Ductility of Timber Beams Strengthened Using Carbon Fiber Reinforced Polymer Plates

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Abstract

This research was conducted to investigate the behavior of timber beams strengthened with carbon fiber reinforced polymer (CFRP) plates using Sikadur-30 as bonding agent. The surface to be bonded was spiked by punching small holes of 2 mm in diameter with 10 mm spacing. The aim is to increase bonding capacity by having small studs when Sikadur-30 is applied to the timber surface. Although from the previous research shows that the strength was increased, the ductility of the strengthened beams needs to be studied as the ductility contributes to the failure modes. Five beams with the dimension of 100 mm × 200 mm × 3000 mm were tested where one of the beams was used as control beam (unstrengthened). The remaining beams were strengthened with different configurations before tested to failure under four-point loading. The ductility behavior of the beams was studied based on their load-deflection characteristics. The results showed that the strengthened beams performed better than the control beam where the ductility were increased as the percentage of CFRP was increased. The ductility was dramatically improved where the highest ductility index based on deflection method was 2.2 where the percentage increase was 37.5% whereas the highest ductility index based on energy method was 3.2 where the percentage increase was 88.2%. From this studies, it was found that 0.3% is the optimum value of CFRP area to achieve maximum ductility index. Ductility index obtained from energy method gives higher values when compared to deflection method for all values of CFRP area. All beams in this study did not fail due to peel off or debonding. It also proved that the spikes that have been made at the wood surface were very effective for bonding. These spikes were new technique introduced in this strengthening scheme.

Keywords: Timber Beams, Carbon Fiber Reinforced Polymer, Strengthening, Ductility.

1. Introduction

The main concerns of using wood for structural members are strength, stiffness and ductility. Softwood or softwood to medium hardwood timber can be strengthened using FRP to improve its mechanical properties. Few years ago, strengthening the timber with materials such as steel was seen as the solution to increase the strength and stiffness of timber (Gardner, 1989) where steel with either thin plates glued onto the outer laminates of beams, or bars bonded into pre-cut slots between laminates in glulam members (Guan *et al*., 2005). More recently, with the development of FRP which has many advantages its application becomes more popular as a strengthening material. In Switzerland a historic wooden bridge was strengthened using CFRP sheets. In Greece historic masonry and wood structures were upgraded while strong activities on wood strengthening using FRP are going on in Italy (Halliwell and Moss, 1999).

Micelli *et al*. (2005) have investigated on flexural reinforcement of glulam timber beams with CFRP rods. The results showed that small amounts of FRP reinforcement produced significant gains in bending strength and stiffness.

Lopez-Anido and Han Xu (2002) have studied on glulam panels strengthened at top and bottom faces by FRP. It was found that FRP-glulam beams not only exhibit significant strength increases, but also they develop wood ductile compression failure, rather than the typical brittle tension failure of wood. Gentile *et al.* (2002) have investigated creosote-treated sawn Douglas Fir timber beams strengthened with GFRP bars. The results have shown that the failure mode has changed from brittle tension to compression failure. Buell and Saadatmanesh (2005) have conducted research on creosote-treated solid-sawn Douglas Fir strengthened with bidirectional CFRP fabric. The deflection ductility of the reinforced beams was increased from 28% to 51%.

Although research has been done to strengthen timber using FRP, but the comprehensive analysis and design were not established in details and clear. This is one of the reasons why the application of FRP to timber is very limited (Shin, 2003). One of the major questions needs answer is how ductile is the flexural behavior and modes of failure of timber beams reinforced with FRP?

This research focuses on the application of carbon fiber reinforced polymer (CFRP) plates to strengthen the timber beams. The plates are attached to the beams by mean of epoxy resin. This attachment will be done on the surface of timber beams. The flexural tests are carried out with different configurations to determine the ductility. The scope of this study was limited to dry timber only where the moisture content was maintained to be below 19%. Thus, these findings are applicable for beams used at dry condition or internal part of the structure.

