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Shear Behaviour of Pre-cracked Continuous Beam Repaired using Externally Bonded CFRP Strips

Noorwirdawati Ali [a]*, Abdul Aziz Abdul Samad [a], Noridah Mohamad[a], J. Jayaprakash[b]

[a]*Faculty of Civil & Environmental Engineering*
Universiti Tun Hussein Onn Malaysia
Johor, Malaysia
[b] *School of Civil Engineering*
Universiti Sains Malaysia
Pulau Pinang, Malaysia

Abstract

Shear failure usually occurs suddenly and without any warning Historically, the strengthening and repairs of existing concrete structures have been done by using conventional techniques such as externally bonded steel plates, steel or concrete jackets and external post-tensioning. However, these conventional techniques have some problems regarding their maintenance where a steel plate has the risk of corrosion due to the environment. As this problem arises, a lot of studies have been carried out to find a solution to overcome the problem. Therefore, an application of composites material has been emphasized to extend the service life of existing concrete structures. In this research, CFRP composite was used as repair material method for continuous beams. A total of five beams were fabricated and tested includes one control specimen while the other four beams were wrapped with CFRP strips. Experimental results shows that beams repaired using CFRP strips achieved higher shear capacity compared with control beam by 18% to 44%. Comparison of the experimental results with theoretical study using existing model also shows good agreement. It shows the effectiveness of CFRP strips in enhancing shear capacity of cracked continuous beam.

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Keywords: CFRP; continuous beam; repair; shear; strips.

1. Introduction

In this few decades, the use of Fibre Reinforced Polymer (FRP) as a strengthening material is a well known method in civil engineering. FRP composites have many advantages such as good corrosion resistance, light weight, high strength to weight ratio, easy to install, non conductive and resistance to the chemicals [1]. The other advantages of FRP composites are reduces field installation time by using engineered system packaging, reduces traffic delays because of the faster construction, increase reliability by pre-engineered systems, enhanced the durability and fatigue characteristics and increase the service life of the structure. Besides that, products and system enable value engineering that result in innovative and efficient installations [2]. Due to the advantages, FRP composites has been widely used in repair and strengthening method of reinforced concrete structures.

* Corresponding author. *E-mail address:*wirda@uthm.edu.my

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Past researches has shown great interest in shear and flexural strengthening on reinforced concrete structures. Flexural behaviour of cracked reinforced concrete beams can be well predicted, however the prediction of shear behaviour of reinforced concrete beams is a though task due to its complexity on shear transfer mechanism [3]. Besides that, structure that fails in shear was dangerous than flexural failure because shear failure usually occurs suddenly and without any warning [4,5and 6]. In general, shear failure is a diagonal tension failure that is brittle in nature and should be avoided [7]. Therefore, this study attempt to address on the shear repair of reinforced concrete continuous beams with parameters includes wrapping scheme and orientation of CFRP (Carbon Fiber Reinforced Polymer) strips.

2. Objective and Scope

2.1 Objective

The objectives of this study are:

i) To study the shear behavior of reinforced concrete continuous beams repaired using CFRP strips through experimental work.

ii) To compare results from experimental work with existing model.

2.2 Scope

This study was conducted with some limitation as follows:

i) This study involves an experimental work of full-scale reinforced concrete continuous beams with a size of 150mmx350mmx5800mm.

ii) All specimens were design to fail in shear with identical design detail and the same concrete compressive strength of 30N/mm^2.

iii) A total of five beams were fabricated and tested with parameters of wrapping schemes and orientation of CFRP strips.

iv) Bi-directional CFRP strips was selected for this study

3. Research Methodology

3.1 Specimen Details

A total of five beams were fabricated and tested at Heavy Structure Engineering Laboratory, Universiti Tun Hussein Onn Malaysia. Table I shows details of each specimen. Beam 1-0 was a control specimen with no wrapped with CFRP strips while the other four beams were pre-cracked prior to wrap with CFRP strips. Figure 1 and 2 shows reinforcement details and cross section of the specimen respectively.

TABLE 1: SPECIMEN DETAILS

Beam	CFRP Strips Orientation (°)	Wrapping Scheme	Loading and Strengthening Condition
Beam 1-0	-	-	-
Beam 2-1	0/90	4 sides	0kN→ 224kN→ apply CFRP & sustained 10kN load for 1 week → loading to failure
Beam 2-2	0/90	3 sides	0kN → 224kN → apply CFRP & sustained 10kN load for 1 week → loading to failure
Beam 2-3	45/135	4 sides	0kN → 224kN →apply CFRP & sustained 10kN load for 1 week→ loading to failure
Beam 2-4	45/135	3 sides	0kN → 224kN → apply CFRP & sustained 10kN load for 1 week → loading to failure

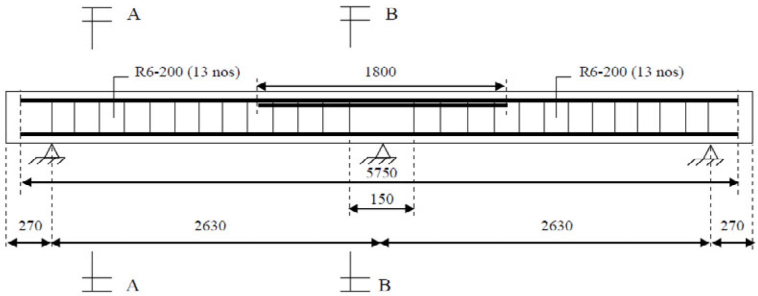

Fig. 1: Reinforcement details (unit in mm)

