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Ductility of Timber Beams Strengthened Using Fiber Reinforced Polymer

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Abstract: This research was conducted to investigate the ductility behavior of timber beams strengthened with CFRP (carbon fiber reinforced polymer) plates. 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. Five beams with the dimension of 100 mm × 200 mm × 3,000 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 results showed that the ductility was increased as the percentage of CFRP 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 study, 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. All beams in this study did not fail due to peel off or debonding. It was also proved that the spikes that have been made at the wood surface were very effective for bonding.

Key words: Carbon fiber reinforced polymer, ductility index, energy method.

1. Introduction

In tropical rain-forest like Malaysia, there is a wide variety of timber with over 4,000 species available. Out of that, 2,500 species of trees attain sizes for sawn timber [1]. Among these, 10% can be used as structural elements. In this country, the application of timber structures in construction is still low. Generally, the use of timber mainly focuses on simple structures or structures that can take small loads such as roof rafters, short span roof trusses, beams and columns for houses which are not more than two storeys. This is because some engineers did not confidence to use timber to sustain high loads such as bridges or long span structures. In addition to that, as a result of a number of failures the popularity of timber is declining [2]. The reasons given for the decline are a strong indication that most people do not have the accurate knowledge about the physical and mechanical properties as well as the performance of timber [3]. Also, Malaysian Building Bylaws 1984 specified that timber should be avoided in high-risk constructions and could only be used in temporary structures [4].

Timber has many advantages such as high strength to weight ratio, lightweight material, high aesthetic value, easy to construct and move and are economic alternatives to concrete and steel [5]. If compared to concrete, timber structures can be constructed easily because there is no formwork required. The actual erection is greatly simplified if all components can be moved by workers instead of by heavy machinery [6]. In civil construction, light weight is seldom sought as a design goal, although there are some examples to the contrary. Light weight may prove advantageous when transportation is a problem and where heavy machinery is not available to aid in assembly. Thus, the use of timber will lower the construction cost.

However, timber also has disadvantages such as poor mechanical properties with a wide variation and

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low fire resistance [7]. Although timbers are widely used in construction but their natural durability is often insufficient to ensure confidence to the people. Durability can be achieved by the appropriate selection and application of effective preservative treatments or by processes that modify the wood structure against insect and fungal attacks.

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 (fiber reinforced polymer) to improve its mechanical properties. Since the 1930s, FRP was developed for aerospace, automotive and sports equipment industries [8]. It has become popular in the rehabilitation of civil engineering projects due to its high strength to weight ratio. Other benefits of FRP over conventional materials are high stiffness, lightweight, corrosion resistance, non-conducting, nonmagnetic characteristics and superior fatigue performance [9-11].

Research on studying and developing the techniques for the strengthening of timber structures has been done and still ongoing. Strengthening the timber with materials such as steel was seen as the solution to increase the strength and stiffness of timber [12], where steel with either thin plates glued onto the outer laminates of beams, or bars bonded into pre-cut slots in glulam members [13]. Previous researches have contributed significantly in encouraging the usage of FRP for timber structures and serve as reference for future researchers. With better development of FRP it 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 [14].

Micelli et al. [15] 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. Apart from that, there was another research done by Fiorelli et al. [8] to evaluate the structural behavior of wood beams strengthened with FRP. The research was focused on the experimental and theoretical analysis of timber beams of the specie pinus caribea var. hondurensis which were reinforced with FRP. The results showed that the flexural stiffness (*EI*, where *E* is modulus of elasticity and *I* is moment of inertia) determined experimentally was greater than the theoretical values. It shows that the increase of stiffness varied from 15% to 29% for beams strengthened with glass fibre (GFRP—carbon fiber reinforced polymer) and with CF (carbon fibre).

Lopez-Anido et al. [16] 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. [17] 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 et al. [18] have conducted research on creosote-treated solid-sawn Douglas Fir strengthened with bidirectional CFRP fabric. The results show that the ultimate bending strength for all reinforced beams was increased from 40% to 53%. The deflection ductility of the reinforced beams was increased from 28% to 51%. Furthermore, those beams were held together after ultimate failure where no catastrophic failure when the beams were wrapped with carbon fabric.

