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Flexural Strengthening of Timber Beams Using Carbon Fibre Reinforced Polymer

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Abstract

This research was conducted to investigate the bending behavior of timber beams strengthened using carbon fibre reinforced polymer (CFRP) plates. Five timber beams of Yellow Meranti species were tested. One of the beams was used as a control beam (unstrengthened) while the remaining four beams were strengthened before tested to failure under four point loading. The results showed that the strengthened beams performed better than the control beam. The ultimate and service load of the strengthened beams were increased between 31.8 – 44.5% and 27.1 – 80%, respectively when the CFRP area was between 0.15 – 0.42%. The strengthening of timber beams with CFRP has enhanced their stiffness. The stiffness of the beams was increased between 32.6 – 87.6%. The tensile crack and crushing occurred simultaneously (balanced reinforced) when the CFRP was about 0.16%. Modification factors for bending strength and stiffness for timber beam strengthened using CFRP plates were proposed from this research.

Keywords: Timber beams; Strengthening; CFRP; Bending strength; Stiffness; Modification factors

INTRODUCTION

Timber has been chosen by engineers for some structural elements in construction. The main reason why timber is still popular is due to its high strength to weight ratio, easy to construct and move because there is no formwork and heavy machinery required. Thus, the use of timber will lower the construction cost and shorten the construction time. Due to its insulation from sound as well as resistance to corrosion and oxidation, timber is also popular in light construction. However, timber structures may have many problems and the most critical aspect is its strength; even timbers taken from the same species and log will have different strength. All these factors will affect the load capacity of the timber structures. Thus, methods of enhancing the timber should be developed in order to increase the load capacity of timber structures. One of the methods employed is by strengthening it with carbon fibre reinforced polymer (CFRP) bonded by resin. Selection of an appropriate adhesive should be carried out in order to bind the timber and CFRP plate firmly.

Reinforced solid timber is a new structural element to Malaysian society, although it has been studied for sometime in other countries. Many reinforcing systems have been developed and tested. However, none have reached commercial application (Gardner, 1989). The reason is that none of the systems were able to convince the end user and offer an economic benefit because the cost of introducing the reinforcing system is greater than the savings in timber. The selection of strengthening method is important to the total cost because different techniques yield different complications and costs.

Quite a lot of research has been done on strengthening of glulam or glued-laminated wood. For instant, Kirn and Davalns (1997) have numerically investigated buckling of fibre reinforced polymer (FRP) layer at the compression zone in laminated wood beams. The debonding and subsequent local buckling of the FRP layer in some cases resulted in a premature failure of a glulam-FRP beam. Reinforcing timber beams with FRP strips on the compression and/or tension side is an efficient way to increase the stiffness and strength of laminated wood beams and to decrease the depth of the member (Kirn and Davalns 1997; Gentile *et al.* 2002; Alam *et al*. 2009).

A study on the performance of resins used in timber repair has been done by Wheeler and Hutchinson (1998). Epoxy resin used to bond Oak test joints was able to confirm the potential of these adhesives for exterior use. Epoxy resins were able to bond timber of up to 22% moisture content without any significant depreciation in bond strength. The tests carried out show that there is not an initial problem with adhesion to timber, but do not prove that resin repairs are appropriate for fully exposed conditions or that long term durability.

Ogawa (2000) has studied the strengthening of glulam using CFRP plate attached at bottom surface of the beam with phenolic resin for fire resistance. The percentage of CFRP used was between 0.08 – 1.3 %. The stiffness and strength were doubled. The strengthened face of glulam was retained even after burning at 800°C for one hour. This test indicates that the use of CFRP with phenolic resin would be able to prevent the supply of oxygen to the wood substrate and also exhibited superior thermal conductivity.

Broughton and Hutchinson (2001) have studied the effect of timber moisture content on bonded-in rods to be used for connections. The rods were steel and GFRP while the adhesives were 2-part ambient cured expoxies. It was found that both strength and the failure modes were significantly influenced by the moisture content of the timber at the time of bonding.

Lopez-Anido and Han Xu (2002) have studied glulam panels strengthened on the top and bottom faces of the glulam panel by a FRP wet layup process. It was found that FRP-glulam beams with sufficient tension reinforcement not only exhibit significant strength increases, but also developed wood ductile compression failure, rather than the typical brittle tension failure of wood.

Gentile *et al.* (2002) investigated creosote-treated sawn Douglas Fir timber beams strengthened with GFRP bars. The beams were obtained from a dismantled bridge that was in service for over 30 years and were tested to obtain initial stiffness before strengthening. The percentage reinforcement ratios were between 0.27 and 0.82%. The results have shown that the failure mode had changed from brittle tension to compression failure. The flexural strength increased by 18 to 46%. The research also indicated that the strengthening overcame the effect of local defects in the timber and had enhanced the bending strength.

The behavior of timber stringers reinforced with GFRP sheets was studied by Gomez and Svecova (2008). The stringers were reinforced for shear and bending. The proposed reinforcement led to an improvement of stiffness of 5.5 – 52.8%. Alam *et al.* (2009) strengthened fractured timber beams using steel and CFRP. The results showed that both reinforcements were very effective in enhancing flexural strength, but the CFRP reinforcement was the more efective. The latest inovative development of the usage of FRP in strengthening works was conducted by Ferrier *et al.* (2010). They have developed a hybrid beam made of glulam and short fibre-reinforced concrete planks with or without internal reinforcement consisting of steel or FRP bars. The results showed that the hybrid beam exhibited higher bending stiffness and ultimate load capacity compared to that of a standard unreinforced glulam beam of similar dimensions.

Many studies have been conducted on glued-laminated timber, however, research on strengthening solid timber is very limited. In Malaysia, there is no published research on timber strengthening of tropical wood. The cost of the strengthening material, such as FRP, is considered high because very few companies are producing the FRP. The high material cost is also due to its least application at site because of a lack of technical knowledge in FRP. Unlike other countries overseas, the FRP is a common material used for strengthening and although the price of material is quite high, it is still reasonable since the material can be produced in a larger volumes.

