams were experimentally evaluated through a series of beam bending tests. Beam specimens were subjected to a three-point, a four-point (ASTM D198-97) and a five-point bending test. For the three-point scenario each beam specimen rested on a simple supporting arrangement with a test span of 276 cm. At mid-span, as illustrated in Fig. 2a, strain gages were mounted onto the top and the bottom surfaces of the beam, and also at quarter depths from the extreme surfaces on the lateral side. Then a concentrated vertical load was applied at mid span of the beam and strain data were recorded. For the four-point bending test, a hydraulic jack connected to a load cell was placed onto a load-distributing I-beam which rests on two roller supports spaced at 92 cm apart on the test beam. Thus on a support test span of 276 cm, a test specimen would be subjected to two equal applied concentrated loads from the hydraulic jack, as shown in Fig. 2b. To analyze strain variation, the mid-span strain data were recorded at predefined surface positions along the depth of the cross-section similar to the strain measuring arrangement for the three-point bending test. All strain data were automatically recorded during the tests via a data acquisition system. For the five-point bending experimental test, a two-span continuous beam with free ends configuration was set up. Each beam specimen rests on three simple supports spaced at an equidistance of 138 cm. Through an I-beam load-distributing scheme similar to that employed in the four-point bending test, two concentrated loads could be imposed onto the test beam at mid span positions between the 2 pairs of supports, rendering a five-point load test configuration as shown in Fig. 2c. Strain gages along the depth of the cross-section of the beam were also set up at the two applied load positions and strain data were measured. As for vertical displacements of the beam specimens, under the three-point and fourpoint tests these were gathered from 5 dial indicators mounted at L/6 intervals along the beam. For the five-point test, 2 dial gages were each mounted directly under mid span positions between the pairs of support where the strain gages were.

### Experimental evaluation of flexural and shear rigidity

To evaluate strength and stiffness of the PW glulam beams, deflection data obtained

from the beam bending tests were employed. To determine equivalent flexural (EI) and shear (GA) rigidity, the three-point and the four-point beam bending tests detailed in Section 3 were conducted to decouple the bending effect from the shear effect. To decouple bending from shear, a back-calculation method based on deflection data had been used herein. The method deals with the experimental load-deflection relations of the PW glulam beams, especially their slopes. Modified Timoshenko beam equations have been utilized in this calculation. Flexural rigidity of the PW glulam beam could be determined from deflection data under the four-point bending test, which are as follows:

Deflection @ mid span ( $\delta_{m4}$ ):

$$\delta_{m4} = \frac{Pa}{48(EI)} (3L^2 - 4a^2) + \delta_{shear}$$
(1)

Deflection @ distance (*a*) from each support ( $\delta_{a4}$ ):

$$\mathcal{S}_{a4} = \frac{Pa^2}{12(EI)} (3L - 4a) + \mathcal{S}_{shear} \tag{2}$$

Since the beam portion between the two applied point loads (P/2) is not under the influence of shear in a four-point bending test, decoupling of bending and shear could be carried out by subtracting deflection at mid span from that at distance (*a*). Thus, flexural rigidity is given as:

$$(EI) = \frac{1}{16} \left( \frac{P}{\delta_{m4} - \delta_{a4}} \right) (aL^2 - 4La^2 + 4a^3)$$
(3)

where: L - the test span,

P - applied load at midspan,

 $P/(\delta_{m4}-\delta_{a4})$  - the slope relation between net deflection ( $\delta_{m4}-\delta_{a4}$ ) and applied load under four point bending.

Coupling between bending and shear effects are thus separated by employing flexural rigidity (EI) obtained from the deflection data while shear rigidity ( $\kappa$ GA) could be calculated by substituting the flexural rigidity and the experimental deflection data into the deflection equation (4) under a three-point bending test which is a function of load and rigidity.

Deflection @ mid span ( $\delta_{m3}$ ):

$$\delta_{m3} = \frac{PL^3}{48(EI)} + \frac{PL}{(\kappa GA)} \tag{4}$$

Thus, shear rigidity (KGA) based on deflection data under three point bending:

$$(\kappa GA) = \frac{L}{\left(\frac{\delta_{m3}}{P} - \frac{L^3}{(48EI)}\right)}$$
(5)

where:  $(P/\delta_{m3})$  - the slope of the relation between deflection  $\delta_{m3}$  and applied load *P* under three point bending.