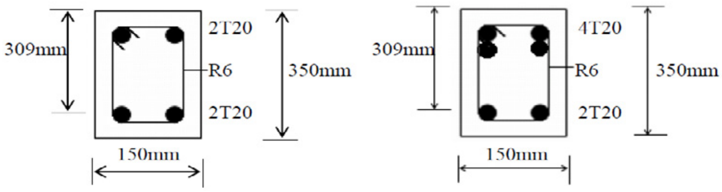

Fig. 2: Cross section of beam (unit in mm)

Beam 2-1 was a pre-crack beam with four-sides wrapped of CFRP strips. The orientation of the CFRP strips was 0/90 degree orientation. For Beam 2-2, it was pre-cracked and wrapped at three-sides of the beam and oriented at 0/90 degree orientation of CFRP strips. Another two beams were wrapped with CFRP strips oriented at 45/135 degree orientation. For Beam 2-3, it was a pre-cracked beam which wrapped at four-sides with CFRP strips while Beam 2-4 was a pre-cracked beam wrapped at three-sides with CFRP strips. Figure 3 and 4 shows wrapping scheme for beams wrapped with CFRP strips oriented at 0º/90 º and 45 º /135 º respectively.

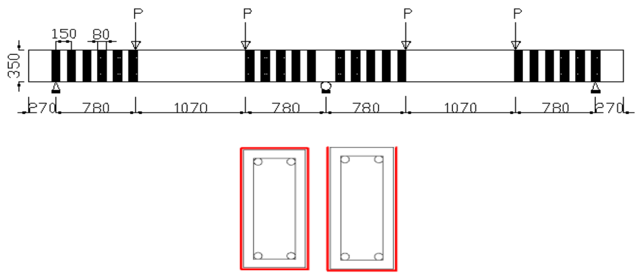

Fig. 3: Wrapping scheme for 0º/90º orientation (unit in mm

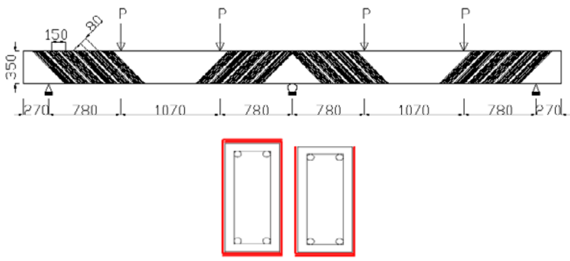

Fig. 4: Wrapping scheme for 45º/135º orientation (unit in mm)

3.2 Materials Properties

All specimens were cast using ready mix concrete with compressive strength of 30N/mm². For internal main reinforcement, it was subjected to tensile test and the measured tensile strength was 545.96Mpa. For this study, bi-directional CFRP sheet was used as external reinforcement and the properties of the CFRP sheet is shown in Table II based on manufacturer's manual sheet. On the other hand, the type of epoxy used in this study was Sikadur-330 and the properties of Sikadur-330 are shown in Table III.

Table 2 Properties of CFRP sheet (Sika Wrap®- 160 BI C/15)[8]

Density	1.75 g/cm³
Tensile strength	3'800 N/mm² (nominal)
Tensile E-modulus	230'000 N/mm² (nominal)
Elongation at break	1.5% (nominal)

Table 3 Properties of epoxy (Sikadur-330)[9]

Elongation at break	0.9 %
Flexural E-modulus	3800 N/mm²
Density	1.3 Kg/L ± 0.1 Kg/L
Tensile strength	30N/mm²

4. Experimental Results

4.1 Ultimate Load, Modes of Failure and Crack Pattern

Table IV shows the experimental results of the beams tested under flexural load. It presents the data of first crack load, ultimate load, contribution of CFRP to the shear capacity and modes of failure of the beam.

Table 4 Experimental result

Beam	**Experimental Results**				
	First Crack Load (kN)	**Ultimate Load (kN)**	**Shear Force (kN)**	**Contribution of CFRP (kN)**	**Modes of Failure**
Beam 1-0	96	286.10	93.70	-	Shear
Beam 2-1	100	373.70	122.39	87.60	Shear & CFRP rupture
Beam 2-2	96	338.08	110.72	51.98	Shear, CFRP rupture & debonding
Beam 2-3	112	411.25	134.68	125.15	Shear & CFRP rupture
Beam 2-4	80	380.74	124.69	94.64	Shear, CFRP rupture & debonding

Beam 1-0

The control beam which was not strengthened with CFRP strips was tested and loaded till failure. It was observed that flexural cracks appeared initially at the bottom part of mid-span at load 96kN which was about 34% of the ultimate load of the beam. Shear cracks occurred later at load 204kN (at about 71% of the ultimate load). Further new cracks developed at the tension zone of the mid-span area during the occurrence of the shear crack. The flexural (or vertical) cracks widened and propagated to the compression zone of the beam as load was increased.