The objectives of this research are to study the bending strength, stiffness and the failure modes of tropical timber beams strengthened using CFRP in the form of plates. Strength and stiffness modification factors are proposed at the end of the study.

RESEARCH SIGNIFICANCE

CFRP has a high strength in tension and thus serves as a good material for strengthening the tension zone of timber members. Compared to timber alone, the combination of timber and CFRP is expected to significantly provide better structural performances for the strength and stiffness. Preliminary studies show that when a beam is strengthened in the tension zone, the mode of failure for the timber structures may change from tension failures to compression failures (Giap 2007). In other words, this method has increased the tensile capacity of the beam, as well as fully utilizing the compression capacity of timber.

Many opportunities exist for the use of CFRP in timber members for both new structural members and rehabilitation of existing structures. Effective strengthening techniques can reduce the size of beams (Haiman & Zagar 2002) while increasing their strength, thereby creating a more efficient use of the timber supply. Obtaining larger sections of timber beams is getting more difficult, thus small sections of timber beams after being strengthened can exhibit equivalent capacity as a larger section. For existing timber structures, the strengthening technique may save the cost of replacing the structure by allowing it to withstand higher loads (Gentile *et al*., 2002). It is also believed that the CFRP reinforcement is capable of acting as a bridge, spanning local defects and discontinuities of the timber reducing the variablility of its properties (Svecova and Amy 2004). Strengthened beams are also suitable to be used in modular construction systems. The development of strength and stiffness modification factors from this study will help engineers to design beams strengthened with CFRP plates.

RESEARCH MATERIALS

Yellow Meranti timber beams

The main research material used in this work was Yellow Meranti timber beams, obtained from a local manufacturer in Malaysia. The dimension of the beams were 100 mm × 200 mm × 3000 mm. Yellow Meranti, also known as Yellow Seraya is an important commercial light hardwood in Malaysia, which is exported as sawn timber and logs (Desch 1981). Code of Practice for Structural Use of Timber in Malaysian Standard, MS 544: PART 2 (2001) categorises Yellow Meranti in strength group 6 and it requires preservative treatment before use in construction. However, in this research, untreated Yellow Meranti was used.

Yellow Meranti has a density between 575 - 735 kg/m^3 in dry air (MTC Wood Wizard, 2006). The average density at 19% moisture content is 680 kg/m^3 (MS 544: PART 2, 2001). The durability of the heartwood can be classified as moderately durable, whilst the sapwood of Yellow Meranti is susceptible to powder-post beetle attack. In terms of working qualities, Yellow Meranti gives a good finish in most operations by hand and machine tools.

Carbon fibre reinforced polymer (CFRP)

The unidirectional CFRP plates were taken from a local supplier in Malaysia, which were imported from Switzerland (Sika CarboDur S5012 and S6014). Two different widths (50 mm and 60 mm) and thicknesses (1.2 mm and 1.4 mm) were used to strengthen the timber beams. The width and thickness used in this study are typical of those used for bending strengthening purposes (Keble 1999, Duthinh and Starnes

2004, and Tingley *et al*. 1997). Sika CarboDur is a heavy duty CFRP strengthening system for reinforced concrete, masonry, stonework, steel, aluminum and timber. Two main materials forming Sika CarboDur are carbon fibre as reinforcement and epoxy resin as matrix.

CFRP is widely used in many countries because of their low weight, available in any length up to 100 m, easy to transport (come in roll form), laminate intersections are simple, very high strength, available in various moduli of elasticity, outstanding fatigue resistance, no corrosion, high alkali resistance, economical application due to no heavy handling and installation equipment.

From the literature review, the modulus of elasticity, the tensile strength, and the strain at break of the CFRP plate are 165 kN/mm^2, 3100 N/mm^2 and 1.7%, respectively (Lorenzis *et al*. 2005). CFRP has similar compression and tensile properties, and therefore can be used in either compression or tension zones of beams (Naghipour *et al*., 2005).

Adhesives

The adhesive used to bond the timber and CFRP plates was Sikadur-30 which. It consists of two components A (resin) and B (hardener) mixed in a ratio of 3:1 by weight. The mixture becomes smooth in consistency and uniform grey color. It is normally used at temperature between 8ºC to 35ºC. Table 1 shows the characteristics of Sikadur-30.

Table 1. Characteristic of Sikadur-30

Characteristics	Sikadur-30
Elastic Modulus (N/mm^2)	12,800 (Static)
Compressive Strength (N/mm^2)	85 – 95 (7 days at +35 ºC)
Tensile Strength (N/mm^2)	26 – 31 (7 days at +35 ºC)
Shear Strength (N/mm^2)	16 – 20 (7 days at +35 ºC)
Shrinkage (%)	0.04
Pot life (minutes)	40 (at 35 ºC)

LABORATORY WORKS

Testing of moisture content of timber beams

Since the strength of the timber beams varies with moisture content, it is necessary to determine the moisture content of each timber beam after being dried in a big oven. The preferred result is that all timber beams will have the same moisture content. This is to ensure that the effect of moisture content to the strength can be eliminated. Hence the variation in strength of timber comes from the effect of strengthening. The testing of moisture content is in accordance to American Standard for Testing and Materials (ASTM: D 4442 – 92, 1992).