Moreover, a five point bending test has been used to induce shear failures on test specimens. To evaluate shear rigidity ( $\kappa$ GA), flexural rigidity (*EI*) is substituted into the two span continuous deflection equation ( $\delta_{mS}$ ) under five point bending. The decoupling of bending and shear is done

by subtracting bending deflection (*EI*), from measured deflection at mid span. Deflection @ mid span ( $\delta_m \varsigma$ ):

$$\delta_{m5} = \frac{PL^3}{219(EI)} + \frac{PL}{(\kappa GA)} \tag{6}$$

Thus, shear rigidity (KGA) based on deflection data under five point bending:

$$(\kappa GA) = \frac{L}{\left(\frac{\delta_{m5}}{P} - \frac{L^3}{219(EI)}\right)}$$
(7)

where:  $(P/\delta_{m5})$  - the slope of the relation between deflection  $\delta_{m5}$  and applied load *P* under five point bending,

L - a distance between the two simple supports as shown in Fig. 2c.

#### Numerical modeling

To determine the maximum moment and load capacity, possible failure modes of the Para rubber wood glued laminated beams are considered in this study. In general, the constitutive models of wood are characterized by elastic – nonlinear plastic behavior. For this study, the stress-strain model for Para rubber wood in tension was assumed to be a linear- elastic behavior until rupture. Also, the elastic – perfectly plastic behavior was approximated as the stress-strain model for Para rubber wood in compression. The following stress-strain model of the Para rubber wood is adopted here:

For elastic tension range  $(0 < \varepsilon \leq \varepsilon_{tw})$ :

$$\sigma = E_{w} \varepsilon \tag{8}$$

For elastic compression range  $(0 < \varepsilon \leq \varepsilon_{crw})$ :

$$\sigma = E_w \varepsilon_{cw} \tag{9}$$

For compression ( $\varepsilon_{cw} < \varepsilon \leq \varepsilon_{uw}$ ):

$$\sigma = f_{cw} \tag{10}$$

In addition, the stress-strain model of glass fiber reinforced polymer (GFRP) materials is linear until fracture.

For 
$$(0 < \varepsilon \leq \varepsilon_f)$$
:

$$\sigma = E_f \varepsilon \tag{11}$$

where:  $\sigma$  - normal stress,

 $\varepsilon$  - normal strain,

 $E_{w}$  and  $E_{f}$  - elastic modulus of Para rubber wood ( $\approx 9313$  MPa) and GFRP (64746 MPa), respectively.  $\varepsilon_{rw}$  and  $\varepsilon_{cw}$  are Para rubber wood tension ( $\approx 1580 \ \mu\epsilon$ ) and compressive strain ( $\approx 2900(10^{-6})$  mm.mm<sup>-1</sup>) at the elastic limit. It should be noted that the elastic modulus of

Para wood  $E_w$  was taken from experimental data at coupon level. The tension and compression parallel to grain according ASTM D 143 2009 were used to evaluate the mechanical properties of small clear Para wood specimens. For GFRP materials, tension tests were conducted to determine tensile strength and stiffness of GFRP strips with dimensions 2×30 cm parallel to the fiber direction. The stress-strain constitutive models of Para rubber wood and GFRP materials are summarized as shown in Fig. 3.



Fig. 3: Constitutive models of Para wood and FRP.



Fig. 4: Failure modes of Para wood glulam beams.

As detailed in Fig. 4, two different possible failure modes; a) and b), of the FRP reinforced Para-rubber wood glued laminated beams were investigated and compared with the experimental results as follows:

1) Failure modes (1-a) and (2-a) of the PW glulam beams reinforced with tensile GFRP reinforcement were experienced at the interface (tension side) while compressive strain at the top fiber is less than the elastic strain limit ( $\approx 2900(10^{-6}) \text{ mm.mm}^{-1}$ ). Thus, the compressive stress of the wood is still higher than the tensile strength. In addition, using top and bottom GFRP reinforcements, failure modes under the linear stress-strain relation will be experienced due to plastic area reduction of the compressive zone (Romani and Bla $\beta$  2001). Details of each failure subset calculations with clarification of symbols notation following at the far end are:

Failure mode 1-a: From equilibrium equation:  $C_w = T_f + T_w$ 

$$\frac{1}{2}E_w\varepsilon_{cw}ab = \frac{1}{2}E_w\varepsilon_{tw}bx + E_f\varepsilon_fbt$$
(12)

$$1 - \left(\frac{\varepsilon_{\text{rw}}}{\varepsilon_{\text{rw}}}\right)^2 a^2 + (2n_f t)a - (2n_f th) = 0$$
(13)

$$x = \frac{\varepsilon_{\rm fiv}}{\varepsilon_f} (h - a) \tag{14}$$

$$M = \left(\frac{1}{2}E_{w}\varepsilon_{cw}ab\right)\left(h - \frac{a}{3}\right) + \left(\frac{1}{2}E_{w}\varepsilon_{tw}bx\right)\left(h - a - \frac{2x}{3}\right)$$
(15)

Failure Mode 2-a:

From equilibrium equation:  $C_w + C_f = T_w + T_f$ 

$$\frac{1}{2}E_w\varepsilon_w^bab + E_f\varepsilon_w^bbt = \frac{1}{2}E_w\varepsilon_{tw}bx + E_f\varepsilon_fbt$$
(16)

$$[1 - \varepsilon_{tw}^{2}]a^{2} + (4n_{f}t)a - (2n_{f}th) = 0$$
<sup>(17)</sup>

$$M = \left(\frac{1}{2}E_{w}\varepsilon_{w}^{b}ab\right)\left(h - \frac{a}{3}\right) + \left(\frac{1}{2}E_{w}\varepsilon_{tw}bx\right)\left(h - a - \frac{2x}{3}\right) + \left(E_{f}\varepsilon_{w}^{b}bth\right)$$
(18)

2) Failure modes (1-b) and (2-b) occurred at the interface (tension side) while the compression side of the cross section is assumed to be in a linear elastic - perfectly plastic state. For beam bending, the compressive stress is larger than the tensile strength due to tensile reinforcement. The compressive strain at the top fiber is higher than the elastic strain limit ( $\approx 2900(10^{-6})$  mm.mm<sup>-1</sup>). Compressive strain of GFRP reinforcement at the extreme fiber is still lower than the failure strain of GFRP. Thus, buckling and delaminating of compressive reinforcement will not take place for maximum moment capacity of the FRP reinforced PW glulam beam.

Failure Mode 1-b: From equilibrium equation:  $C_w = T_f + T_w$ 

$$\frac{1}{2}E_w\varepsilon_{cw}b(a-c) + E_w\varepsilon_{cw}bc = \frac{1}{2}E_w\varepsilon_{tw}bx + E_f\varepsilon_fbt$$
(19)

$$a = \frac{(2n_f t) \varepsilon_f^2 + [\varepsilon_{ew}^2 + (2\varepsilon_{ew} - 1)\varepsilon_{ew}]h}{\varepsilon_{ew}^2 + (3\varepsilon_f + 2\varepsilon_{ew} - 1)\varepsilon_{ew} - \varepsilon_f}$$
(20)

$$x = \frac{\varepsilon_{\rm tw}}{\varepsilon_f} (h - a) \tag{21}$$

$$M = \left(E_w \varepsilon_{cw} b\right) \left(h - \frac{c}{2}\right) + \left(\frac{1}{2} E_w \varepsilon_{cw} b\right) \left(h - \frac{2c}{3} - \frac{a}{3}\right) + \left(\frac{1}{2} E_w \varepsilon_{tw} bx\right) \left(h - a - \frac{2x}{3}\right)$$
(22)

Failure Mode 2-b: From equilibrium equation:  $C_w + C_f = T_w + T_f$ 

$$\frac{1}{2}E_w\varepsilon_{cw}b(a-c) + E_w\varepsilon_{cw}bc + E_f\varepsilon_w^b bt = \frac{1}{2}E_w\varepsilon_{tw}bx + E_f\varepsilon_f bt$$
(23)

