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REINFORCING TECHNIQUES USING FIBER-REINFORCED POLYMER: A REVIEW

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Abstract: Fiber-reinforced polymer (FRP) composites have been used over few decades for structural repair and strengthening schemes for structural element but only optimized the applications recently. This paper presents a concise state-of-art review of the extensive research on reinforcing techniques using FRP for construction applications in civil engineering for last two decades. This review was focusing in flexural strengthening techniques applied for concrete, metal and timber structures by experimental and numerical analytical programs. The experimental specimens used by researchers vary from the existing elements structure and new invention for laboratory program only. Data and information collected in this review were gathered from the previous researches all over the world with some of them are applied to the real applications at construction sites. The review hoped to be a good reference and guidelines for all engineers and researches in fields of composites material especially fiber-reinforced polymer to enhance the application of FRP for new construction or rehabilitation of existing structure.

Keywords: *Fiber Reinforced Polymer; Reinforcing Technique; Flexural Strengthening*

1.0 Introduction

Strengthening of structures has been demonstrated in various research and real applications field sites all over the world since few decades before. Recently, fiber-reinforced polymer (FRP) composites have arises as an invention of new material to reinforce new buildings or bridges for rehabilitation of structures (Ibrahim *et al*., 2011; Mazlan and Awal, 2012). Various reinforcing techniques can be applied suitable to certain types of materials. Attention had been made for flexural retrofit to structures made of various type of material such as concrete, masonry, steel and timber. The advantages of using FRP such as anti-corrosion, lightweight, high durability, high elastic modulus and high resistance to environmental degradation factors may enhance flexural performance of structure and had been made of choices to researchers to be used in their study. This paper will focus on method of repairing and strengthening using FRP and other new composites also their advantages and shortcomings corresponding to different techniques. The review hoped to be a good reference and guidelines for all engineers and researches in fields of composites material especially fiber-reinforced polymer to

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enhance the application of FRP for new construction or rehabilitation of existing structure.

2.0 Summary of Reinforcing Techniques

2.1 Reinforcing Techniques for Concrete

Various reasons arise in field survey of reinforced concrete needed infrastructure renewal or strengthening for better performance. Bonacci and Maalej (2000) have reviewed field applications and experimental database on strengthening or repairing of reinforced concrete flexural members. Most commonly technique used is externally bonded FRP but with different installments for different problems. For flexural and shear resistance, FRP were bonded on the soffit and sides of beams. For deflection control, crack control and strengthening, FRP is installed on the underside of slabs and for lateral confinement, FRP is fixed to wrap columns. Trends in use of steel plates and FRP for externally reinforcing reinforced concrete were depicted in Fig. 1. Over years, applications on FRP are seen replacing the steel as FRP had many advantages compared to steel for instance, long term durability and corrosion resistant; easy to handle on site; supplied in continuous form and do not debond and fall off when loaded in compression.

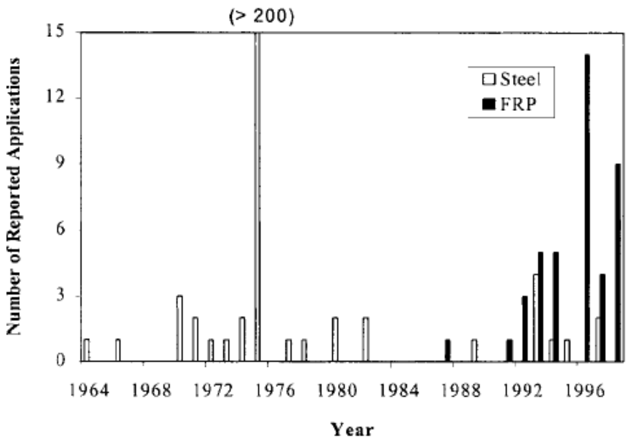

Figure 1: Trends in use of steel plates and FRP for externally Reinforcing RC

Kachlakev and McCurry (2000) worked on experimental work for shear and flexural reinforcing of reinforced concrete beams using carbon fiber-reinforced polymer (CFRP) and glass fiber-reinforced polymer (GFRP) laminates. They conducted the laboratory work for strengthen full scale of bridge beams with flexural only (CFRP sheets), shear only (GFRP sheets) and both flexure and shear (CFRP and GFRP sheets). For accurate reading, fiber optic gauges were installed to observe flexure and shear behavior of the strengthen beams and also monitor behavior on the actual bridge. Fig. 2 shows the behavior of strengthened and control beams. Approximately 150% increases of static load capacity were observed from the strengthened beams compared to control beams. Strengthening beams using both CFRP and GFRP sheets allow static demand of 658 kN m and may sustaining up to 868 kN m with no increase of deflections. Beams retrofit only by shear allowed ultimate deflections up to 200% higher than pre-existing shear deficient beams whilst beams strengthened only by flexure allowed for 31% greater load and fail in diagonal tension cracks.

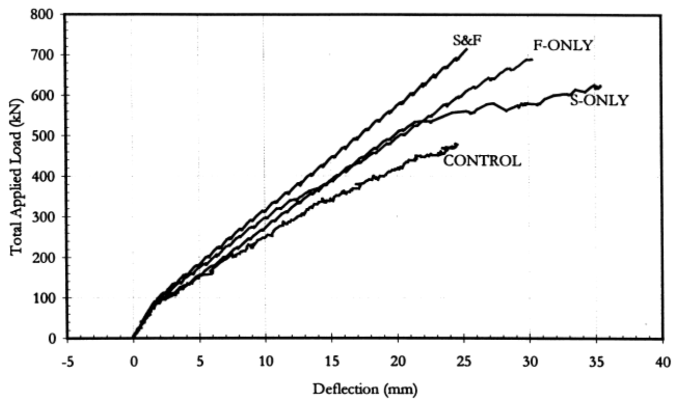

Figure 2: Behavior of strengthened and control beams

Basically, in order to improve strength characteristics of a structure, strengthening materials such as steel or fiber-reinforced polymer (FRP) had to be installed at the weak part of the structure. One of the method used to be implemented is by ensuring good end-anchorage of the strengthening materials. From the study conducted by Duthinh and Starnes (2004), the application of CFRP plates is very effective for flexural strengthening of reinforced concrete beams, provided proper anchorage of the FRP plate is ensured. As the amount of steel reinforcement increases, the additional strength provided by the CFRP external reinforcement decreases. It also found that, mechanical clamping and wrapping with FRP fabric, combined with adhesion, can double or triple the anchorage capacity that can be expected from bond only (Jensen et al, 1999). Steel reinforcement ratio of 75% of the balanced ratio, that was the maximum allowed by ACI, proved that beams reinforced with steel and CFRP plates have adequate deformation capacity in spite of their brittle failure modes.