The first shear crack (or diagonal crack) appeared initially at the bottom part of the middle support area. The crack widened and propagated to the point load in a diagonal direction as load increased. Other shear cracks were also observed propagated in the same direction as the first diagonal crack. As the load increases, the shear cracks widened and propagated until the beam fails due to shear at a load of 286.10kN. Figure 5 shows Beam 1-0 fails in shear. Several vertical cracks were also observed at the negative moment region (middle support area). From observation during beam test, vertical cracks in the flexural zone stopped propagating much earlier than the cracks in the shear span. As expected, the beam eventually failed in shear rather than in flexure as the specimen was designed to have insufficient stirrups in comparison to the longitudinal reinforcements.

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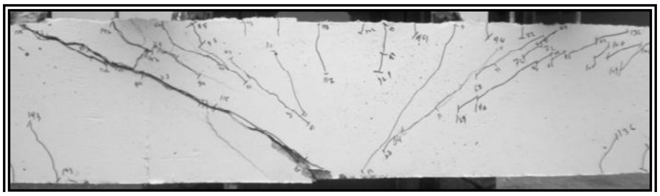


Figure 5: Shear failure of Beam 1-0 at load 286.10kN (shear force 93.70kN)

Beam 2-1

Beam 2-1 is a pre-cracked beam, wrapped at four sides of the beam with CFRP strips oriented at 0º/90º. The beam was pre-loaded to 224kN to develop shear cracks prior to CFRP wrapping. After pre-loaded, the beam was unloaded to zero. At the pre-cracking phase (first phase), flexural cracks and diagonal cracks initially appeared at a load level of 100kN and 212kN respectively. More vertical cracks were then recorded within the area between the two point loads. At this stage, the flexural cracks appeared more than the diagonal crack within the shear span. Cracks were also observed within the negative moment (the area of middle support). The cracks started from the top of the beam and widened to the compression zone which is the bottom part of the beam. At the outer shear span, several diagonal cracks were also observed.

The beam was then strengthened at four sides of the beam with CFRP strips. It was later sustained with 10kN load for one week (second phase). After one week, the beam was loaded again up to failure. Failure of the beam occurred at a total applied load of 373.7kN due to the shear with rupture of CFRP strips along the shear crack. It shows an increase of 30.62% of the shear capacity compared with control beam (Beam 1-0) and slightly lower shear capacity than initially strengthened beam C2.5-UA-V with 2.09% different.

During the loading (third phase), the first crack appeared after repaired with CFRP was recorded at the area between the point load. The crack was an extended crack from pre-crack phase. For most of the earlier existed cracks from the first phase of loading, it extended further towards the compression zone within the mid-span area. As the load increases, new cracks began to appear at the tension zone which widened and propagated to the compression zone of the beam. At negative moment region, the existing cracks extended and move downwards at higher load than the cracks at mid-span area. New cracks were also observed at the negative moment region which appeared at concrete surface between CFRP strips at upper beam area and moves downwards to the compression zone. However, at failure, the cracks did not pass one third of height of the beam where some of it was recorded to stop when it reached CFRP.

As for diagonal cracks, the existing cracks extended and widened along the shear span. As the load increases, new diagonal cracks were observed to be appeared at both inner shear span and outer shear span. At failure, a diagonal crack was clearly seen along the critical shear span with rupture of all five CFRP strips as shown in Figure 6. It was also observed that more diagonal and vertical cracks appeared at the tension zone of the negative moment region. For this beam, a broke of stirrups was also observed as shown in Figure 7. The stirrup that broke was the second stirrups closer to the middle support.

Fig. 6.: Shear failure of Beam 2-1 at load 373.70kN (shear force 122.39kN)

Fig. 7. Stirrup failure of Beam 2-1 at load 373.70kN (shear force 122.39kN)

Beam 2-2

Beam 2-2 is a pre-cracked beam, wrapped at three sides of the beam with CFRP strips oriented at 0º/90º. The beam was loaded with three phases of loading as Beam 2-1. The first phase was the pre-load phase, the second phase was sustained the beam with 10kN load and the third phase was loading to failure. For this beam, at pre-cracked phase, flexural crack initially appeared at a load of 96kN, which is 28.4% of the ultimate load of the beam. It occurred within the area between the point load where it originated from the tension zone and propagated to the compression zone. As the load increases, more flexural cracks were observed. The first diagonal shear crack was observed at the middle of the inner shear span at a load of 196kN, which is around 57.97% from the ultimate load of the beam. Vertical cracks were also observed at the tension zone of the negative moment area which moves downwards to the lower part of the beam. When the load achieved 224kN, the load was stopped and unloaded to zero. The beam was then repaired with CFRP strips.

After repaired with CFRP strips, the beam was loaded to failure where the ultimate load achieved was 338.08kN. The mode of failure for this beam was shear with CFRP strips rupture and debonding of the CFRP strips from the concrete surface. Figure 8 and 9 shows the cracks of the beam at failure. Figure 9 shows the top view of the beam where the cracks were extended along the concrete covers.

Fig. 8. Shear failure of Beam 2-2 at load 338.08kN (shear force 110.72kN)

Fig. 9. Crushing of concrete (top-side view) of Beam 2-2

The increment of shear capacity for this beam was 18.16% compared with control beam (Beam 1-0). It was the lowest increment compared with the other beams. This is due to its condition as a pre-cracked beam and wrapped at three sides of the beam with CFRP strips oriented at 0º/90º orientation. From the observation on the crack pattern, it was observed that for four-sides wrapped beams, the diagonal crack occurred throughout the inner shear span from the bottom of the middle support to the location of the applied load. However, for three-sides wrapped beams, the diagonal crack was shorter than the four sides wrapped beams.