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$$a = \frac{(n_f \varepsilon \varepsilon_f)(2\varepsilon_f - b\varepsilon_w^0) + [\varepsilon_{cw}^2 + (2\varepsilon_{cw} - 1)\varepsilon_{cw}]h}{\varepsilon_{cw}^2 + (3\varepsilon_f + 2\varepsilon_{cw} - 1)\varepsilon_{cw} - \varepsilon_f}$$
(24)

$$x = \frac{\varepsilon_{\rm fit}}{\varepsilon_f} (h - a) \tag{25}$$

$$M = \left(E_{w}\varepsilon_{cw}b\right)\left(h - \frac{c}{2}\right) + \left(\frac{1}{2}E_{w}\varepsilon_{cw}b\right)\left(h - \frac{2c}{3} - \frac{a}{3}\right) + \left(\frac{1}{2}E_{w}\varepsilon_{cw}bx\right)\left(h - a - \frac{2x}{3}\right) + \left(E_{f}\varepsilon_{w}^{b}bth\right)$$
(26)

where:  $C_{qv}$  and  $C_{f}$ - wood and GFRP compression force, respectively,

 $T_f$  and  $T_w$  - FRP and wood tension forces, respectively,

b and b - width and height of the Para wood glued laminated beam cross section, respectively,

t - thickness of GFRP reinforcement,

a - distance between the neutral axis and top surface of the beam cross section and

*c* - depth of plastic compressive zone,

*x* - height of tensile stress distribution,

 $\varepsilon_{f}$ - tension strain of GFRP reinforcement ( $\approx$  the extreme bottom fiber strain),

 $\varepsilon_w^{\ b}$  - wood strain of the bottom fiber.

## Reduction factors of flexural rigidity due to shear deformation

Reduction factors of flexural rigidity due to shear deformation of Para-rubber wood glued laminated beams are determined in this section. These factors are experimentally evaluated using flexural and shear rigidity values obtained via back calculation methods as shown in Section 5. To work out the reduction in flexural rigidity due to shear deformation, Timoshenko's beam theory is utilized. Deflection equations of Timoshenko's beam theory that includes deflections due to bending and shear effects are rearranged by putting deflection due to shear effect in terms of deflection due to bending and hence a deflection equation with shear effect is reduced to a deflection equation of simple beam bending theory with a reduction coefficient from the shear effect. This coefficient represents the effect of shear contribution to flexural rigidity under a specific loading condition. Employing mid-span deflection, a total deflection can be written in general expression as follow:

$$\delta_{mt} = \delta_{mb} + \delta_{ms} \tag{27}$$

where:  $\delta_{mt}$  - total deflection at the mid-span,

 $\delta_{mb}$  and  $\delta_{ms}$  - deflection of the mid-span due to bending and shear effect, respectively. By substituting factor  $(f_{bb})$  into total deflection, the deflection equation (27) is rewritten in terms of deflection due to bending effect and reduction factor  $(R_{bb})$ .

$$\delta_{mt} = \delta_{mb} \left( 1 + \frac{1}{f_{bs}} \right) = \frac{\delta_{mb}}{R_{bs}}$$
<sup>(28)</sup>

where:  $f_{bs}$  - ratio of deflection due to bending  $(\delta_{mb})$  to shear  $(\delta_{ms})$  effect.

 $R_{bs}$  - introduced to be the reduction factor of beam flexural rigidity due to shear deformation under specific load. Using equation (28) and deflection coefficient, reduction factors under three and five point bending are found as follows:

For three point bending:

$$R_{bs} = \frac{1}{\left(1 + \frac{48}{L^2} \left(\frac{EI}{\kappa GA}\right)\right)}$$
(29)

For five point bending:

$$R_{bs} = \frac{1}{\left(1 + \frac{219}{L^2} \left(\frac{EI}{\kappa GA}\right)\right)}$$
(30)

#### Ductility and deformability factor

In this section, the ductility of FRP reinforced Para rubber wood glued laminated beams was evaluated using experimental data. Generally, post-elastic behavior and energy absorption of beams are indicated by ductility or deformability factor. Ductility of a beam is defined as the ratio of deflection (or curvature, or rotation) at the ultimate point to that at the elastic point, whereas deformability factor is defined as the ratio of energy absorption (area under moment-curvature or load–deflection curve) at ultimate to energy absorption at limiting curvature or deflection value. From experimental results, relationships of the load–deflection or the moment-curvature are not exactly bilinear and thus elastic and ultimate points are determined according to the procedure codified in EN 1995-1-1: European Committee for Standardization 2004 (Tomasi et al. 2009) where an ultimate point is defined as the post-elastic point at 80 percent maximum applied load or moment. The procedure to obtain the ductility ratio is presented in Fig. 5 together with a brief explanation in Appendix A.