El Maaddawy and Soudki (2008) studied the possibility of flexural strengthening of reinforced concrete slabs with EBR methods compared with mechanically-anchored unbounded fiber reinforced polymer (MA-UFRP). The effectiveness of the end-anchorage existence was studied by comparing mode of failure for EBR method. Fig 3 shows the anchor system details which consist of 100 × 130 × 10 mm steel plate that placed below the CFRP strips and pre-drilled with four M12 bolts through the slabs. Intends to avoid premature failure, aluminum sheets were placed between every steel plates and CFRP strips. Test results show that both techniques MA-UFRP and EBR were effective in reinforcing flexural strength of RC slabs but EBR system with proper end-anchorage was proved as more effective. In addition, presence of end-anchorage helps to prevent premature failure of CFRP strips and substantially improved deformation of slab ultimate load that was 19% lower than the control slab.

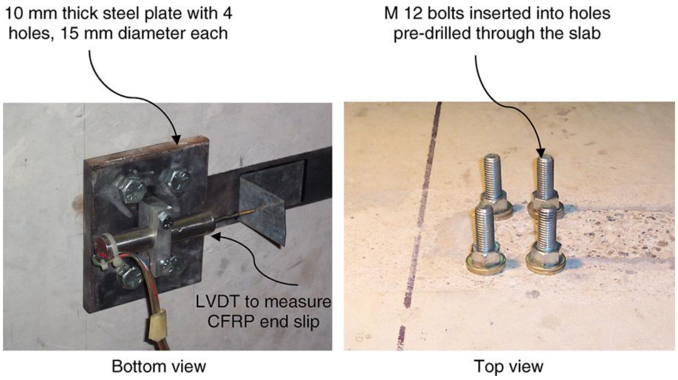

Figure 3: Anchor system details

Another experimental study that works with different end anchorage systems were conducted by Al-Tamimi et al. (2011) on observing flexural behavior of reinforced concrete beams using Self-Consolidating Concrete (SCC) with varies ratio of CFRP plate length to shear span. Eleven beams with inclusion of unstrengthened were tested under four-point bending load test after considering surface preparation. These beams were prepared with different configurations; different plate length with no anchorage; anchored with one layer of transverse unidirectional U-wrap CFRP sheet and sometimes at midspan; anchored with double layer of U-wrap sheet which in perpendicular fiber orientation with one another; and with different width of plate. It can be observed that beam strengthened with CFRP and anchored with tensile U-wrap has higher load-carrying capacity compared to single wraps but less ductile. The most important point to be highlighted, beams with shorter CFRP plates lengths covering about 25% or more of the shear span with proper end anchorages are conceivable to be an effective way to strengthen beams which may reserve in cost and materials used.

Other methods that proved effective to enhance strength performance of structures are near-surface-mounted (NSM) and externally-bonded-reinforcement (EBR) and the latest is externally-bonded-reinforcement-on-grooves (EBROG). Barros et al. (2007) compared the virtue of flexural and shear retrofitting techniques of reinforced concrete beams using CFRP composites. Authority of the longitudinal equivalent reinforcement ratio, $\rho_{l,eq}$ on the effectiveness using near-surface-mounted (NSM) method and externally-bonded-reinforcement (EBR) method were observed for flexural strengthening. The result exhibited that NSM is the most effective method for flexural and shear strengthening of reinforced concrete beams. Eventually, the effectiveness of NSM for flexural strengthening decreased with the increase of the longitudinal equivalent reinforcement ratio, $\rho_{l,eq}$, (steel and CFRP converted into equivalent steel). Wet lay-up CFRP sheets based on EBR method appear as the most efficient way for the beams in service load. These results confirmed that NSM was the most effective method in shear strengthening structure due to the flexibility and fastest of application. Fig 4. similitude load-deflection curves between each techniques presented in this study.

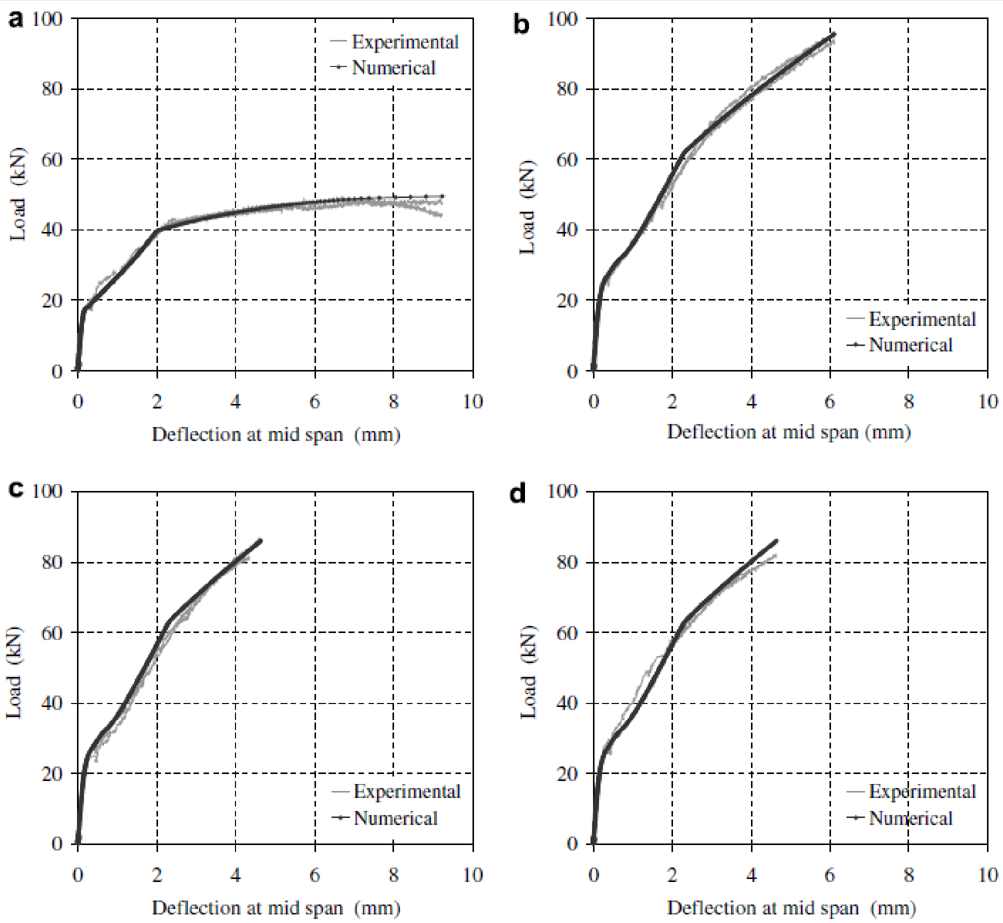

Figure 4: Load-deflection curves between: (a) control beam; (b) NSM; (c) EBR with laminate; (d) EBR with sheets