Tensile test of CFRP plates

Sample preparation, loading procedures, and testing configuration were in accordance with ISO/DIS 10406-2:2007. In this study, the number of samples was twenty. The determination of the tensile properties was accomplished by using prismatic samples having an overall length of 255 mm and a width of 12.5 mm. The clear distance between the grips was 115 mm. The total length of a specimen would be the length of the test region plus that of anchorage devices or clamp zones. The length of the anchorage devices and clamp zones was sufficient in such that the specimen did not break or slip in the anchorage zone during the tension test. Aluminum plates of 70 mm long and 12.5 mm wide were used to grip the CFRP plate at both ends and adhesive was used to bond between CFRP and aluminum plates. The adhesive used for bonding was Sikadur-30. The samples were cured about one week to give the test piece the desired strength. The test was conducted in order to determine direct tensile strength, elasticity modulus and stress-strain relationship for CFRP plates due to the lack of information from supplier.

Strengthening of timber beams

Two types of CFRP plates were supplied and available in the market i.e. Sika CarboDur Type S5012 (the width is 50 mm and the thickness is 1.2 mm) and Type S6014 (the width is 60 mm and the thickness is 1.4 mm). However, CFRP plate of 25 mm wide and 1.2 mm thick (called S2512) and also 30 mm wide and 1.4 mm thick (called S3014) were also required as part of the strengthening scheme. Thus, both CFRP plates of S5012 and S6014 were be cut parallel to the fibres to produce S2512 and S3014, respectively. The CFRP plate was 3000 mm long. Fig. 1 shows the cross section of all beams strengthened with CFRP plates with different area. The beams were named as CP-2512-1B, CP-3014-1B, CP-5012-1B, and CP-6014-1B.

The cutting of the plate is preferably done with a diamond cutting disc. However, a small steel saw was used and it capable to cut the plate easily with smooth edges along the cutting line. The evenness of the surface is important to prevent the carbon fibre plate from peeling off due to deviation forces under tensile bending. It was suggested by Keble (1999) that the profile of the CFRP plate should be a straight edge, with maximum irregularities of 5 mm over a 2 meters.

All surfaces to be glued were cleaned using acetone and compressed air to rid it of loose particles, dirt, dust, sawdust, oil and any other contaminating substances as recommended by the manufacturer. A strain gauge of BFLA-5-3L was attached at the mid-length of each CFRP plate using a cyanoacrylate (CN) adhesive; a product from TML, Japan. A coating material (N-1) was used to protect the strain gauge from direct contact with Sikadur-30. It is desirable to glue the surfaces as soon as possible (within 48 hours) after they have been prepared.

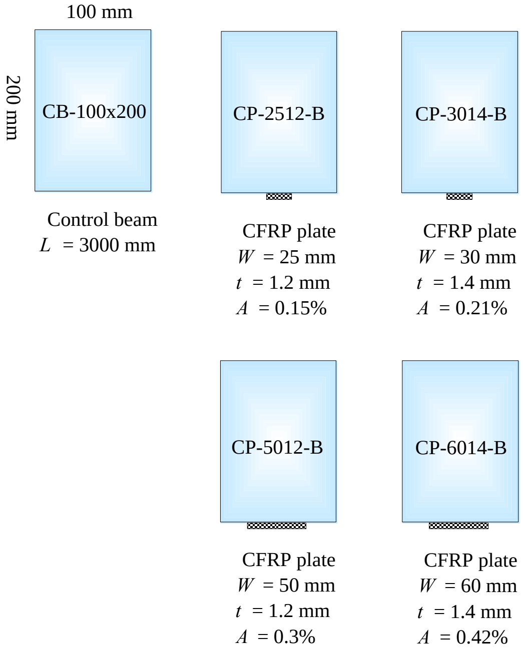


Figure 1. Cross section of beams strengthened with CFRP plates

All beams were put aside for more than seven days to make sure the bonding between CFRP and timber is well established. After seven days, six strain gauges were attached at mid-span across the depth of the beam. The typical samples of the strengthened timber beams are illustrated in Fig. 2.

Figure 2. Timber beams strengthened with CFRP plates

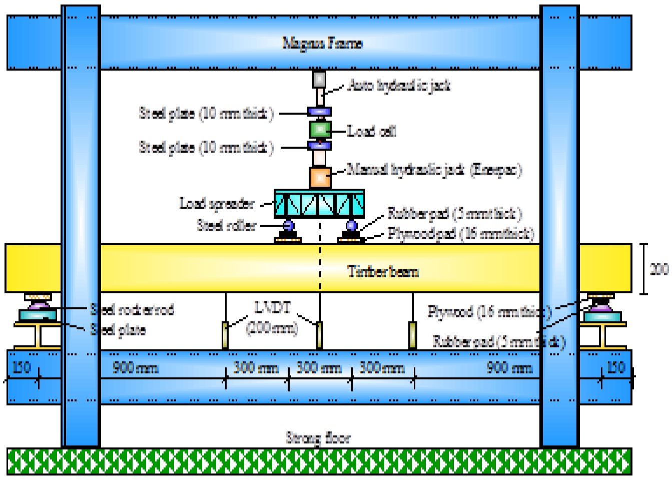
Bending test of timber beams

The control beam was tested first until failure and then followed by the strengthened beams. All timber beams were tested under four-point loading where the half shear span to depth ratio (*a/h*) was 6 which is between 5 and 12 (ASTM D198 1992). The clear span for the timber beam was 2700 mm. The deflections of the beams were measured using three linear variable displacement transducers (LVDT) which were placed at the bottom part of the beam. Fig. 3(a) and (b) shows the configuration of the testing. All beams were laterally braced in order to prevent lateral torsional buckling.