Fig. 5: Procedure for the ductility ratio.

Appendix A: Ductility ratio (Tomasi et al. 2009).

Line 1 passes through the position 10  $P_{max}$  and 40 %  $P_{max}$  on load-deflection curve. Line 2 is a horizontal line passing through the  $P_{max}$  position on load-deflection curve. Line 3 is an angle ( $\alpha$ ) inclined line with respect to line 2.  $P_y$  is defined as an intersection point between line 1 and line 2. Tan  $\alpha$  = (Tan  $\theta$ )/6. An ultimate point is defined as the post-elastic point at 80 %  $P_{max}$ .

## RESULTS

Based on experimental data, the results of FRP reinforced Para-rubber wood glued laminated beams were evaluated and discussed in terms of ultimate load capacity, maximum moment (exper./ theor.) ratio, flexural and shear rigidity, deformability factor and reduction factors due to shear deformation. All FRP reinforced PW glulam beams were tested until failure. The experimental and theoretical ultimate load, the top and bottom fiber strain at maximum load, the flexural and shear rigidity are summarized in Tab. 2. In addition, two typical relationships between load and deflection of the tested beams in this study are presented in Figs. 6 and 7.

			4 Poin	ts	5 Po	3 Points		
Beam	Avg. max. load (kN)		Strain @ max. load (10 <sup>-6</sup> )		Avg. EI ( MN.m <sup>2</sup> )	Avg. max. load (kN)	Avg. KGA (MN)	Avg. KGA (MN)
	Exp.	Theor.	Тор	Bottom		Exp.		
P1	33.4	29.3	1585	1715	0.508	41.5	24.7	31.5
P2	31.1	24.8	1592	2015	0.493	47.1	29.5	41.1
P1B	50.8	44.7	2139	1801	0.758	66.2	48.8	42.5
P2B	49.0	42.6	2072	1878	0.714	53.0	86.5	70.7
P1BT	60.1	66.7	2021	3729	0.851	72.6	93.4	99.8
P2BT	55.6	56.5	1704	2875	0.823	70.6	143.5	131.0

Tab. 2: Experimental and theoretical results.



Fig. 6: Load and deflection relation under 4 point Fig. 7: bending. bending.

*Fig. 7: Load and deflection relation under 5 point bending.* 

# DISCUSSION

It was found that the load and deflection responses under both the four and five point bending tests exhibited a linear behavior (up to approx. 80-90 % of the failure load) before a first major crack near the joints appeared. After several major cracks had developed, the tested beam stiffness significantly reduced corresponding to changes in the slope of the load and the

deflection response. During this stage, these major cracks horizontally propagated in the tension zone of the beam cross-section. After this stage, there was a small increase in load resistance, followed by failure of the tested beam with abrupt rupture on the Para wood. It should be noted that crushing of the wood in compression zone did not occur since the fiber strain at the top surface of the beam cross-section was still lower than the elastic compressive strain limit while the corresponding strain in the tension zone of the wood went beyond the elastic tension strain limit. However, fiber strain of the GFRP was still much less than the GRFP rupture strain. Thus failure mode of the beams can be classified as wood tension failure without GFRP rupture. From experimental results, most tested beams similarly exhibit this failure mode shown in Fig. 8. In addition, it was found that FRP reinforced PW glulam beams developed a better strength and post-peak structural responses compared with those without FRP reinforcement.



Fig. 8: Typical failure mode: Beam P1B.

For experimental results as shown in Tab. 2, it was observed that average flexural and shear rigidity increased with increasing amount of GFRP. However, the magnitude depends on the type of beam laminated pattern and test procedure, especially for shear rigidity. From comparison of average shear rigidity results, a maximum percent difference of average shear rigidity between three-point and five-point bending test was about 28.2 %. Theoretical maximum load (moment) capacity was predicted using numerical models as mentioned in section 5. By assuming neutral axis depth a) and using the recorded strain data across the beam cross-section, an iterative procedure was performed to obtain force equilibrium in tension and compression areas. The ratios of experimental to theoretical moment for all tested beams were varied between 0.901 and 1.254. The average maximum experimental to theoretical load (moment) ratios of tested beams were less than 1 for Para rubber wood glued laminated beams with GFRP on the both top and bottom surfaces. The cause of non-conservative values of moment capacity obtained from the proposed theoretical model is possibly due to the use of inferior quality timber in the above two groups. Average deformability factors increase directly with increases in amount of GFRP. The average deformability factors of Para rubber wood glued laminated beams were 1.643-2.23 for beams with GFRP on the both top and bottom surfaces and 1.529-1.629 for beam with GFRP on the bottom surface. In addition, the average deformability factors of Para wood glued laminated beams without GFRP were found to be 1.353-1.517. Evaluation of reduction factors for FRP Reinforced Para rubber wood glued laminated beams is accomplished by using flexural and shear rigidity based on experimental results outlined in Section 6. As shown in Fig. 9a) for beam pattern Pb2 and Fig. 9b) for beam pattern Pb1, reduction factors were determined and plotted against test span length to depth ratios (L/d) between 7 and 56. From both a) and b), the shear effect is as anticipated, i.e. the effect is higher for beams with GFRP on the bottom surface only because