Beam 2-3

Beam 2-3 is a pre-cracked beam, wrapped at four sides of the beam with CFRP strips oriented at 45°/135°. It was loaded as the previous pre-cracked beams Beam 2-1 and Beam 2-2. From the observation on the pre-cracked phase, no crack was detected at the beam until at a load of 112kN or 27.2% of the ultimate load of the beam. At this level, a flexural crack appeared within the area between the two point loads. On the other hand, diagonal crack initially appeared at near the middle of inner shear span at a load of 212kN or 51.6% from the ultimate load of the beam. As the load increases, more flexural cracks appeared within the same area with similar behavior. It originated from the tension zone and moves towards the compression zone of the beam. At both shear spans, more new diagonal cracks were also observed. However, at the critical shear span, more cracks appeared compared to the outer shear span. The diagonal crack mostly appeared at the upper zone of the beam (tension zone) of negative moment region.

After repaired with CFRP strips, the beam was then loaded to failure and fails at a load of 411.25kN with shear and CFRP rupture failure modes as shown in Figure 10. As the load increases, most of the existing diagonal cracks propagated further to the applied load. However, for flexural cracks at the area between the two point loads, most of the cracks from the pre-crack phase did not extended far although the load was increased until failure. For this beam, it shows an increase of about 43.74% of shear capacity over the control beam (Beam 1-0). Beam with CFRP strips oriented at 45º/135º orientation resulted in higher shear resistance than 0º/90º orientation, where Beam 2-3 gains higher shear capacity of 13.12% compared with Beam 2-1.

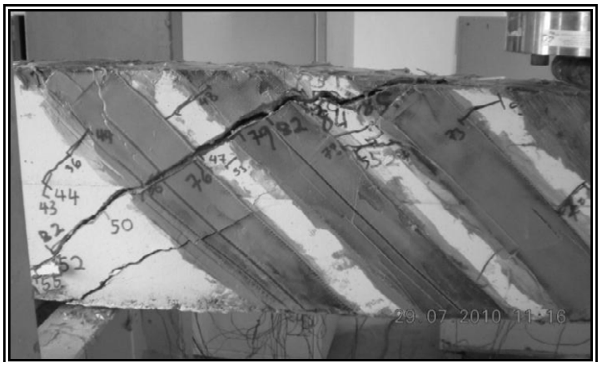


Fig. 10: Shear failure of Beam 2-3 at load 411.25kN (shear force 134.68kN)

Beam 2-4

Beam 2-4 is a pre-cracked beam, wrapped at three sides of the beam with CFRP strips oriented at 45°/135°. The loading history was similar to the other pre-cracked beams. At pre-cracked phase, flexural crack initially appeared at a load of 80kN or 21% from the ultimate load of the beam. On the other hand, the first diagonal crack was observed at a load of 180kN or 47.3% from the ultimate load of the beam. As the other previous beams, without CFRP, the crack pattern of the pre-cracked phase shows that flexural or vertical cracks occurred within the area between the two point loads. For diagonal cracks, it occurred at the shear span which is the area between point load and support. It was also observed that flexural cracks appeared at tension zone on the negative moment region.

The crack beam was then repaired with CFRP strips. After one week, it was loaded again up to failure. As the load increases, cracks started to propagate from the existing cracks at the pre-cracked phase. The existing diagonal crack became wider and propagated through the shear span until the beam reached its ultimate load. The beam then suddenly fails and CFRP rupture can be observed to occur. It was also observed that cracks at the beam with CFRP strips oriented at 45º/135º was less than beam with 0º/90º orientation of CFRP strips.

The ultimate load achieved for this beam was 380.74kN with the mode of failure by shear with CFRP rupture and debonding of CFRP strips from the concrete surface as shown in Figure 11. The increment of the shear capacity was about 33.07% from the shear capacity of the control beam (Beam 1-0). It decreased at about 10.67% compared with Beam 2-3 (same orientation but wrapped at four-sides of the beam) but increased at about 14.91% compared with Beam 2-2 (0º/90º degree orientation wrapped at three sides of the beam).

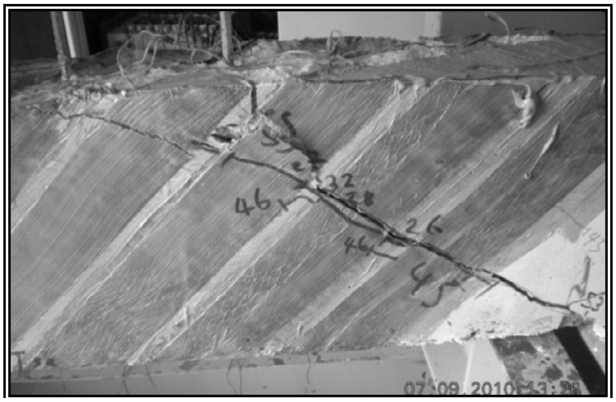


Fig. 11: Shear failure of Beam 2-4 at load 380.74kN (shear force 124.69kN)

4.2 Shear Force-Deflection (V-Δ) Profile

Table V below shows the maximum deflection achieved in each beams. Since there were two spans involved, the maximum deflection in the table was the maximum deflection recorded at span that fails (weaker span). The shear force – deflection curves were also based on the data obtained from the weaker span. The highest deflection recorded was Beam 2-3 at 13.14mm while the lowest deflection was Beam 2-2 at 10.08mm.