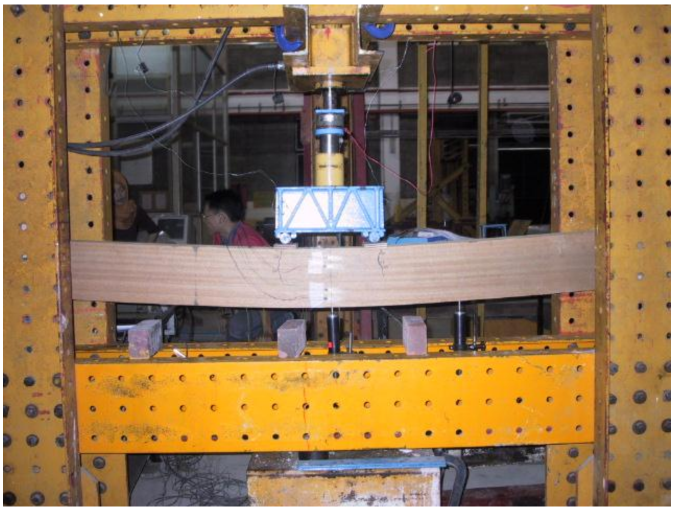
Plywood of 100 mm length, 100 mm width and 16 mm thick and a rubber pad of 100 mm length, 100 mm width and 5 mm thick were used as bearing plates under the steel rollers and rubber pad. The plywood's corners were rounded to minimize stress concentration to the test specimens and to obtain a relatively uniform load level under the loading plates. This was suggested by Lam & Craig (2000)**.** This arrangement is very important as the preliminary testing on beam showed that the timber beam experienced crushing due to local bearing stress at the point load. This local bearing stress generated further compressive stress at compression the zone in the timber beam. A Load spreader, made by a short steel beam of 0.6 m long and 0.15 m height, was put on steel rollers with a distance between them of 0.3 m. A steel plate of 100 mm × 100 mm × 10 mm thick was put on the load spreader followed by a load cell and steel plate. An auto hydraulic jack was used to apply the load, attached to a steel beam and then supported by steel columns.

The testing rig was a Magnus Frame which was a self-reacting frame built-up with steel channel section. The sample was supported on two steel bases through a lubricated pin and roller support. The whole system was anchored and erected on a strong floor. The capacity of the Magnus Frame was 200 kN.

A loading rate of 2.0 kN/min was applied to each timber beam until failure. When the timber beam failed, the crack patterns were drawn on paper. Immediately after the test, the samples from that particular timber were taken to determine its moisture content.



(a)



(b)

Figure 3. Configuration for bending test

RESULTS AND ANALYSIS

All results obtained from the strengthened beams were compared with the control beam in order to study its behavior, especially the strength, stiffness and modes of failure before the modification factors could be developed.

Moisture content of timber

The moisture content (MC) of the timber beams was controlled by placing them into a big oven where the temperature was controlled between 40ºC - 50ºC for one month. Maintaining a low temperature over a long exposure allowed the timber beams to dry slowly without defect. The beams were put aside at room temperature to stabilize its moisture content for another one month. Then the moisture content was found to be approximately 16%.

Stress-strain curves for CFRP plates

The data was analysed and interpreted into a stress-strain curve to find the ultimate load, maximum stress and strain, and elastic modulus. The results of tensile test were plotted showing the relationship between stress and strain of the CFRP plates. The graphs were plotted separately for plate type S5012 and S6014 which are shown in Fig. 4(a) and (b), respectively. The curve was approximately linear elastic up to ultimate load. Failure generally occurred in the gauge length region, exhibiting a consistent failure mode and relatively low scatter in data. This study also found that the provision of end-tabs on the samples provided good resistance to slip on the gripping region during testing. It also concludes that the use of Sikadur-30 to bond between CFRP and aluminum plate to form end tabs was successful.

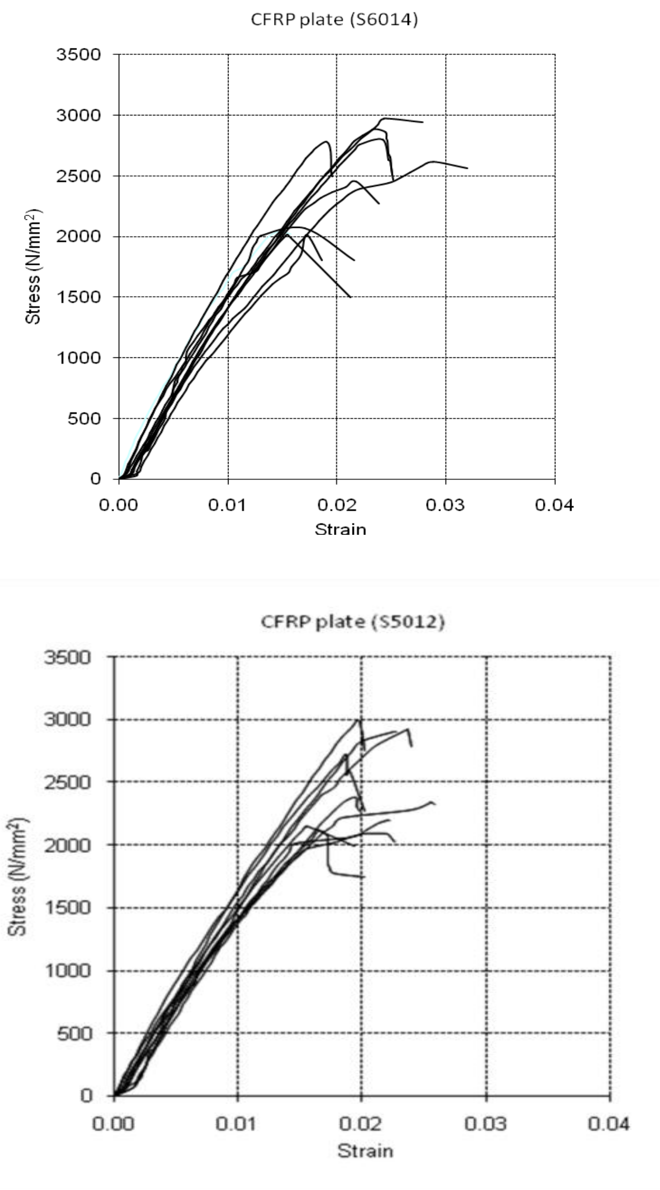


Figure 4. Stress-strain curves of CFRP plates

The summary of results is shown in Table 2. The average ultimate tensile strengths for CFRP plate type S5012 and S6014 were very close each other and these results indicate that the tensile strength of CFRP plates was not significantly affected by the plate thickness. This value is also very close to the results obtained by Spadea *et al*. (1998), which is 2300 N/mm^2 and approximately similar to the testing done by Buell and Saadatmanesh (2005) which is 2068 N/mm^2. The average strain at failure was 2.05%. The average modulus of elasticity was 162 kN/mm^2. Testing done by Chahrour and Soudki (2005) found that the tensile modulus of CFRP was 155 kN/mm^2 whereas the result obtained by Patrick and Zou (2003) was 172 kN/mm^2.