Fig. 9: Reduction factors due to shear deformation.

elastic and shear modulus results of these beams are lower than those with GFRP on both top and bottom surfaces.

## CONCLUSIONS

This study was focused on structural performance of FRP reinforced Para rubber wood glued laminated beams to assist engineers in exploring a more efficient and cost effective structural system prior to actual field implementations. Based on the experimental and analytical investigations, following summaries and conclusions could be dawn: The beam laminated patterns can make a difference in strength, equivalent flexural and shear rigidity; that FRP reinforcement can improve stiffness, strength, deformability and post-peak behavior of original Para wood glued laminated beams. Based on this study, different experimental procedure of shear rigidity can make up to 28 % difference in the results. The failure mode of a simply supported FRP reinforced PW glulam beam is a combination of tension and horizontal shear failure around the beam bottom layers and not in the compression zone. Overall, predicted results from the proposed analytical model are mostly agreeable to the experimental results, more-less on the conservative side.

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# REFERENCES

1. Beng, O.C., 2004: Prediction of beam stiffness for structural glued laminated timber. Master Thesis, Universiti Putra Malaysia, Malaysia.

- 2. Dempsey, D.D., Scott, D.W., 2006: Wood members strengthened with mechanically fastened FRP strips. Journal of Composites for Construction 10(5): 392-398.
- 3. EN 1995-1-1, 2004: Eurocode 5: Design of timber structures. Part 1-1: General rules and rules for the buildings.
- Fiorelli, J., Dias, A.A., 2003: Analysis of the strength and stiffness of timber beams reinforced with caron fiber and glass fiber. Materials Research 6(2): 193-202. doi: 10.1590/ S1516-14392003000200014.
- Fiorelli, J., Dias, A.A., 2006: Fiberglass-reinforced glulam beams: Mechanical properties and theoretical model. Materials Research 9(3): 263-269. doi: 10.1590/S1516-14392006000300004.
- 6. Lindenberg, R.F., 2000: ReLAM: A nonlinear stochastic model for the analysis of reinforcement glulam beams in bending. Ph.D. Dissertation, Dept. of Civil and Environmental Engineering, University of Maine, Orono, ME.
- Lopez-Anido, R., Xu, H., 2002: Structural characterization of hybrid fiber-reinforced polymer - glulam panels for bridge decks. Journal of Composites for Construction 6(3): 194-203. doi: 10.1061/1090-0268.
- Ngamcharoen, P., Ouypornprasert, W., Boonyachut, S., 2007: Influence of uncertainties in structural resistance on glulam girder design. International Journal of Materials & Structural Reliability 5(1): 45-57.
- Plevris, N., Triantafillou, T.C., 1992: FRP-reinforced wood as structural materials. Journal of Materials in Civil Engineering 4(3): 300-317. doi: 10.1061/0899-1561.
- 10. Porteous, J., Kermani, A., 2007: Structural timber design to Eurocode 5. Blackwell Science Ltd., 9600 Garsington Road, Oxford OX4 2DQ, UK, 555 pp.
- 11. Romani, M., Blab, H.J., 2001: Design model for FRP reinforcement glulam beams. In: Proceedings of the International Council for Research and Innovative in Buildings and Construction, Venice, Italy.
- Tomasi, R., Parisi, M.A., Piazza, M., 2009: Ductile design of glued-laminated timber beams. Practice Periodical on Structural Design and Construction 14(3): 113-122. doi: 10.1061/1084-0680.

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