The behavior of timber stringers reinforced with GFRP sheets was studied by Gomez et al. [19]. The stringers were reinforced for shear and bending. The proposed reinforcement leads to improvement of stiffness by 5.5%-52.8%. Alam et al. [20] have strengthened fractured timber beams using steel and

CFRP. The results showed that these reinforcements are very effective in enhancing flexural strength but the CFRP reinforcement endows the greatest flexural strength. The latest innovative development of the usage of FRP in strengthening works was conducted by Ferrier et al. [21]. 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 performed higher bending stiffness and ultimate load capacity compared to that of a glulam of similar dimensions.

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 [22]. 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 ductility behavior of the timber beams strengthened with CFRP plates. 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 were 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.

2. Research Significance

CFRP has a high strength in tension and thus serves a good material in strengthening the tension part of timber structures. Compared to timber alone, the combination of timber and CFRP has significantly provides better structural performances for the strength and stiffness of timber beam. When a beam is strengthened at tension zone, the mode of failure for the timber structures may change from tension failures to compression failures. In other words, this method has increased the tensile capacity of the structure, as well as fully utilizing the compression capacity of timber. As a result, it can be applied in new construction projects, as well as in the rehabilitation of existing timber structures. In addition, effective strengthening techniques will also reduce the size or depth of the timber beams that are required for construction [23].

3. Ductility

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 [24, 25]. 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 index 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 index in different quantitative basis. For instant, Spadea et al. [26], Harris et al. [11] and Stehn et al. [27] have evaluated the ductility index in terms of deflection ratio at ultimate and yield points, Δ_u/Δ_y, curvature ratio at ultimate and yield points ϕ_u/ϕ_y, and energy ratio at ultimate and elastic points under the load-deflection diagram $0.5\,[(W_{tot}/W_{el}) + 1]$.

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.

4. Research Materials

4.1 Yellow Meranti Timber Beams

The timber species used in this study is Yellow Meranti, a widely distributed wood species in Malaysia, is not a high-performance material for structural usage because of its low strength. For this species, the modulus of elasticity, the tensile strength and bending strength are 11.7 kN/mm^2, 100.1 N/mm^2, and 63.2 N/mm^2, respectively. Because Yellow Meranti is cheap and used in furniture industry, research has been conducted at UTM (Universiti Teknologi Malaysia) to study the feasibility of utilizing the low to medium hardwoods like Yellow Meranti for structural usage by reinforcing it with FRP. The 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.

4.2 Carbon Fibre Reinforced Polymer

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. FRP is a material which will react elastically in the beginning until final brittle rupture. Thus the stress-strain relationship can be represented by a straight line. It is clearly shown that the strength of FRP is higher than steel [11]. The modulus of elasticity of CFRP is 165 kN/mm^2, whereas the tensile stress and strain are 2,800 N/mm^2 and 1.7%, respectively.

4.3 Adhesives

Sikadur-30, i.e., a product from local manufacturer was used. It 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 et al. [28]. 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. By mixing these two components (A/B is equal to 3/1), Sikadur®-30 becomes grey color. It is normally used at temperature between 8 ^{o}C to 35 ^{o}C.

5. Laboratory Works

The size of timber beam was 100 mm × 200 mm × 3,000 mm and five timber beams were taken randomly. The clear span was 2,700 mm. All beams were tested in accordance to ASTM: D198-84 (American Standard for Testing and Materials) [29]. Fig. 1 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.

Prior to applying adhesive, the timber surfaces were ground to remove all laitance and to roughen the surface [26]. The surface to be bonded was spiked by punching small holes of 2 mm in diameter with 10 mm spacing as shown in Fig. 2. The aim is to increase bonding capacity by having small studs when Sikadur-30 is applied to the timber surface.