Table 2. Results of tensile test for CFRP plates

	Experimental results (average)			Supplier (Sika Kimia)		
Plate type	Tensile strength σ_{max} (N/mm^2)	Maximum strain ε_{max} (%)	Young's modulus E (N/mm^2)	Tensile strength σ_{max} (N/mm^2)	Maximum strain ε_{max} (%)	Young's modulus E (N/mm^2)
S5012	2483 (SD = 367)	2.1 (SD = 0.30)	157918 (SD = 10311)	2800	>1.7	165000
S6014	2464 (SD = 396)	2.0 (SD = 0.36)	166115 (SD = 12334)	2800	>1.7	165000

Bending behavior of timber beams

The results of load-deflection curves for all beams are shown in Fig. 5. All beams behaved linearly elastic initially, but and as the load increased the beams tended to behave non-linearly until failure occurred. There are some slight irregularities observed in the curve as a result of small cracking during testing.

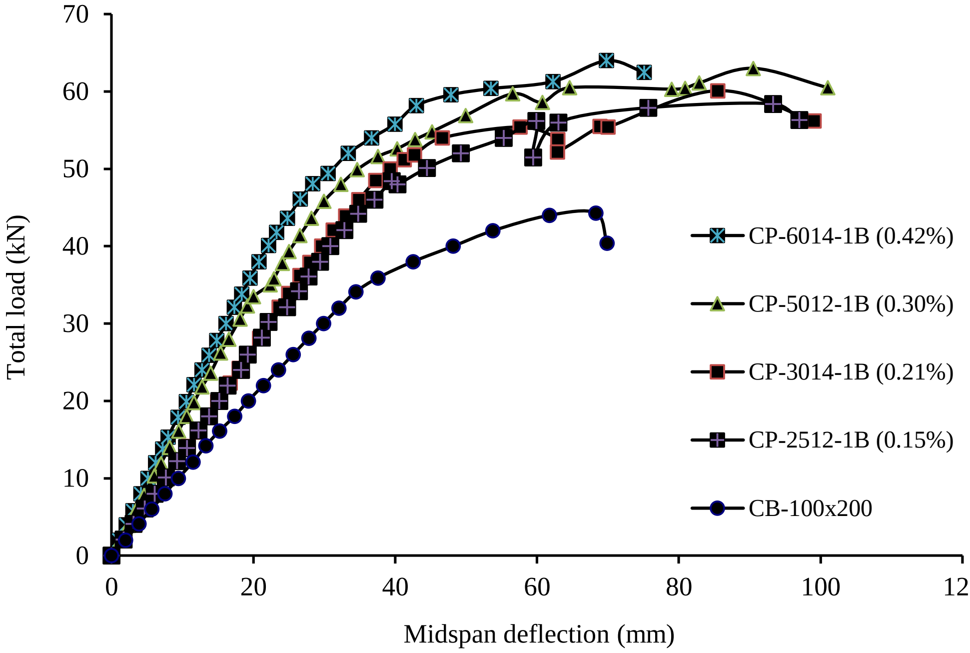


Figure 5. Load-deflection curves for all beams

The figure shows that all the strengthened beams have higher ultimate load carrying capacity than the control beam. When there was significant failure i.e. crushing or simple tensile crack occurred on the beam, the corresponding load was taken as ultimate load. Besides that, the strengthened beams with CFRP also enhance the flexural stiffness. In other words, the strengthened beams experienced lower deflection than the unstrengthened control beam at the same load level. This low deflection phenomenon is desirable in the aspect of serviceability limit state in design to ensure comfortability of timber structures because in timber design, generally the deflection will govern the design. For a beam having a clear span of 2700 mm, the allowable deflection is 8.1 mm. For all beams failure occurred after a deflection of more than 30 mm. Thus, the beams were considered not comfortable to be used. Hence, the bending capacity of the timber beams was not fully utilised. In other words, if the timber beam has high bending capacity but low stiffness, it will not enhance the timber structure according to structural design codes.

Ultimate load carrying capacity

The ultimate load carrying capacity of all beams and their corresponding deflection are shown in Table 3. All strengthened beams have greater load when compared to the control beam. This shows that the beams were successfully strengthened using CRRP plates. Generally, the ultimate and service load were increased as the percentage of CFRP increased. The ultimate load was increased significantly when the percentage of CFRP plate was 0.15%. This percentage was considered small when compared to beam cross section but the strength achievement was very encouraging given the increase in ultimate load was 31.8%. The highest increment for ultimate load among these beams was 44.5% using 0.42% of CFRP. To get better and clearer understanding regarding this relationship, the percentage increase in ultimate and service load were plotted against percentage area of CFRP as shown in Fig. 6. The relationship was not linear. When the beam was strengthened using more than 0.3% of CFRP, it did not enhance the load carrying capacity, as the compression zone has achieved it maximum capacity. Thus, it can be concluded that the beam was over-reinforced above 0.3% CFRP. This is clearly shown by the curve in Figure 6.