The timber species used in this study isYellow Meranti, a widely distributed wood species in Malaysia, is not a high-performance material for structural usage because of its low strength, and is prone to check properties. Because Yellow Meranti is cheap and used in furniture industry, research has been conducted at Universiti Teknologi Malaysia (UTM) to study the feasibility of utilizing the low to medium hardwoods like Yellow Meranti for structural usage by reinforcing it with FRP.

The ductility of a beam can be defined as its ability to sustain inelastic deformation without loss in its load carrying capacity prior to failure. The deformations can be deflections, curvatures, or strains (Grace *et al*., 1998; Mirmiran *et al*. (1999). A ductile system displays sufficient warning before catastrophic failure. Based on this definition, ductility can be expressed in terms of deformation or energy absorption. In the case of steel reinforced beams, where there is clear plastic deformation of steel at yield, ductility can be calculated as the ratio of ultimate deformation to deformation at yield. However, for beam strengthened with FRP, the determination of yield point is a difficult task.

Different researcher has expressed the ductility in different quantitative basis. For instant, Spadea *et al*. (1998), Harris *et al*. (1998), Stehn and Johansson (2002) have evaluated the ductility in terms of ratio at ultimate and yield points such as mid span deflection, Δ_u/Δ_y (Fig. 1a), curvature, ϕ_u/ϕ_y (Fig. 1b), and area under the load-deflection diagram (energy), $0.5[(W_{tot}/W_{el}) +1]$ (Fig. 1c and 1d).

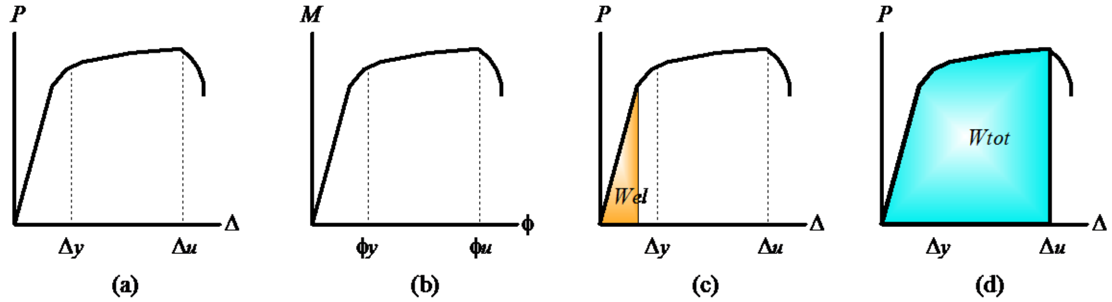

Figure 1 Determination of ductility (Harris *et al*., 1998)

Sufficient ductility is needed in design for example in steel-reinforced concrete beams, the beams are under reinforced by design, so that the failure is initiated by yielding of the steel reinforcement, followed by concrete crushing and ultimate failure. This mode of failure is ductile and is guaranteed by designing the tensile reinforcement ratio to be substantially below the balanced ratio.

2. Methodology

The Yellow Meranti beams used in this research were collected from local factory. The woods come from the same batch in order to minimize the influence of the variability in wood properties.

Two types of CFRP plates were supplied 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) are required in this strengthening scheme. Thus, both CFRP plates of S5012 and S6014 need to be cut parallel to the fibers to produce S2512 and S3014, respectively. Figure 2 shows the cross section of the beams strengthened with CFRP plates with different area. The beams were named as CP-2512-1B-3m, CP-3014-1B-3m, CP-5012-1B-3m, and CP-6014-1B-3m. One beam was used for control (unstrengthened).

