FLEXURAL STRENGTH OF REINFORCED CONCRETE BEAM WITH CFRP

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Abstract
The flexural strengthening of reinforced concrete beam can be considered with applied externally bonded steel plate or carbon fibre composite. This external plate is bonded to the tension face of the concrete beam experimental study on reinforced concrete strengthening with Carbon Fibre Reinforced Plate (CFRP) has been conducted to estimate the effectiveness of using CFRP on the concrete structure as external reinforcement. Two beams were tested in this study to test the flexural strength effect of externally bonded CFRP composite in the reinforced concrete beam. Two beams were tested in this study to test the flexural strength effect of externally bonded CFRP composite in the reinforced concrete beam. One of the beams is a control beam and other beam is the concrete beam without steel bar and laminated CFRP to the bottom of the beam with epoxy. The dimension of the beams is 150x250 mm with length 2000 mm. All beams were tested using two-point loading to get pure bending in the middle span. The result of the experimental research showed that in spite of using laminated CFRP on the concrete beam had increased the cracking moment, but laminated CFRP on the concrete beams as external reinforcement without reinforcing steel bar has no significant effect on the behaviour of beams. Premature failure of externally bonded CFRP plates had occurred before the ultimate flexural capacity of the strengthened section is achieved.

Keywords: *Beam; concrete; Carbon Fibre Reinforced Plate; externally reinforcement bar*

INTRODUCTION

The value of the moment capacity (M) of the reinforced concrete beam (RC Beam) is determined by the distance between centre of concrete to centre of reinforcement bar *(jd)*. If the distance of *jd* is big then the value of moment capacity that occurs will be huge. In order for the moment capacity of the beam to work optimally, then the reinforcement bar must be placed at the bottom surface of the beam, in order to get the maximum value *jd*, therefore the steel reinforcement is placed at the outer tensile part of the beam where *jd2 > jd1* so that M2 > M1 as shown in Figure 1. However, it does not provide sufficient attachment between steel and concrete in the beam, and the expected composite action cannot happen. Moreover, reinforcement bar is a material that is susceptible to corrosion if it is exposed to the air. Therefore, it required some minimum concrete cover as shown in Figure 1.
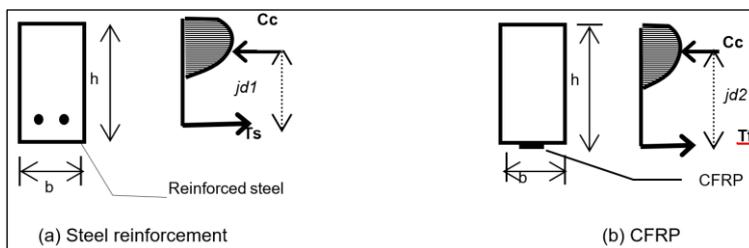

Figure 1. Positions of steel reinforcement and CFRP

Currently there are materials that offer some advantages that reinforced steel do not have, such as CFRP. It has a tensile strength which is higher than the tensile strength of the reinforcing steel, non-corrosive material, light less dense with weight over volume of 1.5 g / cm^3 and is easy to install at side. The bonding between the concrete and CFRP can be formed by using an adhesive material that provides adhesive between the two materials during loading condition. The use of adhesive material on the concrete structure by CFRP reinforcement will have a positive impact on the structure because CFRP placement of the concrete does not need to be embedded in concrete, because the material is corrosion resistant, it is made of non-metallic material. CFRP composite material is not required a cover, so *jd* distance is expected to be optimized to produce maximum bending moment capacity as well.

A summary of research in this area is available by Teng et al. (2002) explained the behaviour flexural and shear strengthening of beams, column strengthening flexural strengthening of slabs. Both the flexural and shear strengths of RC beam can be substantially increased using externally bonded FRP reinforcement in the forms of plates. The failures of such FRP strengthened RC beam often occur by the debonding of the FRP plate from the RC beam in a number of modes. Teng at al. (2009) studied the strengthening of RC structures with bonded FRP reinforcement, seismic retrofit of RC structures, durability of FRP strengthened in RC structures, hybrid FRP concrete structures and smart FRP structures. Brena et al. (2003) reported debonding of longitudinal carbon FRP (CFRP) sheets at deformation levels less than half the deformation capacity of control specimens. A similar result has been reported by Kuriger et al. (2001), Alessandra et al. (2001), DeLorenzis and Nanni (2001). Noorwirdawati et al. (2016) studied RC beams which strengthened in shear using CFRP strips with such scheme only focused on CFRP strips oriented at 45°/135°. The experimental result, beams wrapped with CFRP strips recorded shear capacity enhancement of around 19.05% to 43.74% as compared to the control specimens. Chin (2012) studied experimental and analytical numerical analysis of RC beams with large square openings placed in the shear region and strengthened by CFRP.