Table 5: Experimental result

Beam	Ultimate Load (kN)	Shear Force (kN)	Maximum Deflection (mm)
Beam 1-0	286.10	93.70	10.87
Beam 2-1	373.70	122.39	10.85
Beam 2-2	338.08	110.72	10.08
Beam 2-3	411.25	134.68	13.14
Beam 2-4	380.74	124.69	11.29

Figure 12 shows the shear force versus mid-span deflection (V-Δ) of all beams. It can be observed that all beams exhibit almost similar behavior except for Beam 2-4 where the curve of the beam was the less steep at the beginning of the testing and at shear force of around 20kN to 100kN, the slope of the curve change to the steepest slope amongst all beams. Beyond that load until failure, the slope become less steep where the slope was almost similar with the other pre-cracked beams. This behaviour occurred because of the pre-cracked phase where the beam might be over pre-cracked which lead to the weak behaviour at the beginning of the testing.

The shear force-deflection profile for control beams shows linear elastic behaviour at the beginning of the testing until it reached one point where the slope of the curve started to change due to the development of cracks on the beam. It then started to behave non-linear with more cracks were observed until failure. The shear force – deflection behaviour for control beams acted as expected for a reinforced concrete beam.

For Beam 2-1, at the beginning of the loading process, the curves of Beam 1-0 and Beam 2-1was close to each other with only small different between them. However, at shear force of about 55kN, it can be seen that the deflection of control beam was higher than Beam 2-1. The maximum deflection achieved for Beam 2-1 was 10.85mm where it was lower than control beam for only 0.015mm. This indicated that although the beam was pre-cracked before wrap with CFRP strips, it can still achieved higher load and shear force with lower deflection compared with the control beam. The same behavior was observed for Beam 2-2. Beam 2-3 recorded maximum deflection of 13.135mm which is an increase for about 2.27mm compared with control beam. Although the percent of increase of the deflection was about 20.89%, the beam reached shear force of about 43.74% higher than control beam. Although the deflection was higher than control beam, the allowable deflection was still lower than the permissible deflection.

For comparison of Beam 2-1 and Beam 2-3, it can be seen that Beam 2-3 shows slightly stiffer behaviour compared with Beam 2-1 from the beginning of the testing until failure of Beam 2-1, at the same load level, Beam 2-3 has recorded less displacement compared with Beam 2-1. It shows that 45º/135º orientation of CFRP strips shows stiffer behavior than 0º/90º orientation.

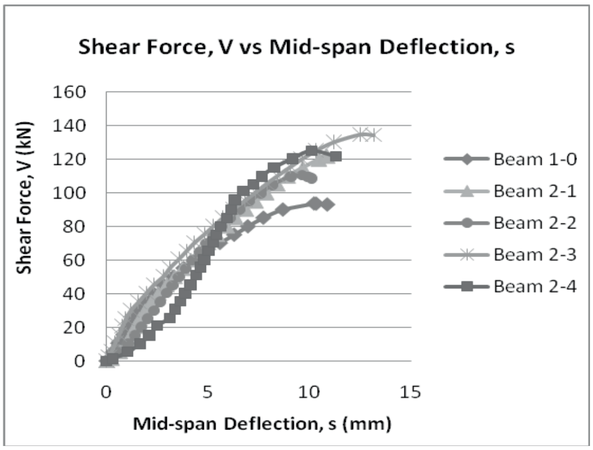


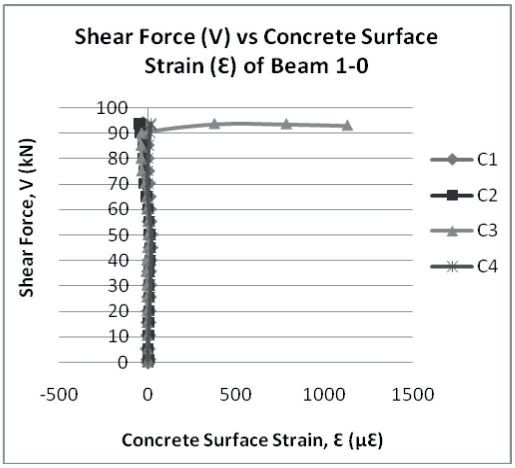
Fig.12. Shear Force – Deflection Behaviour

4.3 Shear Force – Strain Relationship

Figure 13 shows shear force versus strain at concrete surface of Beam 1-0. Strain gauge at C3 attained the highest strain among all strain gauges due to a diagonal crack located nearby the strain gauge. It recorded a strain of 1130.52μɛ where it still in concrete strain limit. The measured strain increase suddenly just before failure at shear force of 93kN. This is due to the sudden failure of the beam.

The graph of shear force versus strain at concrete surface and CFRP of Beam 2-1 was as shown in Figure 14. For strain at concrete surface, it can be clearly seen that C3 attained the highest strain of 2864.79μɛ while the other strain gauges recorded lower strain which represent as linear line until failure. For strain at CFRP strips, F3 attained the highest strain at 9961.50μɛ or 66% from the ultimate strain of the CFRP. It started to show significant elongation at shear force of around 80kN. F2 and F4 also showed an elongation of CFRP strips and it started to behave non-linear at earlier shear force of around 40kN. All strains of concrete surface were within the concrete strain limit while the strains of CFRP were also within the CFRP strain limit.