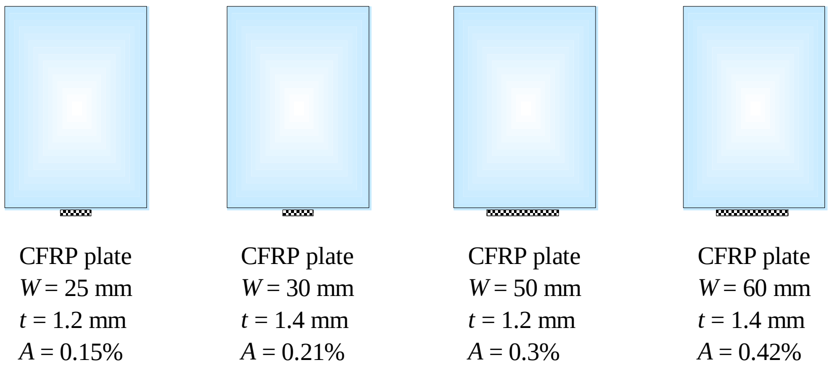

Figure 2 Cross section of beam strengthened using CFRP plates with different area

Sikadur-30 i.e. a product from local manufacturer was used. Sikadur-30 is an adhesive for structural bonding of Sika CarboDur laminates to concrete, steel and timber. The adhesive was commonly used by other researcher such as Chahrour and Soudki (2005). This adhesive is solvent free adhesive based on a combination of epoxy resins and special filler. It is a strong adhesive used to bond between CFRP plates to the timber beams. It comes in two separate components called component A and component B.

The Sika CarboDur plates were cut to the desired length and width. The CFRP plates were 3000 mm long. They were cleaned with acetone as recommended by the manufacturer. The cutting of the plate is preferably done with a diamond cutting disc. Precautions should be taken during cutting the CFRP plate as the dust may effects eyes and skin. The cutter was not made by diamond as suggested by the manufacturer but it capable to cut the plate easily with smooth edges along the cutting line.

In order to have smooth edges, the samples were hand sanded using 100 grit emery papers to remove fuzzy edges caused by cutting. Prior to applying adhesive, the timber surfaces were ground to remove all laitance and to roughen the surface (Spadea *et al*., 1998). The surface to be bonded was spiked by punching small holes of 2 mm in diameter with 10 mm spacing as shown in Figure 3. The aim is to increase bonding capacity by having small studs when Sikadur-30 is applied to the timber surface.

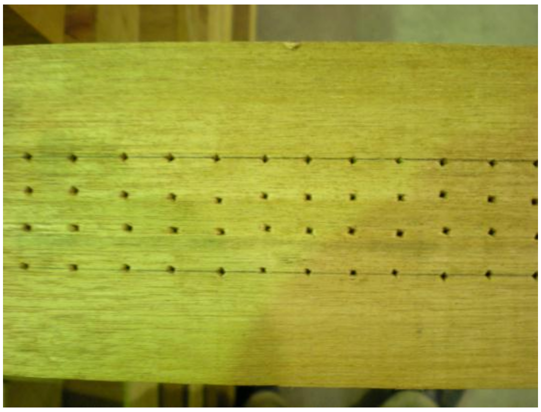

Figure 3 Spike holes at beam surface

The Sika CarboDur plate was placed on a table and the blank side was cleaned. Using a Sika hard rubber roller, the well-mixed Sikadur-30 adhesive was applied carefully to the properly prepared, dust-free substrate with a spatula at a thickness of approximately 1.0 mm onto the bottom part of the prepared timber surface. Sikadur-30 adhesive was applied using a dome shaped spatula onto the CarboDur laminate to a thickness of approximately 2 mm. It should be evenly applied to both surfaces forming the joint recommended by the manufacturer (Zahn and Rammer, 1995). Spadea *et al* (1998) suggested that the thickness of adhesive was 2 mm. A thin glue-line thickness of about 0.5 mm was proposed by Madhoushi and Ansell (2004). However, they reported that the recommended minimum glue-line thickness should be 2 mm for achieving optimum static tensile strength and above that thickness, the strength does not change very much.

