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Experimental Investigation on Shear Resistance Behaviour of RC Precracked and Non-Precracked T-Beams using Discrete CFRP Strips

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Abstract

The exploitation of Fibre Reinforced Polymer (FRP) composites as external reinforcement is an evergreen technique for improving the structural performance of the existing Reinforced Concrete (RC) structures. This paper presents a experimental investigation on shear strengthening capacity and modes of failure of precracked and non-precracked RC beams bonded externally with bi-directional Carbon Fibre Reinforced Polymer (CFRP) fabric strips. Twelve RC T- beams were fabricated with different internal longitudinal and shear reinforcements. These beams were subjected to two types of loading; namely three point and four point bending systems. The beams were classified into three categories namely control, precracked-repaired, and initially strengthened (i.e. non-precracked) beams. Prior to the application of CFRP shear reinforcement, the precracked-repaired beams were partially loaded to develop shear cracks along the shear spans, whereas the initially strengthened beams were strengthened with CFRP reinforcement without the application of any preloading. The overall increase in shear enhancement of the precracked-repaired and initially strengthened beams ranged between 13% and 61% greater over their control beams. It was found that the application of CFRP strips in the precracked-repaired beams attained better performance as compared to the initially strengthened beams.

Keywords: Beam, CFRP, Shear, Strips.

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1. INTRODUCTION

Excluding culverts there are about 2200 bridges on Federal Roads in Malaysia [1]. The highway flyover along the Middle Ring Road 2 (MRR2) in Kepong (Malaysia) has been seriously damaged due to the formation of cracks in the piers and girders. In Malaysia, the construction industry has been facing serious problems such as corrosion of reinforcement, improper planning, inadequate awareness among the engineers, improper maintenance, poor construction, unskilled labours, and design faults [2]. Having this problem, the future of the existing structures is questionable as most of them mainly, flyover, bridges, and high-rise buildings were constructed using RC systems. There are only two viable options to resolve the problem; one is to replace the structure completely and another option is strengthening and repairing the existing structures. Complete replacement is not a realistic alternative because of financial constraint and waste of natural resources. However, strengthening or repairing seems to be promising and feasible to eliminate this problem. To resolve such problems, use of Advanced Fibre Reinforced Polymer (FRP) composite material has been emphasised recently as an alternative solution to extend the service life of existing concrete structures and bridges.

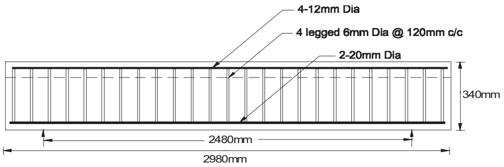
Advanced Fibre Reinforced Polymer (FRP) composite is an innovative material for strengthening or upgrading reinforced concrete elements such as beams, columns, walls, and slabs. The external strengthening technique has been attracted the attention of researchers [3, 4, 5, 6, 7, 8 and 9] due to its major characteristics include high strength to weight ratio, high stiffness, light weight, easy handling, corrosion resistance, and chemicals. Shear strengthening mechanism of RC beams is more complex when compared to the flexural behaviour of strengthened beams. The reason may be due to the nature of shear failure. When a strengthening material added to the concrete surface, the mechanism will be more complicated. The need for shear strengthening is required when the reinforced concrete beams found to be deficient in shear or the shear capacity of RC beams falls below its flexural capacity after flexural strengthening [10]. It may also occur due to the increase of service load, design or construction faults, old design codes, and change in the use of structure [11 and 12].

The overall objective of this paper was to investigate both the shear strengthening capacity and modes of failure of RC precracked-repaired and initially strengthened T-beams bonded externally with bi-directional Carbon Fibre Reinforced Polymer (CFRP) strips. These beams were tested in the presence of both the internal and external shear reinforcements.

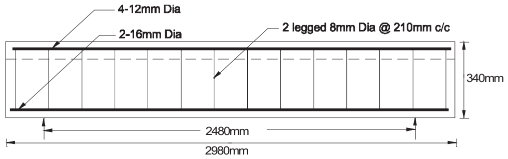
2. EXPERIMENTAL PROGRAM

2.1 Fabrication

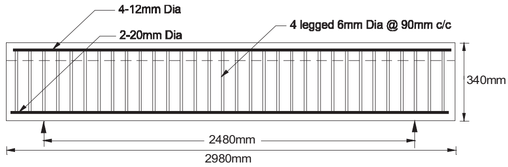
This experimental program consisted of twelve full-scale RC T-beams of span 2980 were fabricated in the Laboratory Environment. These beams were segmented into four categories namely TT1, TS1, TT2, and TS2 with respect to the longitudinal tensile and transverse shear reinforcements. The flange cross section of these beams was of 400mm width by 100mm depth with web thickness of 120mm. The overall depth of T-beams was of 340mm. The amount of tensile reinforcement in categories TT1 and TS1 were similar to that of the categories TT2 and TS2. However, the transverse reinforcement of the specimens in categories TT1 & TS1 and TT2 & TS2 were not identical as tensile steel reinforcement. The internal tensile and shear reinforcement details of RC T-beams are shown in Figure 1.