NSM technique was also applied by Costa and Barros (2010) for flexural strengthening of reinforced concrete beams using CFRP strips by considering the influence of shear failure due to the installment of CFRP strips. From the experimental results, decrease of less than 10% for load carrying capacity were obtained due to the cutting of the bottom arm of steel stirrups with a percentage of steel stirrups higher than the minimum one under increasing of monotonic loading. However, increases of larger than 50% for load carrying capacity were obtained with approximately 0.4% of longitudinal steel reinforcement ratio of the strengthened beams. This technique may yield shear failure to the beams but can be surmounted by effectively strengthen the beams by execute U-wrap or fully wrapped of CFRP wet lay-up sheets.

Performance of concrete beams flexural strengthened by EBR and externally bonded reinforcement on grooves (EBROG) were investigated by Mostofinejad and Shameli (2011). Seven groups of beams with dimension of 120 × 140 × 1000 mm were cast where two similar beams for each groups. Six groups of beams were strengthened by EBR and EBROG with one, two and three layers of CFRP sheets while the remaining was used as control beams. In the EBR method, Sikadur 31 was lay as primary layer after surface preparation prior to CFRP sheets was fixed with epoxy resin Sikadur C300 after left for 24 hours. Whilst, in EBROG method, 850 mm long, 8 mm wide and 10 mm deep of grooves were grouted and filled with Sikadur C31 as primary layer. CFRP sheets were installed with Sikadur C300 after left for one hour. Results of the test show that the feasibility of strengthening concrete beams using EBROG method is very effective which increase up to 146% ultimate loads and strains compared to EBR method. Fig 5 represents the load-displacement relationship for the tested beams. Almost all the retrofitted beams fail in plate end debonding and one group fail due to FRP rupture. Nevertheless, tensile strength of FRP sheets were fully utilized as the FRP laminate stressed and tends to fail in FRP rupture prior to fail in debonding.

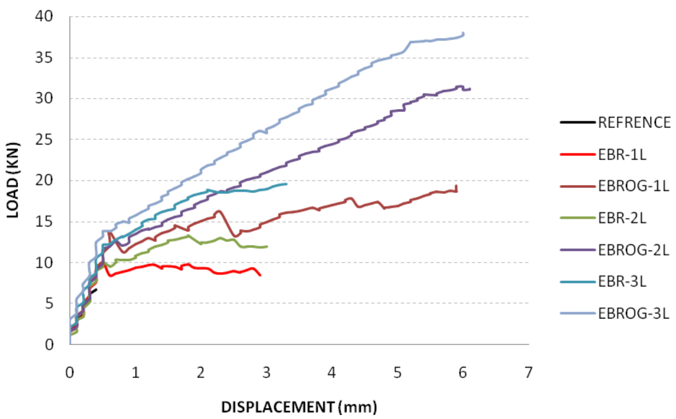

Figure 5: Load-displacement relationship for all beams

D'Ambrisi and Focacci (2011) have presented experimental and theoretical work on flexural strengthening of reinforced concrete beams using fiber-reinforced cementitious matrix (FRCM). They experimentally used other strengthening materials instead of conventional FRP but combine with different types of matrices. The effectiveness of FRCM and FRP applications are being compared. Variance types of matrix were used for these materials. Cement-based namely M50 and M750 were adopted for fiber net and epoxy resin for fiber sheet. These different experimental programs were fixed in strengthening techniques for purpose of studying the effect of fiber materials, fiber arrangements, type of matrices and strengthening configurations. From the result obtained, poliparafenilenbenzobisoxazole-FRCM (PBO-FRCM) and CFRP materials are more effective than carbon-FRCM (C-FRCM) in terms of load-carrying capacity by confirmation from the less obtained strain values. Moreover, 30% increment of load-carrying capacity is being observed from both strengthening materials in the long beams configurations. In spite of that, performance of PBO-FRCM materials and FRP materials are better than C-FRCM materials with the combination of strong matrix design; M750 in this study.

2.2 Reinforcing Techniques for Metal

CFRP externally bonded technique have been applied to different cross-sections of aluminum extrusions box sections by Broughton et al. (1997) to illustrate the flexural behavior as shown in Fig. 6. Ten plies of CFRP were gathered in 2 mm thick of laminates which aligned parallel to the length of beam. Effect of the utilization of adhesive bondline may be neglected when predicting the strength of the beams. From the result obtained lower possibility towards CFRP failure caused by higher span-to-width ratio of the beams. Furthermore, effectiveness of the reinforcement implemented by increase the span length. Shape optimization technique is desirable to applied in the future because this technique utilize the effectiveness of CFRP; in the same time reduce the weight whilst maintaining equivalent sectional properties.

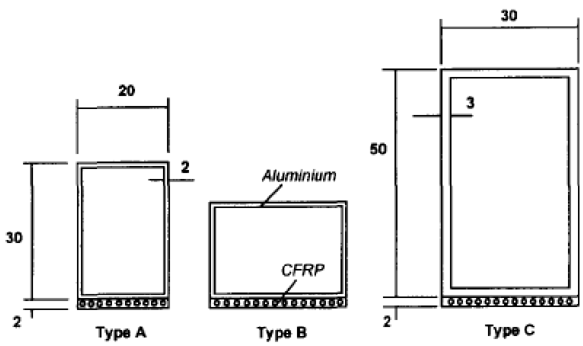

Figure 6: Cross-section of experimental beams

2.3 Reinforcing Techniques for Timber

Bending strength theory was earlier been developed by Buchanan (1990). He solved the relationship between tension, compression and bending strength of timber in detail and verified using in-grade testing of full scale timber by previous literature. Initially, typical stress-strain relationship for timber must be clear intending to predict bending strength as shown in Fig 7.