The CFRP plate was then placed on the wood, epoxy to epoxy, and a rubber roller was used to properly seat the CFRP plate by exerting enough pressure so the epoxy was forced out on both sides of the CFRP plate and the adhesive line did not exceed 3 mm in thickness. The surplus epoxy adhesive was then removed. Putty knives were used to force out the air bubbles from the strengthening materials. The CFRP plates were clamped and allowed to cure. Adequate pressure should be applied to the plates to bring them into intimate contact while the adhesive is still wet and maintained for the period which the glue takes to set. A conditioning period after release of the pressure equipment is necessary for some adhesives as they do not acquire maximum strength during the curing period. Indication that the adhesive is wet at the time pressure is applied is usually indicated by the appearance of glue squeeze out at the edges of the joints.

The strengthened timber beams are then cured for seven days at room temperature of 25±2°C to ensure the bonding between CFRP and timber is well established. Figure 4 shows typical sample of timber beams that have been strengthened using CFRP and being exposed to room environment for curing. Broughton and Hutchinson (2001) have studied the effect of curing period and found that an extended cure period of 21 days resulted in a 25% improvement over similar specimens tested after only 7 days cure. This may be accounted for by the reforming of bonds between the epoxy and timber, in conjunction with improved timber properties as a result of there being less moisture present at the timber-adhesive interface.

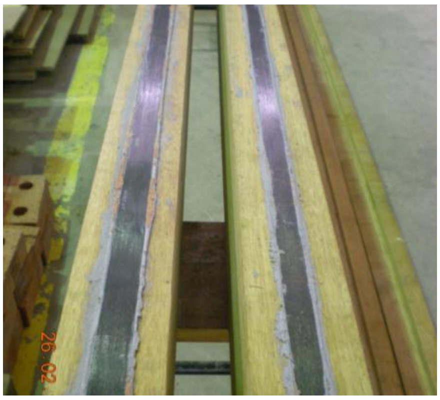

Figure 4 Strengthened timber beams being cured in the lab

The timber beams were tested in four-point loading in general conformance with ASTM D198-84:1992 "Standard methods of static tests of timbers in structural sizes" for flexural strength. Figure 5 shows the configuration of the flexural test.