This research focuses on an experimental study of reinforced concrete beam by placing CFRP at a bottom of the beam and acting as an external reinforcement. The aims to determine the benefits of using CFRP as an external reinforcement of reinforced concrete beams, and to determine the flexural strength and moment capacity of RC Beam under two-point loads.

FLEXURAL STRENGTH OF CONCRETE BEAM

In this section, the moment capacity of the normal and CFRP beam are determined using simplified stress block method. Figure 2 shows the cross section of normal concrete beam together with the stress–strain relationship of the concrete and reinforcement bar. The moment capacity of this concrete beam is determined using simplified stress block method.

From Figure 2, the compressive force is given by Equation 1.

$$Cc = 0.85 f'c \cdot a \cdot b \quad \text{where } a = \beta 1.c \tag{1}$$

The tension in steel is given by Equation 2.
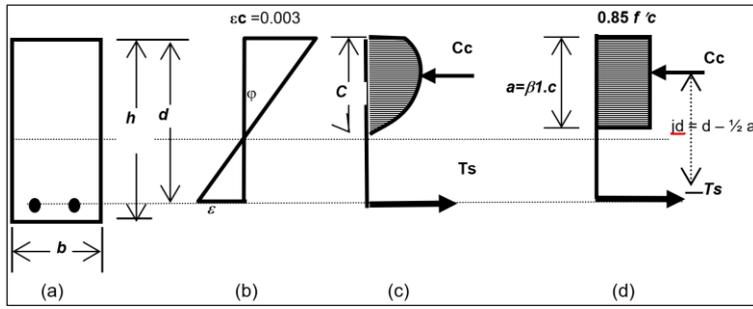
$$Ts = As \cdot fy \tag{2}$$

Figure 2. Distribution of stress–strain of normal beam

The equilibrium of force between the tension of steel and compression of concrete is given by Equation 3, 4 and 5.

$$Cc = Ts \tag{3}$$

$$0.85\,f'c \cdot a \cdot b = As \cdot fy \tag{4}$$

$$a = \frac{As \cdot fy}{0.85\,f'c \cdot b} \tag{5}$$

The nominal moment capacity of the normal reinforced concrete beam is given by Equation 6.

$$Mn = As \cdot fy \cdot jd \qquad \text{where } jd = d - \tfrac{1}{2}\,a \tag{6}$$

When the reinforced concrete beam is mounted by the CFRP external reinforcement the bending strength of the beam occurs as proposed by Kuriger et al. (2001) is shown in Figure 3, where T_F is the tensile force of CFRP and jd_F is the distance from Cc to T_F.
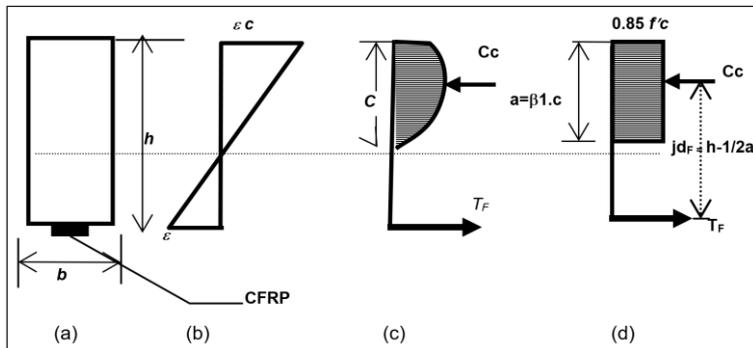

Figure 3. Stress–strain distribution of beam with CFRP

From Figure 3, the nominal moment of the cross section is given by Equation 7.

$$Mn_F = As_F \cdot fy_F \cdot jd_F \qquad \text{where } jd_F = h - \tfrac{1}{2}\,a \tag{7}$$

It can be seen that the moment capacity of beam with CFRP is bigger than normal beam due to the lever arm ($jd_F > jd$). Furthermore, the tensile strength of CFRP is higher than reinforcement bar. Based on Figures 2 and Figure 3 are seen that $jd_F > jd$ so that both equations (7) and (8) will produce a larger moment (Mn_F), or it can be said that with the installation of CFRP externally the bending capacity will increase proportionally.