Sikadur-30 of approximately 1.0 mm was applied onto the bottom part of the timber surface. It should be evenly applied to both surfaces forming the joint recommended by the manufacturer (Zahn et al. [30]). Spadea et al. [26] suggested that the thickness of adhesive was 2 mm. A thin glue-line thickness of about 0.5 mm was proposed by Madhoushi et al. [31]. 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. 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. Adequate

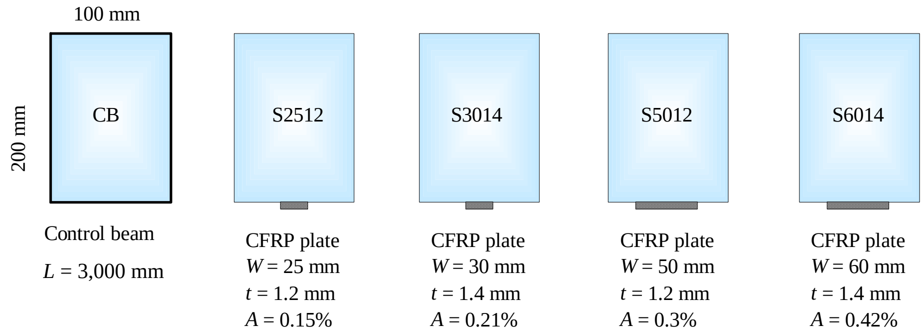

Fig. 1 Cross section of beam strengthened using CFRP plates with different area.

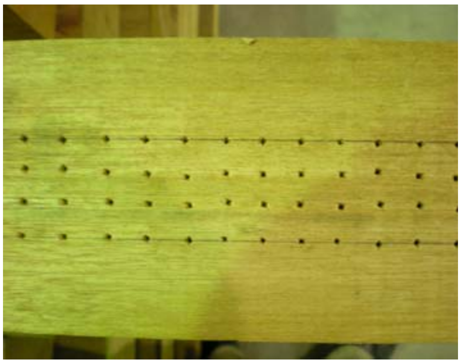

Fig. 2 Spike holes at beam surface.

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. Then the strain gauge of BFLA-5-3L was attached at the mid-span of CFRP plates to measure its strain.

The strengthened timber beams are then cured for seven days at room temperature of 25 ^{o}C ± 2 ^{o}C to make sure the bonding between CFRP and timber is well established. Fig. 3 shows typical sample of timber beams that have been strengthened using CFRP. Broughton et al. [32] 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 seven days cure.

All timber beams were tested under four-point loading where the half shear span to depth ratio (*a/h*) should be between five and twelve in accordance to ASTM D198-84:1992 “Standard methods of static tests of timbers in structural sizes” for flexural strength. The deflections of all the beams were measured using three LVDT (linear variable displacement transducers) which were placed at the bottom of the beam. Fig. 4 shows the setting of the testing. For each test, a loading rate of 2.0 kN/min was applied to each timber beam until failure.

6. Results and Discussions

The beams were tested successfully and the graphs of load versus mid-span deflection were plotted in Fig. 5. 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. When the load was applied to the beam, the bending stress occurred in the timber fiber and this stress increases as the load increases. The bending stress varies linearly across the depth of the beam and the maximum compressive and tensile stress occurred at top and bottom layer, respectively, assuming the plane section remain plane throughout the testing programme. When the tensile strain in the beam exceeds the limit (0.6%), the beam starts to crack and the first crack load was recorded. This phenomenon was shown by the drop in load deflection curves. This first crack load does not produce any significant changes in the overall rigidity or cause failure to the strengthened beams [26]. This crack growth was prevented by the help of CFRP plate where the bending stress was transferred to the plate and at this stage the beam can further sustain extra load. Any loads now were transferred to the compression timber fiber and CFRP plate until the strain in the top compression fiber was exceeded. Since the maximum strain for timber was

Fig. 3 Strengthened timber beams being cured.