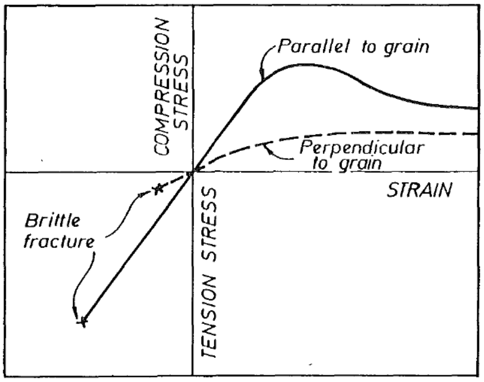

Figure 7 : Stress-strain relationship for timber

Variation in timber size may affect the failure mode; therefore, by applying brittle fracture theory, length and depth effects can be calculated using (1) and (2) respectively.

$$\frac{x_1}{x_2} = \left(\frac{L_2}{L_1}\right)^{1/k_1} \tag{1}$$

$$\frac{x_1}{x_2} = \left(\frac{d_2}{d_1}\right)^{1/k_2} \tag{2}$$

k_1 and k_2 in the equations above represents the variability in strength properties of different length and depth respectively for each board. From this theory, narrow beams may have higher stress than wider beams. In elastic behavior, flexural strength may be computed from (3).

$$f_m = \left(\frac{k_3+1}{c}\right)^{1/k_3} f_t \tag{3}$$

where k_3 represents the variability in strength properties within the depth of a member and c reflects the depth of the neutral axis as a ratio of the depth of the cross section and may be counted as 0.5. The maximum moment that connected with a tension failure and some compression failure may be computed as in (4).

$$M = f_c \frac{wd^2}{6} \left[\frac{n + (2n - 1)r}{n + r} \right] \tag{4}$$

where w is the width of the beam, d is the depth of the beam and f_c is the compression strength while value of r and c can be calculated using (5) and (6) respectively.

$$r = \sqrt{1 - m\ (n^2 - 1)} \tag{5}$$

$$n \left[\frac{n(1 + r)}{(n + r)(n + 1)(k_3 + 1)} \right]^{1/k_3} = \frac{f_t}{f_c} \tag{6}$$

where m is assumed as the slope of the falling branch of the stress-strain relationship and f_t is axial tension strength. Whereas, maximum moment with no tension failure assumed were calculated by using (4) but with different value of n as in (7).

$$1 + m - mn^3 + \left[1 - m\left(n^2 - 1\right)\right]^{3/2} = 0 \tag{7}$$

This analysis has been calibrated by several experimental results from literature and is accepted to date but have new invention presently.

Plevris and Triantafillou (1992) have done research on enhancing mechanical properties of wood beams and wood beams column strengthen using CFRP by analytical and experimental program for short-term behavior. Uniaxial stress-strain relationship for wood was based on Bazan (1980) and Buchanan (1990). Moment-curvature (M-Ø) relationship obtained for the cross-section was used in explaining flexural behavior of the reinforced timber beam. This research indicates the successful of earlier strengthening technique of wood structure by using FRP adhered to their tension face and even enhance stiffness and ductility properties.

Triantafillou and Deskovic (1992) have adhered prestressed CFRP sheets externally on the tension faces of timber beams. In designing timber beams in this case, it is essentially to ensure the strength of pretensioned beams greater than the nonpretensioned beams in utilizing benefit of installing prestressed sheets to the beam. Area fraction of FRP and the magnitude of the initial pretension are the main subjects to be determined to achieve good design. Experimental results confirm the effectiveness of this technique in reinforcing timber beam.

Flexural development and applications for strengthening timber beams have been carried out by Gentile et al. (2002). They proposed experimental technique by reinforcing the timber by implementing GFRP bars with varies reinforcement ratios percentage; between 0.27 and 0.82. Twenty two half-scale and four full scale timber beams were tested to examine the size effect and to compare the performance of the reinforcing techniques. The results have shown that size has deficient influence towards structural behavior of the beams and increment by 18 to 46% of flexural strength was observed. Besides, this technique have proven changes of failure mode from brittle tensile tension in the reinforced beams to ductile compression failure in the reinforced beams and may solve problems due to local defects in the timber.

Gentile et al. (2002) have modified an analytical model by Buchanan (1990) for predicting bending strength of the half-scale GFRP reinforced beams. Tensile strength in bending, f_{mr} for reinforced timber is calculated by using (8).

$$f_{mr} = \alpha_m \left(\frac{k_3 + 1}{c}\right)^{1/k_3} f_{tu} \tag{8}$$

where α_m is a constant modification factor; where c is the nondimensional ratio of the depth of the neutral axis from the tension face with respect to the depth of the section, d; and k_3 is the stress distribution parameter, which reflects the variability in strength properties within the depth of the section. Using experimental results from Buchanan (1990), k_3 were calibrated to give a value of 10 while f_{tu} is unreinforced timber tensile strength at first, but were modified later. The computer program was changed to increment the strain until $f_{tu} = f_{mr}$. After calibrated with the laboratory results, the constant modification factor, α_m counted and accepted as 1.30 to account the effect of FRP on tensile strength in bending. Ultimate bending strength (MOR) was calculated using (9). The correlation between predicted values of MOR for GFRP-reinforced timber beams with the experimental was shown on Fig. 8.

$$MOR = \frac{M_{ult}}{S_t} \tag{9}$$

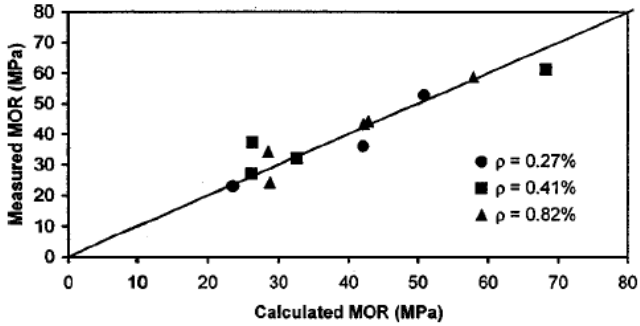

Figure 8 : Comparison with the experimental Correlation between predicted value of MOR for GFRP-reinforced timber beams

Flexural reinforcing techniques for existing wood beams were presented by Borri et al. (2005) by numerical procedure and experimental program. Twenty beams of 4000 mm long and cross section of 200 × 200 mm2 were tested under four-point bending test from varies schemes reinforcement configurations executed, the case of three layers externally bonding of FRP sheets demonstrated the best performance in flexural capacity up to 60.3 % compared to unreinforced beams. Loading reinforcement to the beam under flexion load does not help to increase in stiffness with 30 % maximum increase. Numerical procedure proposed in this research is possible to predict failure load but the procedure does not consider shear failure.