CONCRETE COMPRESSIVE STRENGTH

The concrete compressive strength is determined by the highest voltage of the 150 mm and 300 mm diameter cylinder test pieces tested after 28 days; it was tested using a compression test machine until the specimen is destroyed. The amount of compressive strength of concrete is calculated using Equation 8.

$$\sigma_c = \frac{Pc}{Ac} \tag{8}$$

Where:

σ_c = concrete compressive strength

Pc = axial force

Ac = cross-sectional area

According to Park and Paulay (1975), the behaviour of concrete compressive strength can be illustrated by using the Hognestad stress-strain parabolic curve as shown in Figure 4, with the concrete compressive strength as follows:

$$fc = f'c\ (2\varepsilon c/\varepsilon o - (\varepsilon c/\varepsilon o)^2) \tag{9}$$

Where fc is the compressive stress of concrete, f'c is the maximum stress of concrete, and εo is the strain of concrete at the maximum compressive stress.
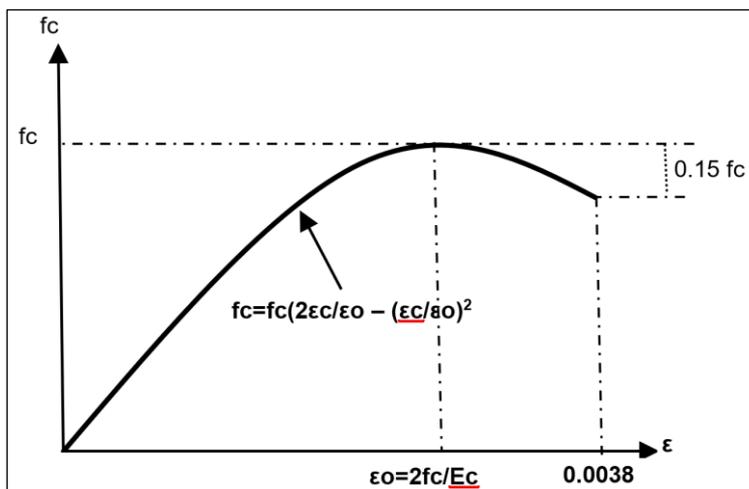

Figure 4. The Hognestad stress-strain parabolic curve (Park and Paulay,1975)

Properties of CFRP

CFRP is a flexible bending material and is mounted on the lower surface of the beam. The CFRP technical data specifications used is shown in Table 1.

Table 1. Properties of CFRP

Properties of CFRP	
Tensile Strength	2800 MPa
E-Modulus	165,000 MPa
ε_{cu}	> 1.7 %
Thickness / width	0.8 mm / 50 mm
Density	1.50 g/cm^3

Properties of Epoxy (Adhesives)

The usage of CFRP as an external reinforcement in a concrete structure requires a binder to obtain a composite action between the concrete and CFRP by epoxy adhesives that applied to the surface of concrete and CFRP surface evenly with thickness about 2 mm each side. Specification of epoxy technical data used is shown in Table 2.