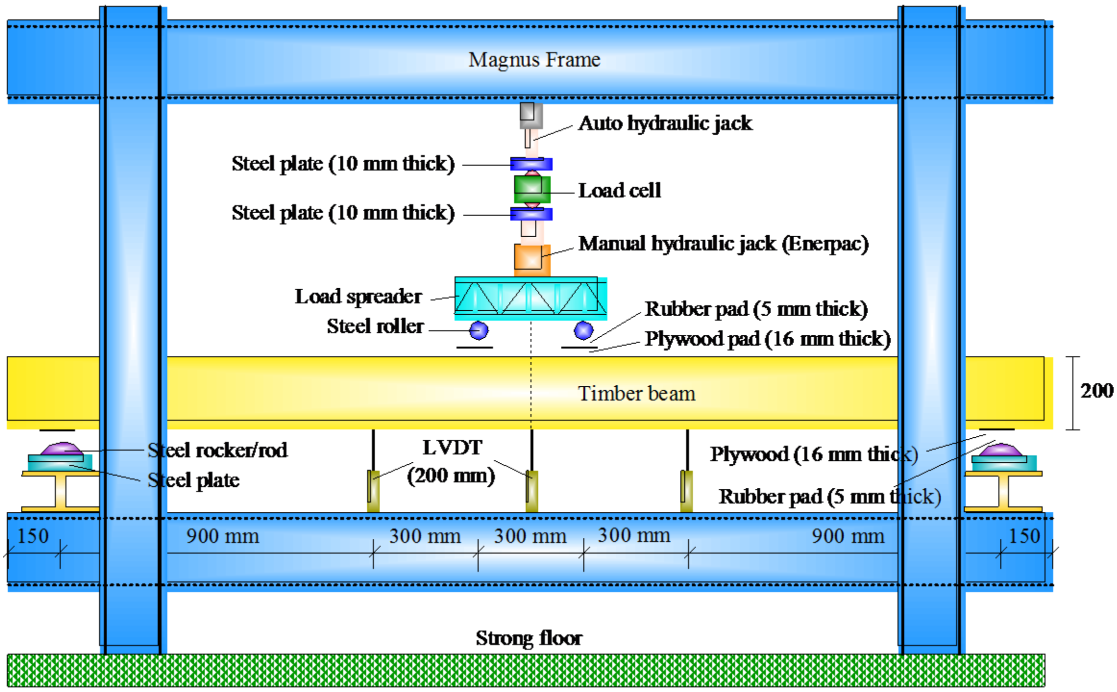

Figure 5 Flexural test

3. Results and Discussions

The beams were tested successfully and the graphs of load versus mid-span deflection were plotted in Figure 6. All the strengthened beams exhibited linear elastic behavior in the first stage followed by non-linear in a short period and showed almost linear plastic behavior in the last stage before the beams failed.

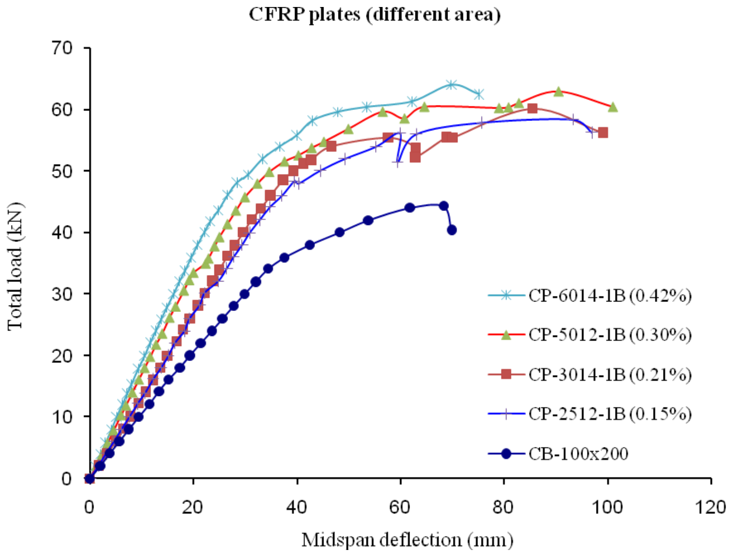

Figure 6 Load-deflection curves for beam strengthened using CFRP plates

Beam CP-5012-1B was taken as a typical example for discussion of ductility. The Load-deflection curve for the beam is shown in Figure 7. From the curve, the maximum elastic load, the estimated yield load, the ultimate load and the corresponding deflections were determined.

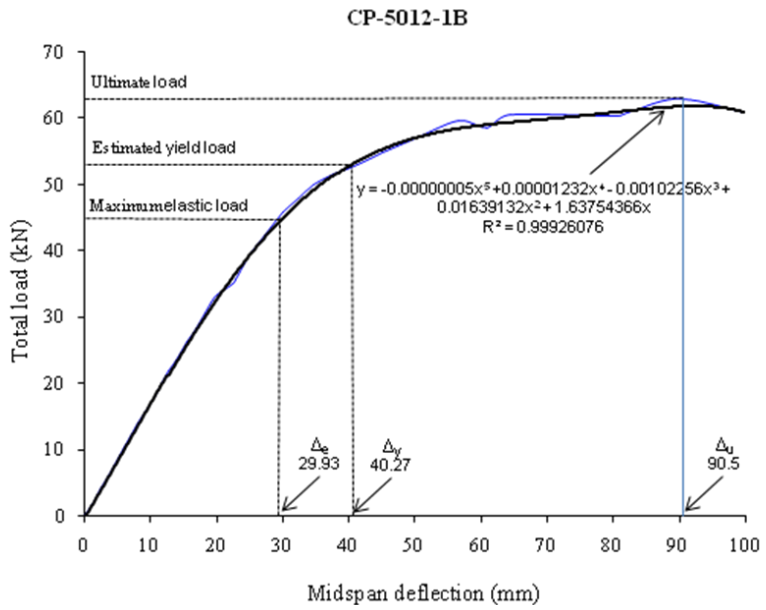

Figure 7 Typical load-deflection curve for ductility

None of the CFRP plate has yielded because the yield strain for CFRP is higher than the yield strain of the timber. Hence the compressive zone of the timber will reach its yield point before