Table 3. Results summary of bending test

Beam	Area of CFRP (%)	P_{uls} (kN)	δ_{uls} (mm)	P_{sls}^{*} (kN)	Load increase in ULS# (%)	Load increase in SLS# (%)	*MOE* (kN/mm^2)	Increase of *MOE** (%)
CB-100×200	-	44.3	68.31	8.5	0.0	0.0	6.079	0.0
CP-2512-1B	0.15	58.4	93.31	10.8	31.8	27.1	8.066	32.6
CP-3014-1B	0.21	60.1	85.47	10.8	35.7	27.1	8.066	32.6
CP-5012-1B	0.30	63.0	90.50	13.8	42.2	62.3	10.260	68.7
CP-6014-1B	0.42	64.0	69.78	15.3	44.5	80.0	11.408	87.6

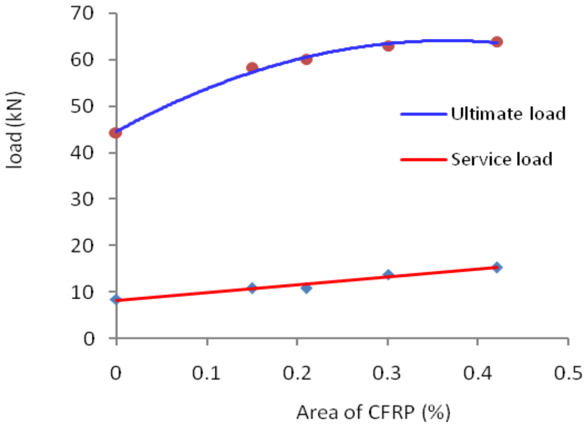


Figure 6. Effect of CFRP area on ultimate and service load

Modulus of rupture (MOR)

Modulus of rupture was calculated based on equivalent area. Thus, the CFRP plate was transformed first to equivalent timber area so a new position of neutral axis and moment of inertia could be determined. A summary of the location of neutral axis (NA), moment of inertia and *MOR* is shown in Table 4. All calculations shown here were based on the exclusion of the adhesive, assuming that the contribution was not significant since the thickness and the modular ratio was relatively small to the timber beam cross section.

Table 4. Bending strength for beams strengthened with CFRP plates

Beam	Area of CFRP (%)	Location of NA (from bottom of beam, mm)	Moment of inertia (×10^6 mm^4)	Modulus of rupture (N/mm^2)	Modification factor for *MOR*
CB-100×200	-	96.8	55.93	46.0	1.00
CP-2512-1B	0.15	95.5	60.38	56.2	1.22
CP-3014-1B	0.21	94.7	62.11	56.2	1.22
CP-5012-1B	0.30	93.0	64.60	56.6	1.23
CP-6014-1B	0.42	91.4	67.85	54.8	1.19

From this table, the neutral axis moves down below the beam mid-depth as the area of CFRP plates was increased, to a maximum of 5.4 mm when the area of CFRP was 0.42%. This movement causes lower stress in the tension zone and higher stress in the compression zone. The moment of inertia also increased as the area of CFRP increased. The maximum increment was 21.3% for the same amount of CFRP. The results suggest that by using CFRP plates increases the *MOR* level and when the area of CFRP plates is about 0.30%, the *MOR* achieved its maximum value and then becomes almost constant when the area is more than 0.30%. It was found that the *MOR* for beam CP-6014-1B was slightly lower compared to beam CP-5012-1B. The main reason is that the ultimate load for beam CP-6014-1B was almost close to beam CP-5012-1B (see Table 3) but its section modulus ($Z = I/y$, see Table 4) was higher, yields to lower *MOR* value. For the purpose of design, the modification factors were plotted as shown in Fig. 7. It can be written that the modification factors for modulus of rupture when the timber beam is strengthened using CFRP plate as follow:-

$$C_{MOR} = 7.440A_{CFRP}^3 - 7.836A_{CFRP}^2 + 2.429A_{CFRP} + 1.0 \quad \text{if} \quad 0 \le A_{CFRP} \le 0.3\%$$

$$C_{MOR} = 1.23 \quad \text{if} \quad A_{GFRP} > 0.3\%$$

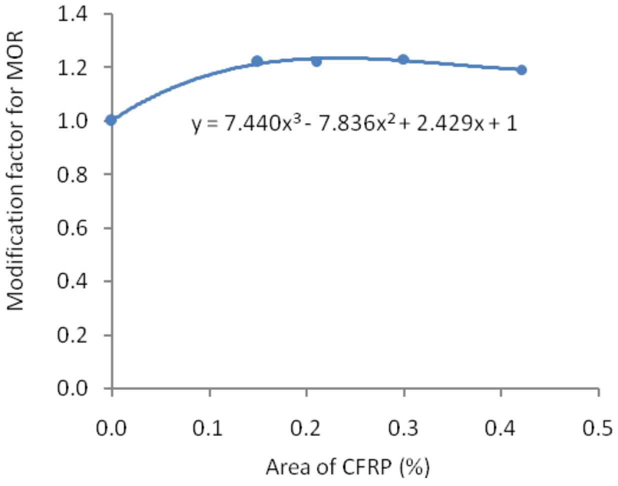


Figure 7. Effect of CFRP area to modulus of rupture (*MOR*)

Stiffness

The straight line at the initial part of the curves shown in Figure 5 indicates that the timber beams initially behaved linearly elastically. For each curve, the loading data up to 30 kN were taken for determination of stiffness. Linear regression analysis for that region was carried out to determine the gradient of the curve.

The bending modulus of elasticity was calculated from the following equation Gere and Timoshenko (1984):

$$\Delta = \frac{Pa}{24EI}\left(3L^2 - 4a^2\right); \text{ thus } \quad E = 6042.3P/\Delta$$

where Δ = deflection at mid-span, P = load, a = half of shear span, L = beam span, E = modulus of elasticity, and I = moment of inertia.