Table 2. Properties of epoxy

Properties of Epoxy	
E-Modulus	12, 800 MPa
Bond Strength	> 4 MPa

FINDINGS FROM PREVIOUS RESEARCH

Nanni (2001) had compared the static behaviour of full-scale simply supported highway bridge deck panels which had strengthened in flexure using internally placed Near Surface Mounted (NSM) CFRP bars. Failure of the CFRP laminate reinforced deck spans was through a combination of rupture and peeling of the CFRP laminates. The NSM CFRP-reinforced span failed by tensile rupture of the CFRP bars. Relative to the capacity of an unstrengthened control deck, moment strength increases of 17 and 29% were reported for decks which retrofitted with externally bonded CFRP laminates and internally placed NSM CFRP bars, respectively.
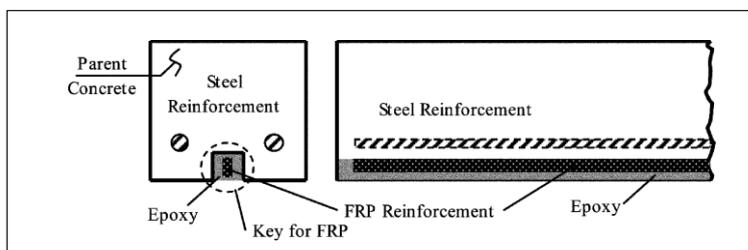

Figure 5. Concrete member strengthened in flexure with Near-Surface-Mounted FRP (Nanni, 2001)

DeLorenzis et al. (2001) had tested three steel-reinforced concrete T-beams strengthened in flexure with NSM glass FRP (GFRP) and NSM CFRP bars. The CFRP retrofitted beams experienced increases in strength of 30% (two No. 3 CFRP bars) and 44% (two No. 4 CFRP bars) over an unstrengthened control specimen. Both CFRP strengthened beams failed due to

debonding of the NSM rods. The specimen strengthened with two No. 4 GFRP bars also failed due to debonding of the NSM GFRP bars at a load 26% higher than the control specimen.

Kuriger et al. (2001) reported the pattern of rupture in the beam structure given CFRP can be divided into three types: shear failure, debonding failure, and rupture of CFRP, as shown in Figure 6. Of the three types of failure it is desired that the collapse in CFRP rupture, because then all CFRP forces can work optimally. Research showed that flexure testing of CFRP on concrete beams would result in a reduction in strain of 11.5% to 58.6% in tensile reinforcement, and reduction of 3% to 33.5% concrete press strain and reduced deflection at Beam 8% to 53.1%. The type of failure that occurs is the shear failure in the concrete, and debonding on CFRP. Brena et al. (2003), experimental test had indicated that debonding of the bottom strip from the concrete surface is the mode of failure for concrete beams strengthened CFRP. Due to FRP debonding failures, the strength utilization ratio was sometimes only 15 - 35%, depending on the cause of debonding.
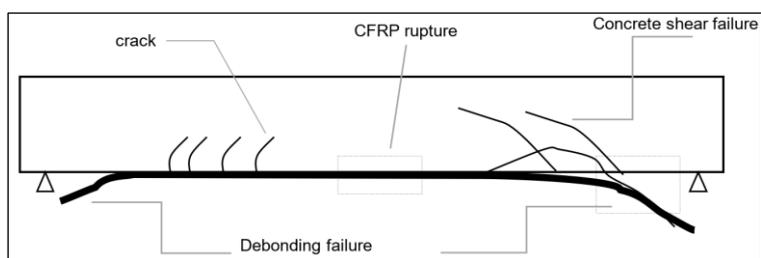

Figure 6. The mechanism of rupture in the beam given CFRP (Kuriger et al., 2001)

Aprile et al. (2001) reported that the CFRP plate attached to the bottom of the beam is calculated as a unity of structures that accepts the loads together. Such composite action can only occur because of the good bond between the two materials. The performance of bond is very important in delivering stress from concrete to CFRP. Reinforced concrete beam failure with CFRP plates always begins with debonding on the plate. Hedong and Zhishen (2005) reported that the debonding behaviour and failure mechanisms caused by different types of flexural crack distributions in FRP-strengthened R/C beams, which has not been solved so far. Using a discrete crack model for concrete crack propagation and a bilinear bond–slip relationship with softening behaviour to represent FRP–concrete interfacial behaviour, a nonlinear fracture mechanics-based finite-element analysis is performed to investigate the effects of crack spacing and interfacial parameters such as stiffness, local bond strength, and fracture energy on the initiation and propagation of the debonding and the structural performance. Hawileh et al. (2014) investigated the behaviour of reinforced concrete beams strengthened in flexure by means of different combinations of externally bonded hybrid Glass and Carbon Fibre Reinforced Polymer (GFRP/CFRP) sheets. The RC beams were tested under four point bending to study the flexural effectiveness of the proposed hybrid FRP sheets. It is observed that the increase in the load capacity of the strengthened beams ranged from 30% to 98% of the unstrengthened control RC beam depending on the combination of the CFRP/GFRP sheets.