Connection at joints was identified as a critical matter that should be made attentively since joints render on transferring flexural moment between adjacent beams. Research done by Micelli et al. (2005) have reported the use of CFRP rods as glued-in flexural reinforcement of glulam beams yet focusing on flexural reinforcement at joints. 5000 mm long and cross section of 120 × 200 mm specimens and 12.5 mm diameter of CFRP rods and a peel-ply rough surface were prepared. Fig. 9 showed a schematic illustration of carbon fiber-reinforced polymer timber flexural joint. Experimental test showed ultimate moment increases to 26% and 82% which shows effective usage of CFRP rods to the glulam beam. Micelli et al. (2005) also reported the increasing of ultimate capacity influenced by anchorage length; in this case, 93% increases of ultimate load reached by anchorage length of 1000 mm. High performance of bonding during stress transfer can be observed thru strain detected along the connectors. However, these reinforcing techniques are only applicable for wood with same class strength and the results are accordance to the amount of reinforcements used in this study only.

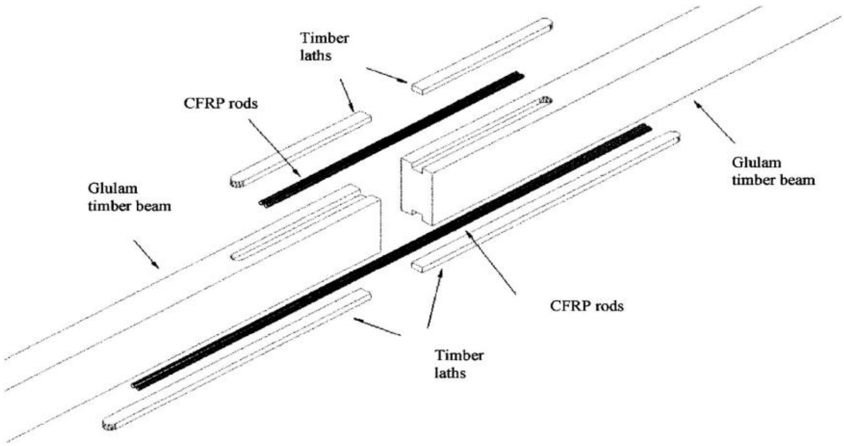

Figure 9 : Scheme of carbon fiber-reinforced polymer timber flexural joint

Dempsey and Scott (2006) have investigated the feasibility of increasing the flexural strength of wood members using mechanically fastened FRP strips. The experimental work showed that increase in ultimate moment and initial stiffness were up to 29% when adding hybrid-FRP (HFRP) consisted of two layers of continuous strand mats and a combination of E-glass rovings and carbon tows compared with GFRP strengthened members. Under a third-point bending configuration as part of the experimental program, fifteen specimens were tested with varies spacing of fasteners and the result showed reduction in member ultimate moment, initial stiffness and ductility ratio when fastener spacing are increased. Besides, moisture content has a significant impact on the member ductility ratio.

The use of pultruded elements in the interest of strengthening timber beams were applied in real field to the timber floor of the XVII century palace (Palazzo Cllicola). The interesting result has prompted Corradi and Borri (2007) to led an investigation in order to characterize flexural stiffness and strength of wood reinforced with GFRP pultruded element. Two types of pultruded elements were used; H-type and I-type where, I-type were obtained by joining two C-shaped elements using epoxy system. Notches were made same as in the real field application, for the insertion of the wood rafters of floor. From the test conducted, I-type pultruded elements is much more stiffer and stronger than H-types. Penetration of epoxy system to the timber were proved negligible refers to microscopic analysis. Alternatively, mechanical reinforcing technique were applied to the timber beams by using metal screws. It is advisable to insert the screws at slightly angle into the wood or use greater size of the screws in order to avoid withdrawal the screws from the wood.

Simple analytical procedure were conducted by Corradi and Borri (2007) based on Bazan-Buchanan Law to previse the experimantal results. A linear-elastic model were used concerning the FRP material with assumption that wings and web of the pultruded elements have the same elastic modulus E_p (10),

$$\sigma_p = E_p \cdot \varepsilon_p \tag{10}$$

Position of the neutral axis determined by (11), as can be refer to Fig. 10.

$$y = \frac{A_w\left(h_1 + \frac{h_2}{2}\right) + A_p\,\frac{E_p}{E_w}\,\frac{h_1}{2}}{A_w + \frac{E_p}{E_w}\,A_p} \tag{11}$$

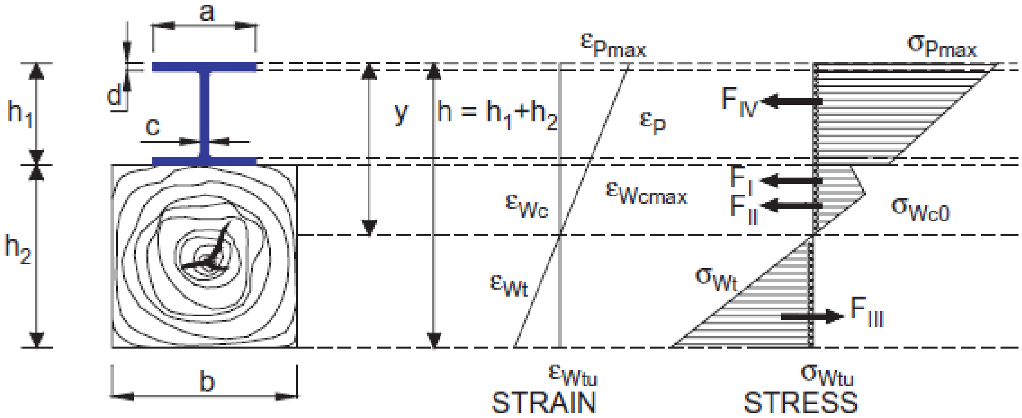

Figure 10 : Cross-section stress and strain analysis

where h_1 is the height of the pultruded element and h_2 is the height of the timber beam. Estimation of compression and tensile streses for timber and the compression stress for the pultruded element were based on the capacity P obtained from the experimental result.

$$\sigma_{Wt} = \frac{M}{J_x} \cdot (h_1 + h_2 - y) \tag{12}$$

$$\sigma_{Wc} = \frac{M}{J_x} \cdot (y - h_1) \tag{13}$$

$$\sigma_P = \frac{M}{J_x} \cdot y \cdot \frac{E_p}{E_w} \tag{14}$$

Error ranging between 10-20% by comparing the experimental and analytical results for I-type element. A non-linear model were also used in describing non-linearity behavior based on strain and stress analysis.