The stiffness of all beams is tabulated in Table 3. Generally, the stiffness increased as the percentage of CFRP plate increased. It seems that strengthening using a wider plate was very efficient to enhance the stiffness. Wider plate is more effective to prevent the initial crack at bottom layer because most of the tensile cracks started at the unstiffened portions (area between corners and CFRP at bottom layer of timber beams). The stiffness of beam for CP-2512-1B and CP-3014-1B was found to be same. The stiffness of the beams was increased between 32.6% – 87.6% when the timber beams were strengthened using CFRP plate for area between 0.15 – 0.42% provided that the beams were reinforced with CFRP that has similar mechanical properties as the CFRP used in this study.

Fig. 8 shows the relationship between the modification factor for *MOE* and the area of CFRP plates. From the experimental results, a linear regression line was plotted. The graph shows that applying a small amount of CFRP (0.42%) to the timber beam will enhance the stiffness by almost double. More data is required to confirm that the relationship would continue to behave linearly when the area of CFRP is greater. It is expected that there must be a limiting value for the elasticity modulus after a certain amount of CFRP reinforcement and hence the relationship would yields an optimum value. The proposed modification factor for stiffness, C_{MOE} would therefore be:

$$C_{MOE} = 1.985A_{CFRP} + 1.0 \quad \text{for} \quad A_{CFRP} < 0.42\%$$

where A_{CFRP} is the area of CFRP plate in term of percentage with respect to the beam cross section.

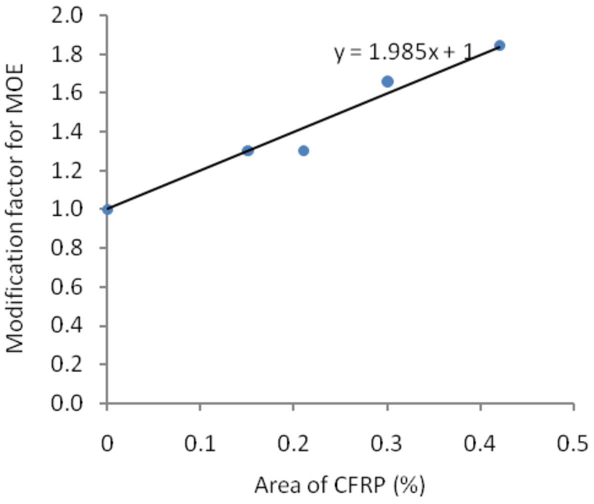


Figure 8. Effect of CFRP area on stiffness

Mode of failure

The strains at failure load for all beams are shown in Table 5. These strains will determine the failure of the beams. These failure modes have been confirmed by looking to the crack or crush pattern during testing. Given, it is quite difficult to judge whether a beam failed in tension or compression, especially when the tension and the compression zone almost have the same strength. It is often appropriate to use strain values. Generally, the resulting tensile strains were decreased and the compressive strains were increased as the percentage of CFRP plate increased. It shows that the CFRP plate reduced the tensile strain (maximum reduction was 37.8%) at the lower surface and increased the compressive strain (maximum increment was 32.8%) in the top surface of the beams. Thus, the tension zone was successfully strengthened if the percentage of CFRP was greater than 0.16%. Above this value, the failure was controlled by the compression zone. In conclusion, a beam with a CFRP plate ratio of less than 0.16%, equal 0.16%, and greater than 0.16% was taken to be under reinforced, balanced reinforced, and over reinforced, respectively.

Table 5. Modes of failure for all timber beams

Beam	Area of GFRP (%)	Tensile strain (%)	Compressive strain (%)	Failure type based on strain value
CB-100×200	-	0.751 > 0.60	0.265 < 0.30	Failed in bending with simple tensile crack (unreinforced)
CP-2512-1B	0.15	0.691>0.60	0.285<0.30	Failed in bending with simple tensile crack (under reinforced)
CP-3014-1B	0.16	0.604≈0.60	0.312>0.30	Tensile crack and crushing occurred simultaneously (balanced reinforced)
CP-5012-1B	0.30	0.539<0.60	0.352>0.30	Crushing followed by simple tensile crack (over reinforced)
CP-6014-1B	0.32	0.467<0.60	0.323>0.30	Crushing followed by simple tensile crack (over reinforced)

CONCLUSIONS

Timber beams strengthened with CFRP plates have demonstrated an increase in ultimate load capacity. The ultimate and service load of the strengthened beams were increased between 31.8 - 44.5% and 27.1 - 80%, respectively when the CFRP area was between 0.15 - 0.42%. The addition of CFRP also enhanced the stiffness of the beam. The stiffness of the beams was increased between 32.6 - 87.6% when the timber beams were strengthened using CFRP between 0.15-0.42%. No debonding or delaminating occurred between CFRP plates and timber beams, which confirmed that the load carrying capacity was dependent on the strength of timber and CFRP. The failure mode was governed by the strength of timber beams, since no rupture of the CFRP plates occurred. Sikadur-30 showed good performance as a bonding agent between CFRP plates and timber beams. The timber beams failed in tension when the flexural tensile strain was more than 0.6% whilst the beams failed in compression when the flexural compressive strain was more than 0.3%. A balanced reinforced beam occurred when the CFRP was about 0.16%, denoted by compression failures above this. Thus, the beam experiences over-reinforced if the percentage of CFRP is greater than 0.16%. Modification factors, based on the testing herein for bending strength and stiffness were proposed for timber beam strengthened using CFRP plates.

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REFERENCES

[1] Alam, P., Ansell, M.P., and Smedley, D. (2009), “Mechanical Repair of Timber Beams Fractured in Flexure Using Bonded-in Reinforcements”, *Journal of Composites*: *Part B*., **40**, 95-106.