CFRP. From the curve, the elastic deflection, the yield deflection and the ultimate deflection were Δ_e = 29.93 mm, Δ_y = 40.27 mm and Δ_u = 90.50 mm, respectively. The curve was very smooth exhibiting no sudden crack or crush occurred. The total failure occurred when the deflection at mid-span was 90.5 mm which is considered high. This value provides good performance in the ductility point of view where the people will have ample time to escape from the building before collapse.

For the ductility based on energy method, the equation for the curve is required to calculate the energy under the curve. Thus, a polynomial regression analysis was carried out to determine the equation. The order of the polynomial was five and the number of decimal places was eight for all beams. The coefficients of regression equation is very sensitive to the accuracy of the results and after details study, the writer found that each coefficients should be taken up to eight decimal places. For each curve, the energy on the elastic zone and the total energy up to failure were computed and the detail typical calculations are shown here.

The elastic energy, W_e is equivalent to the area under the curve between Δ = 0 and Δ_e = 29.93 mm which is given by the following integration

$$W_e = \int_0^{29.93} y\,dx = \int_0^{29.93} \begin{pmatrix} -0.00000005x^5 + 0.00001232x^4 - 0.00102256x^3 \\ +0.01639132x^2 + 1.63754366x \end{pmatrix} dx = 728 \text{ Joule}$$

The total energy, W_{tot} is equivalent to the area under the curve between Δ = 0 and Δ_u = 90.50 mm which is given by the following integration

$$W_{tot} = \int_0^{90.50} y\,dx = \int_0^{90.50} \begin{pmatrix} -0.00000005x^5 + 0.00001232x^4 - 0.00102256x^3 \\ +0.01639132x^2 + 1.63754366x \end{pmatrix} dx = 3987 \text{ Joule}$$

The ductility index for all beams is shown in Table 1.

Table 1: Ductility index for beams reinforced with CFRP plates

Beam Designation	**GFRP Area (%)**	**Deflection at**			**Energy**		**Ductility index**	
		elastic Δ_e (mm)	**yield Δ_y (mm)**	**ultimate Δ_u (mm)**	**Elastic W_e (J)**	**Ultimate W_{tot} (J)**	**Based on deflection**	**Based on energy**
CB-100x200	0.00	37.56	42.51	68.31	707	1765	1.6	1.7
CP-2512-1B	0.15	32.82	44.48	93.31	707	3083	2.1	2.7
CP-3014-1B	0.21	27.94	42.73	85.47	520	2697	2.0	3.1
CP-5012-1B	0.30	29.93	40.27	90.5	728	3987	2.2	3.2
CP-6014-1B	0.42	26.6	36.66	69.78	648	2748	1.9	2.6

There was significant increase in ductility from both measurement techniques (deflection and energy) when the timber beams are strengthened using CFRP plates. Even after ultimate failure, the beams still held together. In other words, there was no catastrophic failure when the beams were externally plated. This shows that the CFRP plates provide effective strengthening material to the timber beams where the ductility of the beams was improved. Ductility index obtained from energy method gives higher values when compared to deflection method for all values of CFRP area. By taking control beam as a reference, the highest ductility index based on deflection method was 2.2 where the percentage increase was 37.5% whereas the highest ductility index based on energy method was 3.2 where the percentage increase was 88.2%.