Reinforcement techniques for restoration and strengthening of existing timber structure under bending load were investigated by Schober and Rautenstrauch (2007). They conducted experimental program consist of three series of different reinforcement schemes that were external applied reinforcement and wood embedded reinforcement with laterally bonded and centrally bonded. Based on the result shown, quoted crack opening arrest causing increases of the load-carrying capacity especially in wood embedded reinforcement. Existing of natural defects may reduce initial bending stiffness and moment of inertia of about 20%. Although predicting the stiffness and strength increase in a reinforced timber beam is a complicated problem, the result showed that CFRP reinforced beams is more ductile than un-reinforced beams. Separating of the section in longitudinal direction between cracks may cause the shear failure in the structure for this case.

Johnsson et al. (2007) have exhibited NSM method to enhance flexural strength of glulam using CFRP. Flexural capacity of the beams was analyzed by using a transformed cross section of concrete beams' analogy based on model developed by Borri et al. (2005) and Gilfillan et al. (2003). Fig. 11 shows the assumed stress distribution for the case of reinforcing on the tensile and the compressive side of the beam. They also study the anchorage length effect of the reinforcement which is beneficial crucial for the application for existing structure. Increases of 44% to 63% and 10% of short-term flexural capacities and stiffness were reported respectively.

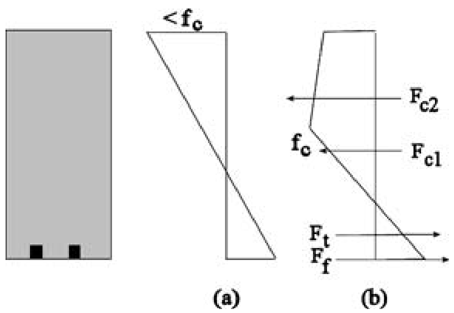

Figure 11 : Stress distribution (a) Elastic region and (b) ductile compression failure

Li et al. (2009) have carried out research by theoretical analysis and experimental program to retrofit timber beams using CFRP composite sheets. For theoretical analysis, classic beam theory was used to derive the force-displacement relationship of the CFRP wood composite beam. The relationship between the neutral axis and the strain of the composite was obtained from micro-strain reading. Using curvature-area method with moment-curvature relationship, the load displacement relationship of the beam could be determined (Fig. 12).

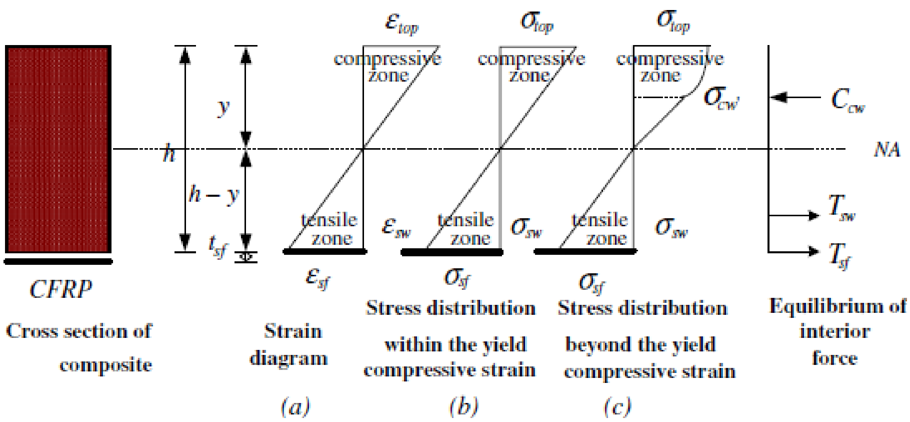

Figure 12 : Strain and stress distributions diagram of the composite beam section.

For the experimental work, CFRP sheets were installed to the tensile side of the timber beams with varies number of layer of two different species of timber. The result showed that increasing number of CFRP composite sheets layer will leads to the increment of flexural strength with decreasing result for the middle vertical displacement. Experimental and theoretical analysis showed good agreement with absolute error of the ultimate load ranging from 5.05% to 8.65% in average for both species of wood.

Mechanical repair of flexure fractured timber beams was studied by Alam et al. (2009). They repaired the beams by bonding in reinforcements either mild steel or pultruded composite consist of CFRP, GFRP or thermoplastic matrix glass fiber reinforced polyurethane (FULCRUM) prior to grooves routed into the top, bottom or both fractured faces of the beams. As predicted, installing the reinforcements into faces, top and bottom of the beams showed the best performance. In terms of flexural increment, steel and GFRP give the highest results on the transformed flexural strength. Beams strengthened with steel are the stiffest.

Yusof and Saleh (2010) have reinforced timber beams by preparing grooves along the bottom part of the beams which is parallel to grain, then fitting GFRP rods inside the grooves. In order to study the bending behavior, they found that strengthened using

GFRP rod for area from 0.16% to 0.63%, may increase the ultimate load and flexural stiffness between 20% to 30% and 24% to 60% compared to unstrengthened beam respectively. Failure signs are observed when the flexural compressive strain reached about 0.3% and when the flexural tensile strain more than 0.6% with no sign of debonding or delamination between GFRP rods and timber also the GFRP are unruptured.

Flexural performance for low-grade glued laminated timber reinforced with FRP plate was investigated by Raftery and Harte (2011). By implement four phase with unreinforced and reinforced beams arrangement, they found that, unreinforced beam demonstrated linear elastic behavior compared to pseudo-ductile behavior for reinforced beams. Modest enhancement in stiffness achieved when FRP reinforcement is included. Ultimate moment capacity improved when the glulam is reinforced in comparison to when it is not. It can be seen that ultimate moment capacity for 190 mm deep beams, have greater increased of 38% compared to 215 mm deep beams of 28.6%. Higher utilization of compressive strength of the timber obtained with inclusion of FRP in tension region.