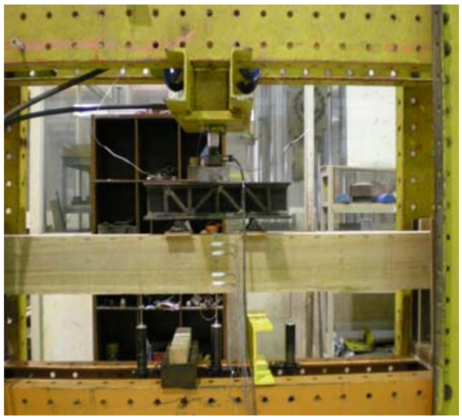

Fig. 4 Flexural test.

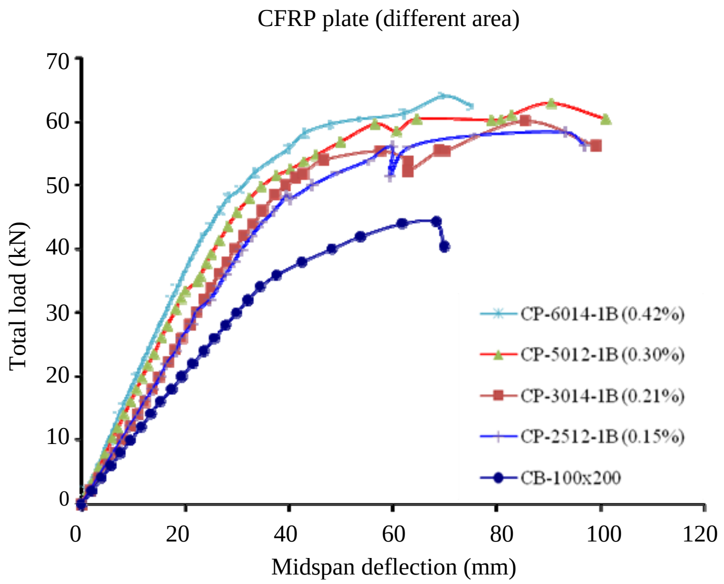

Fig. 5 Load-deflection curves for beam strengthened using CFRP plates.

less than CFRP (1.7%), therefore the compression zone fails first after the timber fiber in tension zone fails. It is interesting that after the timber fails both in tension and compression, the CFRP plates still intact with the bonding agent and no rupture was observed in the CFRP plates for all strengthened beams. The breaking loads for the five tested beams with 0%, 0.15%, 0.21%, 0.30% and 0.42% of CFRP were 44.3 kN, 58.4 kN, 60.1 kN, 63.0 kN and 64.0 kN, respectively.

Beam CP-5012-1B was taken as a typical example for discussion of ductility. The load-deflection curve for the beam is shown in Fig. 6. From the curve, the maximum elastic load, the estimated yield load and the ultimate load and the corresponding deflections were determined.

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.

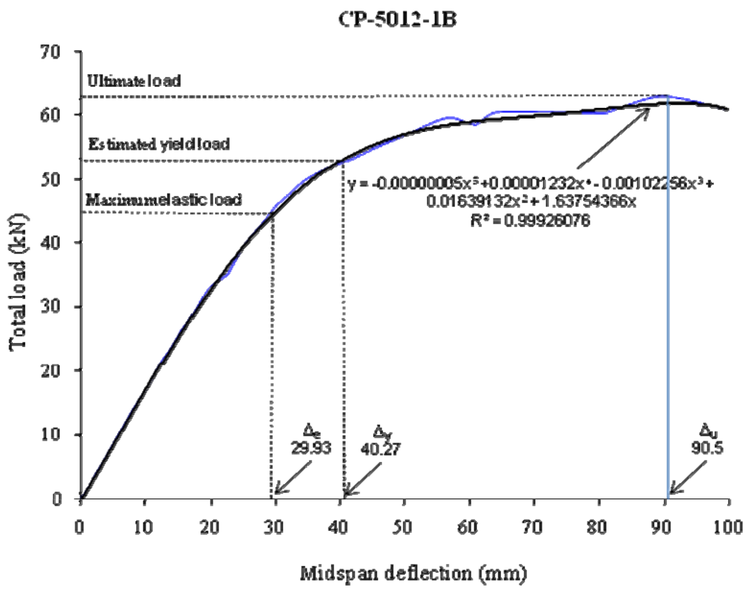

Fig. 6 Typical load-deflection curve for ductility.