From the results, there is a relationship between the CFRP area and the ductility index. The relationship is shown by polynomial regression lines in Figure 8. The patterns of the curves were almost identical where the ductility index increased non-linearly as the area of CFRP plates increased for both methods. When the area of CFRP is about 0.3%, both method give maximum value for the ductility index and any increases in CFRP area beyond this value will not improve the ductility performance.

Beam CP-6014-1B exhibited low ductility index and the main reason was due to shorter range of plastic region in the compression zone. It is very obvious that this beam failed at very low deflection i.e. 69.78 mm compared to other beams, yields to low ultimate deflection and least total energy. From this study, it is concluded that 0.3% is the optimum value of CFRP area for maximum ductility index. More data are required to get better relationship and further research should be carried out to study on ductility aspect if the CFRP area is more than 0.42%.

Although ductile material is important in design, consideration should be given not to have too ductile which will lead to a decrease in the load-carrying capacity and an increase in total deflections of the structural system. Both effects are regarded as negative for practical design (Stehn and Johansson, 2002).

It seems possible to create ductile timber beams simply by adequately strengthening the brittle tension zone. Since the reinforced timber beams exhibited ductile due to plastic behavior at compression layer, there is possibility to design the timber beams up to plastic limit as steel design does. The plastic design approach promises an advantage in timber beam design which have been strengthened in the tension zone. In such cases the engineer may be able to take advantage of the ductile compression zone in order to improve the load carrying capacity.

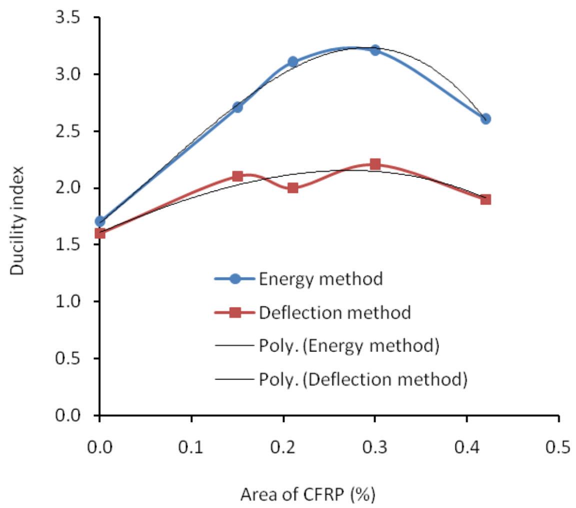

Figure 8 Effect of percentage of CFRP area to the ductility index

The tensile strains were decreased and the compressive strains were increased as the percentage of CFRP plate increased as shown in Table 2. It shows that the present of CFRP plate was able to reduce the tensile strain (maximum reduction was 37.8%) and increased the compressive strain (maximum increment was 32.8%) in the timber beams. Thus, the tension zone of timber beams was successfully strengthened if the percentage of CFRP is greater than 0.16%. Above this value, the failure was controlled by compression zone and the ultimate load was not increased significantly unless the compression zone is strengthened. However, better results are expected to be obtained by testing more beams. In conclusion, the beam with CFRP plate of less than 0.16%, equal 0.16%, and greater than 0.16% was under reinforced, balanced reinforced, and over reinforced, respectively.

Table 2: Strain at failure load and mode of failure for beams strengthened with CFRP plates

Beam	Area of CFRP (%)	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 (under reinforced)
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)

4. Conclusions and Suggestions

The highest ductility index based on deflection method was 2.2 where the percentage increase was 37.5% whereas the highest ductility index based on energy method was 3.2 where the percentage increase was 88.2%. Ductility index obtained from energy method gives higher values when compared to deflection method for all values of CFRP area. It is concluded that 0.3% was the optimum value of CFRP area for maximum ductility index.

All beams in this study did not fail due to peel off or debonding between CFRP plate and the adhesive and between adhesive and wood substrate. It also proved that the spikes that have been made at the wood surface were very effective for bonding. These spikes were new technique introduced in this strengthening scheme which never done before by other researchers.

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