Research on using high strength steel cords to fortify timber beams was investigated by Borri and Corradi (2011). A four point bending test was conducted to determine the stiffness, ductility and strength of the rafters and beams in this experimental work. The steel cords were positioned in the middle of the tension zone and were glued with an epoxy resin. Additionally, to avoid delamination of the strengthening materials, two metal plates were fixed with eight screws at both sheet ends. A mechanical device consisting of a metal cylinder end and clamp were used to fixing the strips to the beam as shown in Fig. 13 and Fig. 14. Using steel cords may be an alternative effective method that is beneficial economically rather to use conventional FRP composites as reinforcing materials.

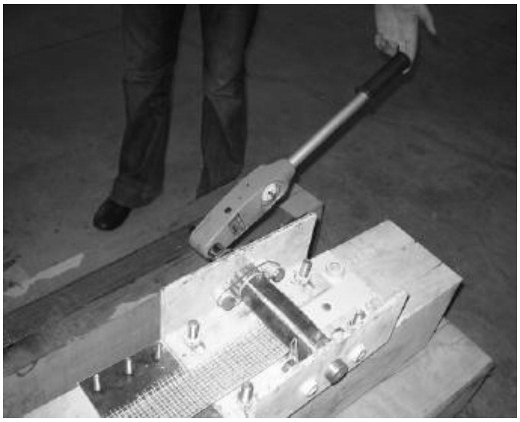

Figure 13 : Fixing the strips using the metal cylinder

Figure 14 : Fixing the strips using the clamp

Valipour and Crews (2011) have developed a framework finite element (FE) to estimate load-carrying capacity of timber beams strengthened with externally bonded fibre reinforced polymer (FRP) strips or sheets and near-surface mounted (NSM) FRP bars. The framework of the formulation considers material nonlinearities, continuity of slip shear force and size effect. New approach was developed based on central difference method by utilizing a composite Simpson's Integration method to take account bond shear-slip. It was observed that the agreement between experimental (Gentile et al., 2002; and Buell and Saadatmanesh, 2005) and numerical modeling in estimating loading capacity of timber beams is outstanding with the mean of the ratio between FE simulation and experimental result is 1.01 and its coefficient of variation is COV=0.057. The developed FE model can be applied in design-oriented parametric studies rather than to use other complex and costly FEs.

2.4 Reinforcing Techniques for New Composite

The latest innovative development in the industry application is focused on wood plastic composites (WPC) material. Although WPC material outline beneficial usage as it is a lightweight material, high durability, corrosion resistance and low maintenance requirements, but its lower mechanical properties than woods make it require strength improvement. Pulngern et al. (2011) proposed reinforcing wood/poly(vinyl chloride) (WPVC) composite by implementing varies type of flat bar strips externally to the tension side of the member. Most suitable material to reinforce WPVC composites is using High Carbon Steel (HCS) flat bar because the test at laboratory shows flexural properties improvement of WPVC. Increasing number of bar strips and their thickness may result in enhancement of flexural performance. Moreover, creep resistance of WPVC were improved by strengthen using HCS flat bars.

Flexural performance of WPC-FRP beams was investigated by Naghipour et al. (2011) using theoretical analysis and short-term experimental works. The analysis were presented by referring on nonlinear WPC properties which deliberate exponential function in the stress-strain diagram of WPC in tension and compression parallel to fibers. The model were compared with the experimental works which is done by adhering CFRP and GFRP sheets to the tension face of the beam with varies number of layers. Good correlation between experimental and theoretical result were achieved referring to the difference percentage error which are 5.25% and 4% to calculate the ultimate load for WPC-CFRP and WPC-GFRP beams respectively. Three layers of FRP showed significant increases on ultimate load and initial stiffness of the beams.

3.0 Conclusions

From the literature review of reinforcing structures using fiber-reinforced polymer (FRP), it is clearly demonstrated that FRP is efficient to be used as strengthening material for new low strength structure and rehabilitation of existing and damaged structures. Generally, FRP need to adhere to the tension side of the structure in order to increase the tensile strength and to assure the failure initiated from the compression zone of the structure. Effectiveness of the research was evidenced from the increment of flexural strength and fail due to rupture of FRP which indicates that high properties of FRP are fully utilized with perfect bond are assumed. Conventional methods on reinforcing structure by using FRP are externally-bonded reinforcement (EBR) method and near-surface-mounted reinforcement (NSM). NSM reinforcing techniques were the most effective method proved by literature in increase strength capacity and change brittle mode of failure to ductile of structures but further study are needed for the influence of cyclic and fatigue loading to NSM method of strengthened structure. Other than that, mechanically-anchored FRP for strengthening structures is also effective but less strength gain compared to externally-bonded reinforcement method. Presently, new reinforcing technique i.e. externally bonded reinforcement on grooves (EBROG) had proved to be an efficient method for reinforcing structure purposes but need further investigation on the condition of application and the durability of this technique.

FRP have greatly potential in strengthening new composites material too such as wood plastic composites (WPC). In author's opinions, long-term behavior including proper designs for flexural strengthening structures especially for externally bonded, mechanically anchored and near surface mounted method need more consideration as these techniques presently, proved greatly enhance strength for new and existing structures and it can be implemented and commercialized in field applications.

From the experiments conducted in the literature, the following comments and conclusions were drawn future research improvement:

1. Testing of structures strengthened in laboratory need conditions similar to the field application to access the real feasibility application of strengthening material i.e. FRP composites.

2. Durability of strengthened structures under excessive and extreme environmental e.g., freezing and thawing, fatigue and extreme weather conditions needs further investigation.

3. Half scale beams used as specimens does not show real application result. Therefore, full scale sizes of specimens are required. Small number of specimens also does not show consistency of related research on studying performance and behavior of the strengthened material.

4. Application of reinforcing techniques to the timber structure need to consider environmental effect, timber bio degradation, effects of moisture content, variation of timber quality and wood chemical preservatives.

5. Retrofitting metal structure with FRP was successfully proven by literature but, least study was interested in the field of strengthening metal structure.

6. Slightly imperfect bond or strain lag of FRP phenomenon incorporating with bond strength between adhesive and surface structure need further investigation since these circumstances is inadmissible for accuracy in calculations.

7. The presence of end-anchorage system was proved to help utilizing the uses of FRP in strengthen structures. Requirement for end-anchorage system and the required length in strengthen structures needs to be studied in order optimizing reinforcing purposes by gaining greater strength and save in cost.

References

Al-Tamimi, A. K., Hawileh, R., Abdalla, J., & Rasheed, H. A. (2011). Effects of Ratio of CFRP Plate Length to Shear Span and End Anchorage on Flexural Behavior of SCC RC Beams. *Journal of Composites for Construction, 15*(6), 908-919.