Figure 15 shows shear force versus strain at concrete surface and CFRP strips of Beam 2-2. From the figure, it can be observed that strain at CFRP was higher than strain at concrete surface. The maximum strain recorded at concrete surface was C3 with the strain of 2774.65μɛ while the maximum strain recorded at CFRP strip was F4 with the strain of 5102.35μɛ. F2, F3 and F4 shows nearly zero strain at the beginning of the loading and then increased gradually until failure. Just before failure, strain gauge F4 showed a decreased of strain when ruptured of CFRP strip occurred.



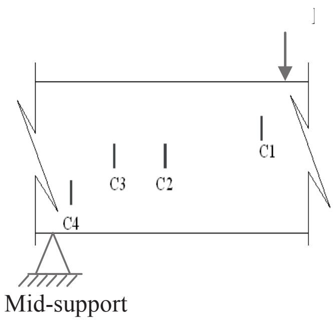


Fig.13. Shear force versus strain at concrete surface of Beam 1-0

In Figure 16, a relationship of shear force – strain at concrete surface and CFRP strips of Beam 2-3 can be observed. C3 and F3 showed a significant increased of strain at concrete surface and CFRP respectively. A maximum strain of 2283.57μɛ was recorded at strain gauge C3 while a maximum strain of 8756.94μɛ was recorded at strain gauge F3. The other strain gauges showed a nearly zero value might be due to the strain gauge not located nearby the cracks on the beam.

Figure 17 shows shear force versus strain at concrete surface and CFRP strips of Beam 2-4. For concrete surface strain, as the other previous beams, only one of the strain gauge recorded an obvious increase of strain. For this beam, strain gauge C3 recorded the highest strain of concrete surface at 1160.56με. On the other hand, for strain of CFRP strips, all strain gauge showed an increased of strain with more complex behavior when dissimilar trend was observed in each strain gauge. F1 showed a gradually increased until failure while F2 while F2 starts to behave non-linear as early as 20kN. For F3, it also starts to behave non-linear at shear force of 20kN. After shear force 20kN, it gradually increased until at shear force of around 50kN, it then gradually decreased until at almost failure or around 120kN, a sudden decreased occurred. For F4, at shear force of 20kN, a sudden increased of strain occurs and it recorded the highest strain among all strain of CFRP strips at 6107.04με or 41% from the ultimate strain of CFRP.

The elongation of CFRP shows an effectiveness of the CFRP in resisted the shear force of the beam. The magnitude of the strain also greatly depends on the location of strain gauge with respect to cracks. It can also be observed that with higher strain at concrete surface, the fiber of CFRP also stressed in order to resist the shear force and restrained the widening of the shear cracks.

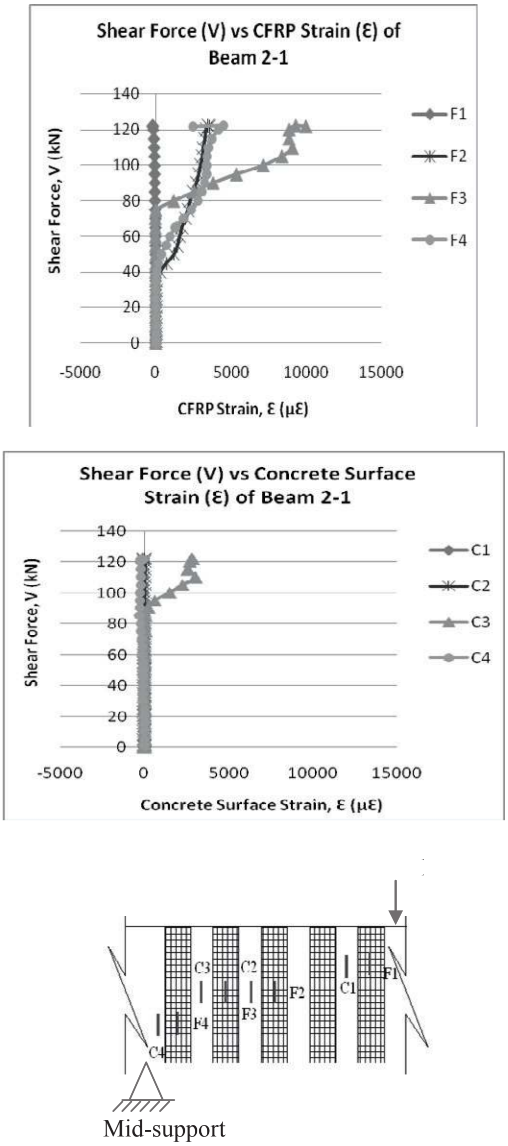


Fig. 14. Shear force versus strain at concrete surface and CFRP strips of Beam 2-1