RESEARCH METHODOLOGY

Figure 7 shows the reinforced concrete beam with simply beam is symmetrically loaded with two forces (P) as far as a from the supported, a pure bending state occurs where the

constant moment in the region between the two loads P. All test beam had a shear span to steel reinforcement-depth ratio (a/d) ≥ 3. This ratio was intentionally designed so that ultimate strength would be controlled by flexural failure and not shear failure will occur.
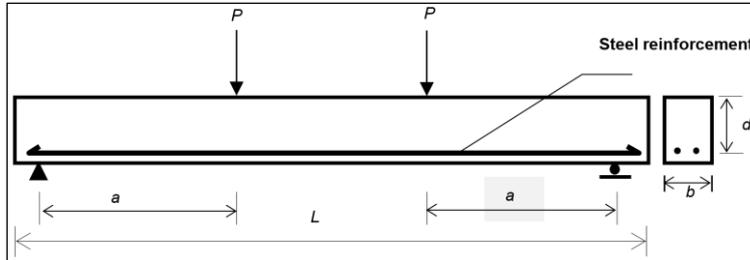
Figure 7. Experimental set-up in normal beam

The test specimens in this research were made two beams, such as the beam with steel reinforcement is called as normal beam (BN) and non-reinforced beam with CFRP as an external reinforcement is called as BF. Figure 8 shows the reinforcement detailing for BN and beam with CFRP (BF). The dimensions of concrete beams are 150 mm wide, 250 mm height and 2000 mm long. The static loading was represented by two points symmetrically with a distance of 600 mm between the point of loading and as far as 650 mm from each support.
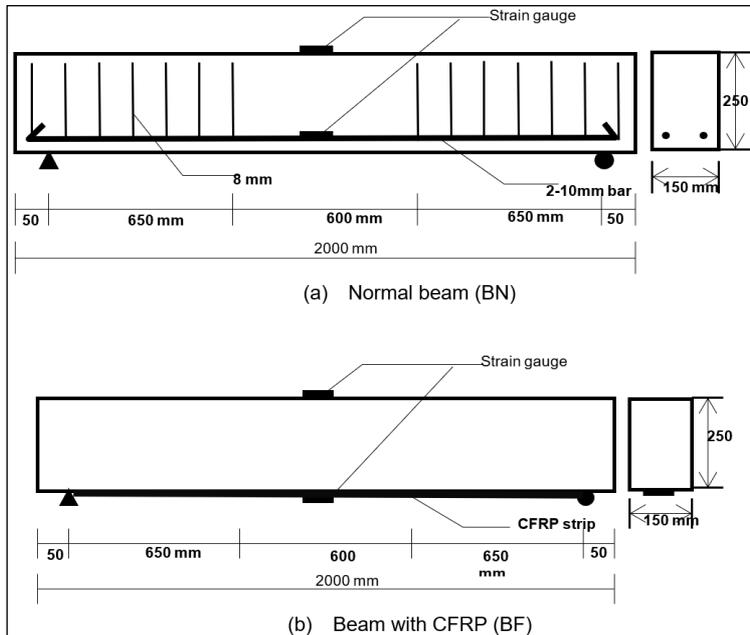
Figure 8. Reinforcement detailing in normal beam (BN) and beam with CFRP (BF)

The specimen was made from concrete with an average compressive strength (f'c) of 30 MPa. Two tensile reinforcement bars with diameter 10 mm are placed at a depth (d) = 203.5 mm of the beam. In order to measure the strain on the concrete of the specimens, a strain gauge was located on the top compression side of the centre span, to measure the tensile strain of reinforcement and CFRP one strain gauges was placed on their surface. Linear Vertical Displacement Transducers (LVDT) were installed to measure displacement that occurs at the

centre of span test beam. Figure 9 displays the experimental set-up for the normal beam and beam with CFRP. The static load, deflection and strain data were recorded using the data logger. The applied loading was stopped if the specimen has collapsed and the data logger reading of the load from the load cell cannot increase anymore.