Alam, P., Ansell, M. P., & Smedley, D. (2009). Mechanical repair of timber beams fractured in flexure using bonded-in reinforcements. *Composites Part B: Engineering, 40*(2), 95-106.

Barros, J. A. O., Dias, S. J. E., & Lima, J. L. T. (2007). Efficacy of CFRP-based techniques for the flexural and shear strengthening of concrete beams. *Cement and Concrete Composites, 29*(3), 203-217.

Bonacci, J. F., & Maalej, M. (2000). Externally Bonded FRP for Service-Life Extension of RC Infrastructure. *Journal of Infrastructure Systems, 6*(1), 41-51.

Borri, A., & Corradi, M. (2011). Strengthening of timber beams with high strength steel cords. *Composites Part B: Engineering, 42*(6), 1480-1491.

Borri, A., Corradi, M., & Grazini, A. (2005). A method for flexural reinforcement of old wood beams with CFRP materials. *Composites Part B: Engineering, 36*(2), 143-153.

Broughton, J. G., Beevers, A., & Hutchinson, A. R. (1997). Carbon-fibre-reinforced plastic (CFRP) strengthening of aluminium extrusions. *International Journal of Adhesion and Adhesives, 17*(3), 269-278.

Buchanan, A. H. (1990). Bending strength of lumber. *Journal of structural engineering New York, N.Y., 116*(5), 1213-1229.

Buell, T. W., & Saadatmanesh, H. (2005). Strengthening Timber Bridge Beams Using Carbon Fiber. *Journal of Structural Engineering, 131*(1), 173-187.

Corradi, M., & Borri, A. (2007). Fir and chestnut timber beams reinforced with GFRP pultruded elements. *Composites Part B: Engineering, 38*(2), 172-181.

Costa, I. G., & Barros, J. A. O. (2010). Flexural and shear strengthening of RC beams with composite materials – The influence of cutting steel stirrups to install CFRP strips. [doi: 10.1016/j.cemconcomp.2010.03.003]. *Cement and Concrete Composites, 32*(7), 544-553.

D'Ambrisi, A., & Focacci, F. (2011). Flexural Strengthening of RC Beams with Cement-Based Composites. *Journal of Composites for Construction, 15*(5), 707-720.

Dempsey, D. D., & Scott, D. W. (2006). Wood members strengthened with mechanically fastened FRP strips. *Journal of Composites for Construction, 10*(5), 392-398.

Duthinh, D., & Starnes, M. (2004). Strength and ductility of concrete beams reinforced with carbon fiber-reinforced polymer plates and steel. *Journal of Composites for Construction, 8*(1), 59-69.

El Maaddawy, T., & Soudki, K. (2008). Strengthening of reinforced concrete slabs with mechanically-anchored unbonded FRP system. *Construction and Building Materials, 22*(4), 444-455.

Gentile, C., Svecova, D., & Rizkalla, S. H. (2002). Timber Beams Strengthened with GFRP Bars: Development and Applications. *Journal of Composites for Construction, 6*(1), 11-20.

Gilfillan, J. R., Gilbert, S. G., & Patrick, G. R. H. (2003). The use of FRP composites in enhancing the structural behavior of timber beams. *Journal of Reinforced Plastics and Composites, 22*(15), 1373-1388.

Ibrahim, I.S., Bakar, M.B.C., Sarbini, N.N. and Mohamed, R.N. (2011). "Shear Capacity Of Composite Slab Reinforced With Steel Fibre Concrete Topping", *Malaysian Journal of Civil Engineering*, Vol. 23(1), pp.1-23.

Johnsson, H., Blanksvärd, T., & Carolin, A. (2007). Glulam members strengthened by carbon fibre reinforcement. *Materials and Structures, 40*(1), 47-56.

Kachlakev, D., & McCurry, D. D. (2000). Behavior of full-scale reinforced concrete beams retrofitted for shear and flexural with FRP laminates. *Composites Part B: Engineering, 31*(6–7), 445-452.

Li, Y.-F., Xie, Y.-M., & Tsai, M.-J. (2009). Enhancement of the flexural performance of retrofitted wood beams using CFRP composite sheets. *Construction and Building Materials, 23*(1), 411-422.

Mazlan, D. & Awal A.S.M.A (2012), "Properties Of Cement Based Composites Containing Oil Palm Stem As Fiber Reinforcement", *Malaysia Journal of Civil Engineering*, Vol. 24(2), pp.107-117.

Micelli, F., Scialpi, V., & La Tegola, A. (2005). Flexural reinforcement of glulam timber beams and joints with carbon fiber-reinforced polymer rods. *Journal of Composites for Construction, 9*(4), 337-347.

Mostofinejad, D., & Shameli, M. (2011). Performance of EBROG Method under Multilayer FRP Sheets for Flexural Strengthening of Concrete Beams. *Procedia Engineering, 14*(0), 3176-3182.

Naghipour, M., Nematzadeh, M., & Yahyazadeh, Q. (2011). Analytical and experimental study on flexural performance of WPC–FRP beams. *Construction and Building Materials, 25*(2), 829-837.

Plevris, N., & Triantafillou, T. C. (1992). FRP-Reinforced Wood as Structural Material. *Journal of Materials in Civil Engineering, 4*(3), 300-317.

Pulngern, T., Padyenchean, C., Rosarpitak, V., Prapruit, W., & Sombatsompop, N. (2011). Flexural and creep strengthening for wood/PVC composite members using flat bar strips. *Materials & Design, 32*(6), 3431-3439.

Raftery, G. M., & Harte, A. M. (2011). Low-grade glued laminated timber reinforced with FRP plate. *Composites Part B: Engineering, 42*(4), 724-735.

Schober, K. U., & Rautenstrauch, K. (2007). Post-strengthening of timber structures with CFRP's. *Materials and Structures/Materiaux et Constructions, 40*(1), 27-35.

Triantafillou, T. C., & Deskovic, N. (1992). Prestressed FRP Sheets as External Reinforcement of Wood Members. *Journal of Structural Engineering, 118*(5), 1270-1284.

Valipour, H. R., & Crews, K. (2011). Efficient finite element modelling of timber beams strengthened with bonded fibre reinforced polymers. *Construction and Building Materials, 25*(8), 3291-3300.

Yusof, A., & Saleh, A. L. (2010). Flexural strengthening of timber beams using glass fibre reinforced polymer. *Electronic Journal of Structural Engineering, 10,* 45-56.