[2] American Society for Testing and Materials (ASTM), 1992, *Standard Methods of Static Test of Timbers in structural Sizes*, Race St. Philadelphia, ASTM : D198 – 84.

[3] American Society for Testing and Materials (ASTM), 1992, *Standard Test Methods for Direct Moisture Content Measurement of Wood and Wood-Base Materials*, Race St. Philadelphia, ASTM : D4442 – 92.

[4] Broughton, J. G. and Hutchinson, A. R. (2001), "Effect of timber moisture content on bonded-in rods", *Journal of Constr. and Building Materials.,* **15**, 17-25.

[5] Buell, T.W. and Saadatmanesh, H. (2005), "Strengthening Timber Bridge Beams Using Carbon Fibre", *Journal of Structural Engineering.*, **131**(1), 173-187.

[6] Chahrour, A. and Soudki, K. (2005), "Flexural Response of Reinforced Concrete Beams Strengthened with End-Anchored Partially Bonded Carbon Fibre-Reinforced Polymer Strips", *Journal of Composites for Construction*., **9**, 170-177.

[7] Desch, H.E. (1981), *TIMBER: Its Structure, Properties and Utilisation,* 6th *edition*, The Macmillan Press Ltd., London.

[8] Duthinh, D. and Starnes, M. (2004), "Strength and Ductility of Concrete Beams Reinforced With Carbon Fibre-Reinforced Polymer Plates and Steel", *Journal of Composites for Construction*., **8**, 1-96.

[9] Ferrier, E., Labossiere, P. and Neale, K.W. (2010), "Mechanical Behavior of an Inovative Hybrid Beam Made of Glulam and Ultrahigh-Performance Concrete Reinforced with FRP or Steel", *Journal of Composites for Construction*., **14**, 217-223.

[10] Gardner, G. P. (1989), "A Reinforced Glued Laminated Timber System", *2nd Pacific Timber Engineering Conference,* Auckland, New Zealand, August.

[11] Gentile, C., Svecova, D. and Rizkalla, S. H. (2002), "Timber Beams Strengthened with GFRP Bars: Development and Applications", *Journal of Composites for Construction*., **6**, 1-71.

[12] Gere, J. M. and Timoshenko, S. P. (1984), *Mechanics of Materials, 2nd Edition*, PWS Engineering, Boston, Massachusetts.

[13] Giap, L.H. (2007), "Behavior of Timber Beams Strengthened with Fibre Reinforced Polymer", *Thesis of Bachelor in Civil Engineering.,* UTM.

[14] Gomez, S. and Svecova, D. (2008), "Behavior of Split Timber Stringers Reinforced with External GFRP Sheets", *Journal of Composites for Construction*., **12**, 202-211.

[15] Haiman, M. and Zagar, Z. (2002), "Strengthening the Timber Glulam Beams with FRP Plates", *The Proceedings of 7th World Conference on Timber Engineering, WCTE 2002,* Shah Alam, Malaysia, August.

[16] International Organization for Standardization (2007) *ISO/DIS.10406-2. Test Methods-Part 2: FRP sheets*. Geneva.

[17] Keble, J. (1999), "Alternative Structural Strengthening With Advanced Composites", *Proceedings of Composites and Plastics in Construction,* Watford, UK, November.

[18] Kirn, Y. and Davalns, J. F. (1997), "Delamination buckling of FRP layer in laminated wood beams", *Journal of Composite Structures.,* **37**, 311-320.

[19] Lam, F. and Craig, B.A. (2000), "Shear Strength in Structural Composite Lumber", *Journal of Materials in Civil Engineering*. **12**, 196-204.

[20] Lopez-Anido, R. and Han Xu. (2002), "Structural Characterization of Hybrid Fibre-Reinforced Polymer-Glulam Panels for Bridge Decks", *Journal of Composites for Construction*. **6**, 141-203.

[21] Lorenzis, L. D., Scialpi, V. and La Tegola, A. (2005), "Analytical and experimental study on bonded-in CFRP bars in glulam timber", *Journal of Composite Structures.,* **36**, 279-289.

[22] Malaysian Standard, *Code of Practice for Structural Use of Timber: Part 2, Permissible Stress Design of Solid Timber,* Malaysia, MS544, 2001

[23] MTC Wood Wizard, Malaysian Timber Council, woodwizard@mtc.com.my, 2006

[24] Naghipour, M., Taheri, F. and Zou, G. P. (2005), "Evaluation of Vibration Damping of Glass-Reinforced-Polymer-Reinforced Glulam Composite Beams", *Journal of Structural Engineering*., **131**, 1001-1152.

[25] Ogawa, H. (2000), "Architectural Application of Carbon Fibres: Development of New Carbon Fibre Reinforced Glulam", *Carbon Journal, Pergamon.,* **38**, 211-226.

[26] Patrick, X. W. and Zou. (2003), "Long-Term Properties and Transfer Length of Fibre-Reinforced Polymers", *Journal of Composites for Construction*. **7**, 1-82.

[27] Spadea, G., Bencardino, F. and Swamy, R. N. (1998), "Structural Behaviour of Composite RC Beams with Externally Bonded CFRP", *Journal of Composites for Construction*., **2**, 115-148.

[28] Svecova, D. and Eden, R. J. (2004), "Flexural and Shear Strengthening of Timber Beams Using Glass Fibre Reinforced Polymer Bars – An Experimental Investigation", *Canadian Journal of Civil Engineering*., **31**, 45-55.

[29] Tingley, D. A., Gai, C. and Giltner, E. E. (1997), "Testing Methods to Determine Properties of Fibre Reinforced Plastic Panels Used for Reinforcing Glulams", *Journal of Composites for Construction*., **1**, 131-174.

[30] Wheeler, A. S. and Hutchinson, A. R. (1998), "Resin Repairs to Timber Structures", *Journal of Adhesion and Adhesives.,* **18**, 1-13.