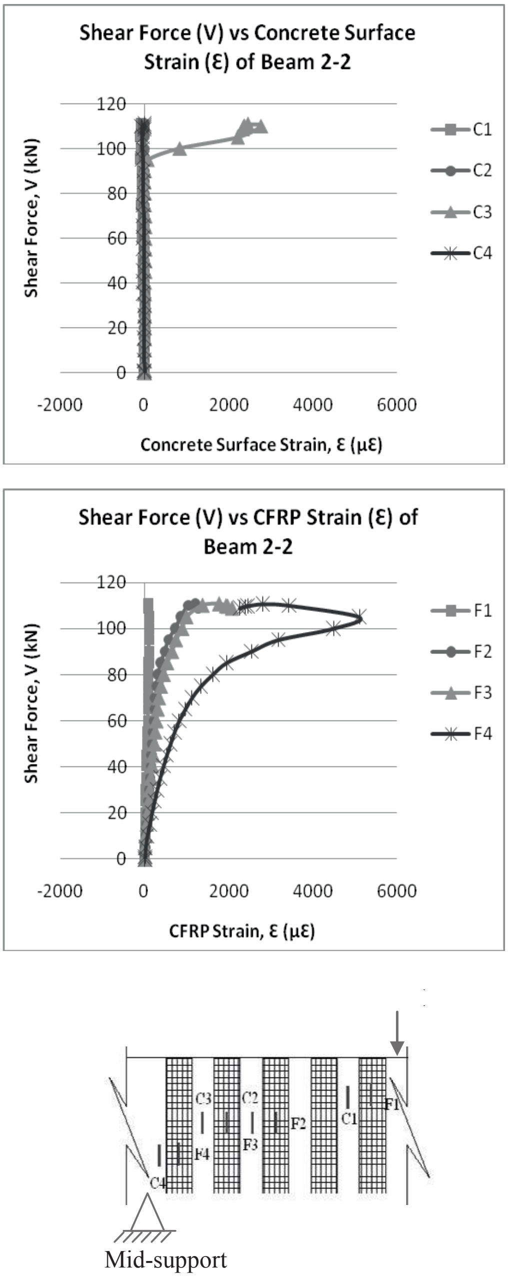


Fig. 15. Shear force versus strain at concrete surface and CFRP strips of Beam 2-2

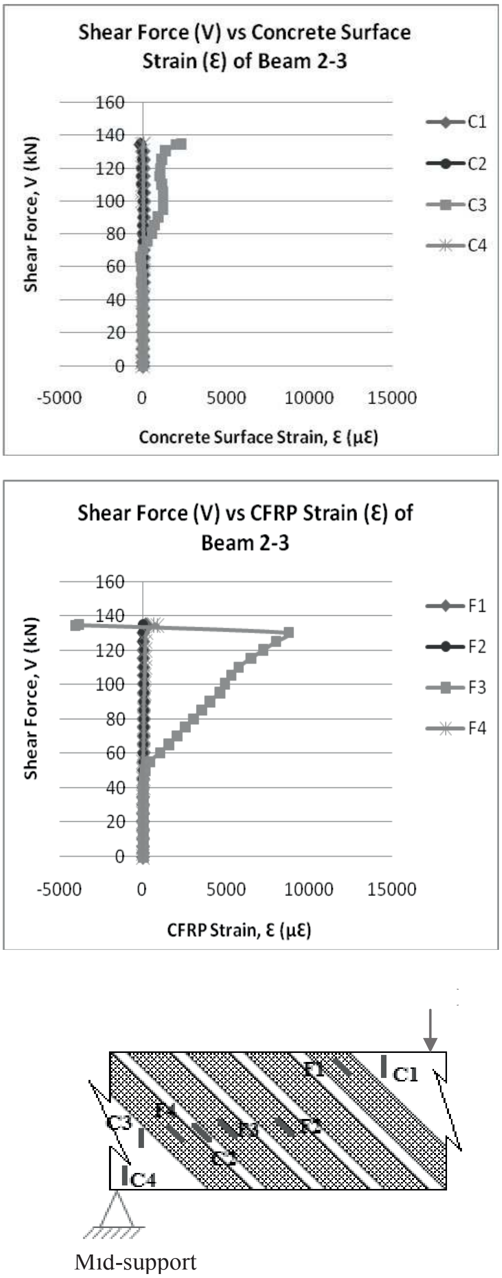


Fig.16. Shear force versus strain at concrete surface and CFRP strips of Beam 2-3