Figure 9. Experimental set-up for the normal beam and beam with CFRP

EXPERIMENTAL RESULT

Material Properties

The reinforcing steel used in this study is deform reinforcement with a diameter of 10 mm. The result of test of tensile strength of steel obtained the yield strength value of 340.50 MPa and the ultimate tensile strength of 454 MPa. Based on the results of the compressive strength test cylinder with size 150 mm x 30 mm, tested using Universal Testing Machine (UTM). The average compressive strength of the concrete obtained 32.55 MPa greater than the compressive strength of concrete designed of 30 MPa.

Table 3. Average compressive strength of concrete

Specimen	Average Compress Concrete (MPa)
BN	34.0
BF	31.1

Flexural Strength for Normal Beam

The first crack was occurred 16 kN where the concrete entering the cracked stage and passed through the limit of its tensile strain. The tensile force that appear is bonded by the reinforcement bar with the appearance of cracks propagation in the bending area of the beam, shown at Figure 10(a) shows the load versus deflection and Figure 10(b) shows the stress versus strain relationship of BN.

Initially, the specimen test section is uncracked zone until 16 kN as shown in Figure 9(a). The cracking load P_{cr}, behaviour changes from uncracked to cracked-elastic zone. The cracked load occurs with a very small increment of deflection, meaning to say the load-deflection response in the BN beam shows rigidity of concrete beam. The strain increase in steel reinforcement at the beginning of loading to 16 kN and proving that in under uncracked stage conditions the concrete is still able to hold up the tensile forces, so the role of reinforcement bar still carrying the tensile force but with small force. As the load is increase

further, the section responded elastically until the yield strength of steel reinforcement (fy) is reached. The steel yield fy occur at 16 kN corresponds to a flattening of the load-deflection trace and stress-strain response as shown in Figure 10. When the load is increased to 36 kN, the ultimate vertical load (P_{max}) occurred by concrete crushing, and the deflection is stopped at 28.9 mm as shown in Figure 11. There were shear cracks and flexure cracks at the both of point load the compression side concrete collapse in horizontal cracking.
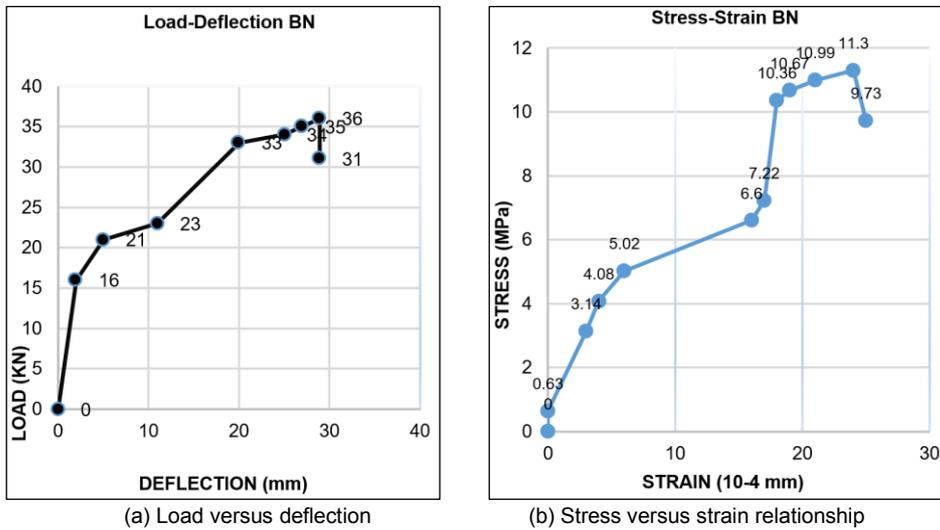

(a) Load versus deflection (b) Stress versus strain relationship

Figure 10. Load–deflection and stress–strain for normal beam (BN)

Figure 11. Normal beam failure under two points loads

Flexural Strength Beam with CFRP (BF)

The first crack is occurred at 18 kN which indicated that the concrete entering the cracked stage, passed through the limit of its tensile strain (uncracked condition). The tensile force in the beam with CFRP carried more load, it is signed with the appearance of cracks in the bending area of the beam.