For energy method, the equation for the curve is required to calculate the energy under the curve. Thus, a polynomial regression line was used to determine the equation. 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 $\Delta = 0$ and $\Delta_e = 29.93$ mm which is given by the following integration:

$$W_e = \int_0^{29.93} y\,dx$$

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

$$= 728 \text{ Joule} \quad (1)$$

The total energy, W_{tot} is equivalent to the area under the curve between $\Delta = 0$ and $\Delta_u = 90.50$ mm which is given by the following integration:

$$W_{tot} = \int_0^{90.50} y\,dx$$

$$= \int_0^{90.50} \begin{pmatrix} -0.00000005x^5 + 0.00001232x^4 - 0.00102256x^3 \\ +0.01639132x^2 + 1.63754366x \end{pmatrix} dx$$

$$= 3{,}987 \text{ Joule} \quad (2)$$

The ductility index for all beams is shown in Table 1. There was significant increase in ductility from both measurement techniques (deflection and energy) for the strengthened beams. Even after ultimate failure, the beams still held together. In other words, there was no catastrophic failure. 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. The ductility index calculated based on energy is more reliable since it almost covers the energy of the beam up to failure whereas the ductility index calculated based on deflection will consider the deflection values at yield and ultimate point only. 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 these results, there is a relationship between the CFRP area and the ductility index. The relationship is shown by polynomial regression lines in Fig. 7. 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%,

Table 1 Ductility index for beams reinforced with CFRP plates.

Beam designation	CFRP area (%)	Deflection at			Energy		Ductility index	
		Elastic	Yield	Ultimate	Elastic	Ultimate	Based on	Based on
		Δ_e (mm)	Δ_y (mm)	Δ_u (mm)	W_e (J)	W_{tot} (J)	Deflection	Energy
CB-100 × 200	0.00	37.56	42.51	68.31	707	1,765	1.6	1.7
CP-2512-1B	0.15	32.82	44.48	93.31	707	3,083	2.1	2.7
CP-3014-1B	0.21	27.94	42.73	85.47	520	2,697	2.0	3.1
CP-5012-1B	0.30	29.93	40.27	90.5	728	3,987	2.2	3.2
CP-6014-1B	0.42	26.6	36.66	69.78	648	2,748	1.9	2.6

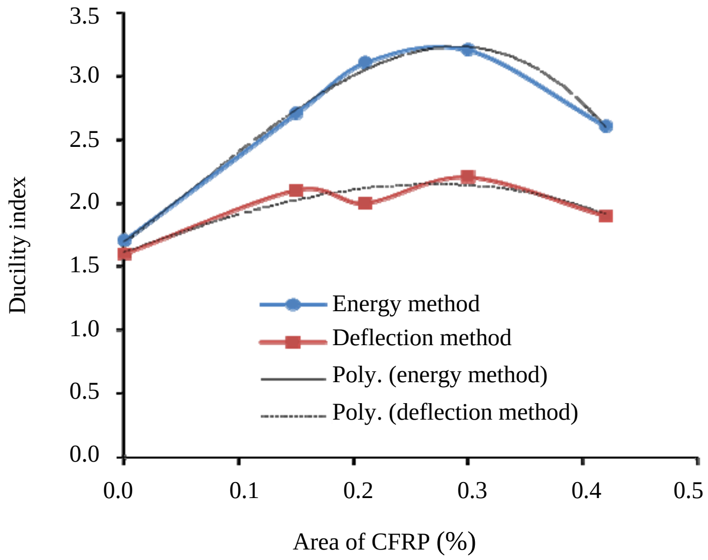

Fig. 7 Effect of percentage of CFRP area to the ductility index.

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 [27].

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 has 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.

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

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)

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.

7. Conclusions

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. This finding was synchronized with the results for strength where the optimum value for CFRP area that can provide maximum strength was also 0.3%. 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 shows that the bonding length for all beams (3.0 m) was sufficient. 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.

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