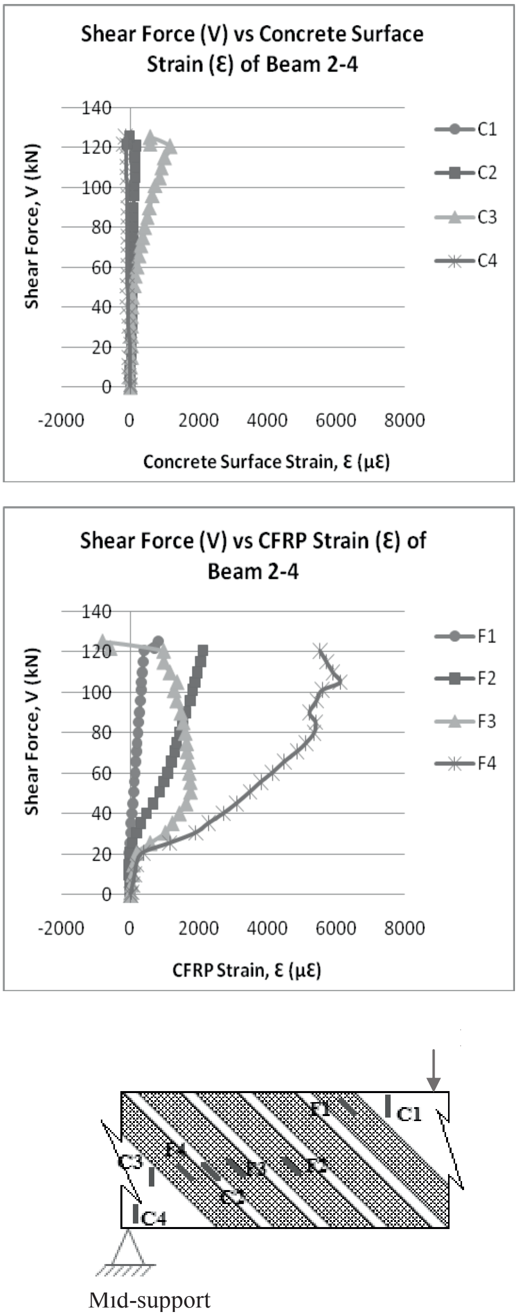


Fig. 17. Shear force versus strain at concrete surface and CFRP strips of Beam 2-4

5. Theoretical Comparison

Table VI to VIII shows the comparison of shear capacity contributed by CFRP strips (V_f) between theoretical and experimental analysis using ACI, Khalifa & Nanni and *fib* model. For ACI and Khalifa & Nanni models, all beam recorded less 20% difference except for Beam 2-2. Meanwhile, theoretical value using fib model higher more than 30% compared with the experimental results. Comparison with all model shows that the theoretical equation using ACI 440 and Khalifa & Nanni model gave conservative value of shear capacity contributed by CFRP (V_f) compared to value obtained from experiment.

Table 6 Comparison of V_f between experimental results and theoretical value using ACI 440 model

Beam	**Theoretical Value (ACI 440)[10]**		**Experimental Results**	**Difference**	$\frac{V_{f,exp}}{V_{f,theory}}$
	V_f **(kN)**	ΦV_f **(kN)**	V_f **(kN)**	**%**	
Beam 1-0	-	-	-	-	-
Beam 2-1	27.90	26.51	28.69	-8.22	1.08
Beam 2-2	27.90	23.72	17.02	28.24	0.72
Beam 2-3	39.45	37.48	40.98	-9.24	1.09
Beam 2-4	39.45	33.53	30.98	7.61	0.92

Table 7 Comparison of V_f between experimental results and theoretical value using khalifa & nanni model

Beam	**Theoretical Value (Khalifa & Nanni Model)[11]**		**Experimental Results**	**Difference**	$\frac{V_{f,exp}}{V_{f,theory}}$
	V_f **(kN)**	ΦV_f **(kN)**	V_f **(kN)**	**%**	
Beam 1-0	-	-	-	-	-
Beam 2-1	46.09	32.26	28.69	11.07	0.89
Beam 2-2	36.12	25.28	17.02	32.67	0.67
Beam 2-3	65.18	45.63	40.98	10.19	0.90
Beam 2-4	51.09	35.76	30.98	13.37	0.87

Table 8 Comparison of V_f between experimental results and theoretical value using FIB model

Beam	**Theoretical Value (*fib* model)[12]**		**Experimental Results**	**Difference**	$\frac{V_{f,exp}}{V_{f,theory}}$
	V_f **(kN)**	ΦV_f **(kN)**	V_f **(kN)**	**%**	
Beam 1-0	-	-	-	-	-
Beam 2-1	53.78	43.03	28.69	33.33	0.67
Beam 2-2	39.19	31.35	17.02	45.71	0.54
Beam 2-3	76.06	60.85	40.98	32.65	0.67
Beam 2-4	55.42	44.33	30.98	30.12	0.70

6. Conclusion

From the observation on the behavior of the beams during testing, loading history, ultimate load, crack pattern and modes of failure, there are some important point that can be deduced and summarized. Furthermore, graphs plotted gave significant information on the behavior of deflection, strain at concrete surface and CFRP strips. It can be concluded that:

I. The mode of failure of beams wrapped at four sides of the beam was shear with rupture of the CFRP strips. For beams wrapped at three sides of the beam, it fails in shear with CFRP rupture as well as debonding of CFRP strips from concrete surface.

II. Fewer or less cracks has been observed to appear for beams with CFRP strips oriented at 45º/135º compared with beams with CFRP strips oriented at 0º/90º. This shows that 45º/135º orientation of CFRP strips was effective in control the crack propagation on the beam.

III. The presence of CFRP strips with higher modulus of elasticity was found to be effective in enhancing the stiffness of repaired beams.

IV. Although with the presence of CFRP strips wrapped around the beams, the deflection of Beam 2-3 and Beam 2-4 was recorded to be higher than the deflection of control beam. However, higher shear force was observed to be achieved by the repaired beams compared with control beam. Higher deflection could be preventing by placing CFRP sheet throughout the bottom of the beam. However, the allowable deflection was still lower than the permissable deflection.

V. Beams with CFRP strips oriented at 45º/135º shows higher stiffness than beams oriented with CFRP strips at 0º/90º.

VI. The elongation of CFRP shows an effectiveness of the CFRP in resisted the shear force of the beam. The magnitude of the strain depends on the location of strain gauge with respect to cracks. It can also be observed that with higher strain at concrete surface, the fiber of CFRP also stressed in order to resist the shear force and restrained the widening of the shear cracks.

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