Figure 12 shows that at 14 kN deflection of concrete beam occurs very small increment where the static response in the BF beam shows greater stiffness then BN beam. The load has reached maximum load at 24 kN and then decrease back until 20 kN. The maximum deflection

of concrete beam has reached at 6 mm and less ductile as compare with BN beam. After the load of 18 kN, the CFRP strain has grown larger which proves that the tensile force is fully borne by CFRP. This situation lasts until the load is almost 24 kN as shown in Figure 12. The stress-strain relationship shows there is changing from the elastic zone to plastic zone. At a load of 24 kN, CFRP is debonded at one end side, which is indicated by a reversed graph toward zero, followed by collapse of the beam. This indicates that when CFRP was separated from concrete, the beam where adhesive does not have enough capability to borne tensile force so that the beam ruptures as shown in Figure 13.
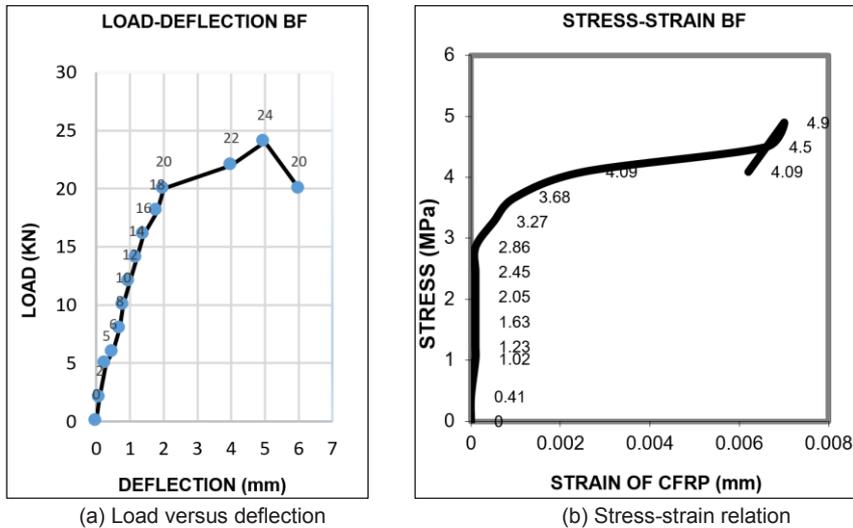

(a) Load versus deflection	(b) Stress-strain relation

Figure 12. Load–deflection and stress–strain relationship for beam with CFRP (BF)

Figure 13. Beam with CFRP failed through debonding mechanism

Comparison of Moment Capacity between Normal Beam and Beam with CFRP

From experimental results, the maximum load of the normal concrete beam (BN) reached 36 kN and BF with CFRP reached 24 kN and then these loads are used to calculate the ultimate bending moment that occurs as tabulated in Table 4.

Tabel 4. Comparison of Ultimate Moment BN and BF

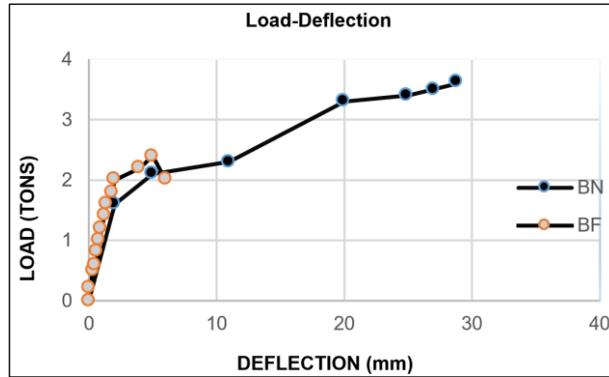| Specimen	Maximum Load (kN)		Maximum Bending (kNm)		% Different
	Experiment	Theory	Experiment	Theory	
BN	36	31	11.70	10.07	116 %
BF	24	82.5	7.80	26.11	29 %

Figure 14. Comparison between load versus deflection between BN and BF

Failure Mode

The normal concrete beam (BN) had few flexural cracks pattern with large width due to concrete compressive crushing after steel yielding as shown in Figure 15. Concrete cracking was identified in specimens at a load of about 16 kN, then propagated towards to up, after which the steel reinforcement maintains an almost linear strain increase until yielding, and until load at 36 kN then concrete crushing.
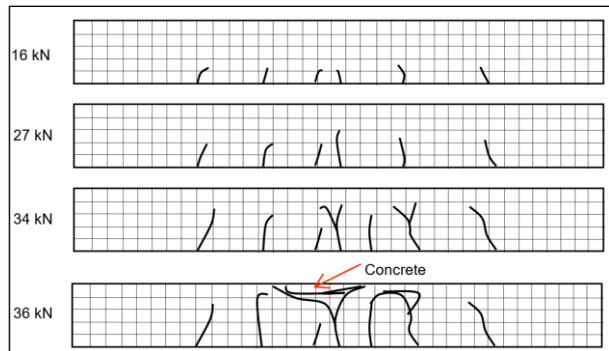

Figure 15. Cracks Pattern for normal concrete (BN)

For concrete beam with CFRP (BF), the cracks had initiated in the pure bending region of the beam at a load of 18 kN, then the cracks increased and propagated towards to up. At the load of 24 kN there was a debonding failure on CFRP had initiated at one of the support beams accompanied by a fracture. Due to the release of CFRP, the vertical crack in the concrete beam was not inhibited, so it propagated very fast towards to up and caused the concrete beam was broken, as shown in Figure 13. The cracks pattern of the normal concrete beam BN as shown in Figure 16.
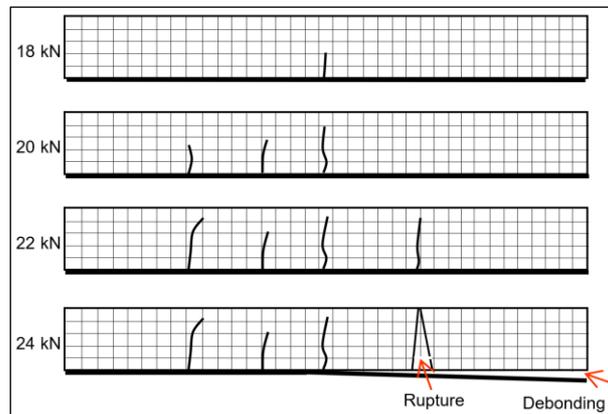
Figure 16. Cracks Pattern of BF

Effectiveness of CFRP

Based on the results from experimental work, beam with CFRP located externally show not a good performance as compared to normal beam (BN). As the load on the BF beam reaches ultimate, the CFRP strain occurs at 0.0070, thus the working tensile strength of 812.5 MPa or only 30% of maximum strength is 2800 MPa, because of debonding on CFRP before CFRP works optimally in increasing its moment capacity. Normally, CFRP is used to repaired and retrofitted the existing structure which suffered severe damage under earthquake or impact load.

DISCUSSION

The role of bond is very important in forming a composite action between concrete and CFRP. Bonds between concrete and CFRP were used based as the adhesive properties is shown in Table 2 where the bonding strength is only more than 4 MPa, the expected composite structure does not occur. Furthermore, the modulus of elasticity of epoxy used is E = 12000 MPa which is smaller than the modulus of elasticity of concrete which is 20000 MPa. There is very weak bonding between epoxy resin with the concrete surface which required better bonding between them.

The contact surface between concrete and CFRP is less widespread because it occurs on one side of the surface and not between steel reinforcement and concrete with less contact areas on the entire surface of the reinforcement. Thus, the bond required by CFRP to be a composite unit with concrete becomes less perfect and should provide better bonding for future research.

CONCLUSIONS

The following conclusions can be drawn based on the experimental and observation:

1) The position of CFRP plates as external reinforcement on the tensile fibre of the beam may inhibit the appearance of first crack of the beam as an indication of concrete tensile strain achieved. The ability of the beam to hold the load until the initial crack increase on the BF beam by 12.5% as compare with the BN beam.

2) By putting the CFRP plates as external reinforcement (BF beam) is less effective, because the bending strength decreases by 33.3% and the deflection decreases 79% as compared with BN beam. This is because the debonding failure of CFRP of the concrete beam is not able to hold the pull force that occurs, consequently beam collapses and failed due to brittle condition.

3) The collapse occurred on the test beam with the external reinforcement of CFRP is the occurrence of debonding failure such as loose bond between the concrete with CFRP and it can be said that the composite material has not been able to work optimally under static loading.

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