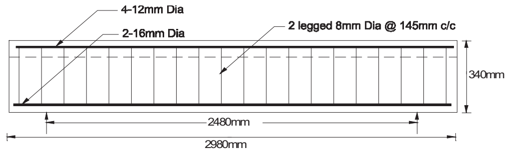
1(a) Category TT1



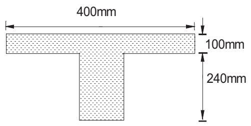
1(b) Category TS1



1(c) Category TT2



1(d) Category TS2



1(e) Cross-Section

Fig. 1: Internal reinforcement details of RC beams in categories TT1, TS1, TT2, and TS2

3. MATERIAL PROPERTIES

Concrete: All beams used ready mix concrete with a grade of 30MPa.

Steel: The average yield stress values of the tensile rebars 16mm and 20mm were of 311.22MPa and 554.17MPa, respectively. However the average yield strength of transversal reinforcement 8mm and 6mm mild steel bars was 620.31MPa and 660.82MPa, respectively.

CFRP Fabric Reinforcement and Epoxy Resin: Bi-Directional CFRP fabric strips were used as external shear reinforcement. Sikadur 330 epoxy was used for bonding CFRP fabric strips with the concrete stratum. Table 1 illustrates the properties of bi-directional CFRP fabrics and Sikadur 330 based on the Sika Manufacturer's manual sheet [13].

Table 1: Material properties of carbon fabrics and epoxy resin (Sika Manufacturer's manual)

	CFRP Fabrics	Epoxy Resin (Sikadur330)
Fibre orientation	0/90 (Bi-Directional)	---
Thickness (mm)	0.09	---
Tensile strength (MPa)	3,800	30
Modulus of Elasticity (MPa)	230,000	3,800
Adhesive Strength (MPa)	---	4

Table 2: Internal and external reinforcements details of T-beams

CATEGORy	SPECIMENS	fc, MPa	Internal Steel Rebars		CFRP Reinforcement	
			Tensile	Stirrup	Width and spacing	Orien-tation
TT1	TT1a	27.4	2 Nos. 20mm rebars (ρ= 1.69%)	4 legged 6mm @ 120mm c/c	---	---
	TT1-1 (P-R)				80mm U-strips @ 150mm c/c	0/90 degree
	TT1-1I (I)					
TS1	TS1a	16.7	2 Nos. 16mm rebars (ρ= 1.08%)	2 legged 8mm @ 210mm c/c	---	---
	TS1-1 (P-R)				80mm U-strips @ 150mm c/c	0/90 degree
	TS1-1I (I)					
TT2	TT2a	27.4	2 Nos. 20mm rebars (ρ= 1.69%)	4 legged 6mm @ 90mm c/c	---	---
	TT2-2 (P-R)				80mm Inclined L-strips @ 150mm c/c	45/135 degree
	TT2-2I (I)					
TS2	TS2a	16.7	2 Nos. 16mm rebars (ρ= 1.08%)	2 legged 8mm @ 145mm c/c	---	
	TS2-1 (P-R)				80mm U-strips @ 150mm c/c	0/90 degree
	TS2-1I (I)					

*ρ=internal tensile reinforcement ratio; P-R – Precracked–Repaired Beam; I – Initially strengthened beam

4. TEST METHODOLOGY

The categories TT1 & TS1 and TT2 & TS2 were subjected to three point and four point bending systems, respectively. One Linear Variable Displacement Transducer (LVDT) was placed at the centre of the beam to measure the mid displacement. The control beam was loaded at equal intervals to develop precracks followed by unloading to zero load, then reloaded to failure. The test procedure of the precracked-repaired specimen consisted of two phases. In the first phase, the beam was loaded for two cycles in order to develop precracks and the second phase of loading was conducted after the application of discrete CFRP strips. On the other hand, the initially strengthened specimens were strengthened without any preloading or precracks. After strengthening, the beams were loaded at equal intervals till the failure. During the application of loading, the modes of failure, ultimate failure load, mid displacement, and cracking pattern were observed.

5. RESULTS AND DISCUSSIONS

5.1 Ultimate Enhancement and Modes of Failure

Categories TT1 and TS1: These categories were subjected to four point bending system with shear span to effective depth ratio of 2.5. The first flexural crack in the control beam was observed at a load of approximately 42kN in the constant moment zone, whereas the shear cracks were emerged in close proximity to the middle of the shear span when the applied load reached approximately at 82kN. In the reloading phase, the flexural cracks were propagated towards the flange, however the shear cracks were further propagated along the bottom of the flange towards the loading point. Subsequently, the beam TT1a failed in shear at a peak load of 175kN. Figure 2(a) depicts the shear failure pattern of the control beam TT1a. Specimens TT1-1 and TT1-1I were strengthened using discrete CFRP strips of width 80mm spaced at 150mm c/c. A CFRP strip width of 120mm was also applied along the soffit of the beam to control the early flexural failure. These specimens TT1-1 and TT1-1I were attained a gain in shear enhancement of 39% and 61%, respectively. After repairing the specimen TT1-1, the early-developed shear cracks were arrested due to the application of CFRP reinforcement; nevertheless new cracks were emerged in the unstrengthened portion of the beam. However, in the case of initially strengthened beam TT1-1I (i.e. non-precracked), the first flexural crack was observed approximately at a load of 48kN. When the applied load increased, the web shear crack was emerged in the unwrapped portion of the beam at 108kN followed by a shear crack at 121kN. A critical diagonal crack was observed at a load of 194kN and a CFRP strip ruptured at the right shear span near the support. The failure in specimens TT1-1 and TT1-1I was controlled by flexural failure under the loading point. It was also observed that the shear cracks in the precracked-repaired (TT1-1) and initially strengthened (TT1-1I) specimens were propagated along the bottom of the flange towards the loading point. The shear capacity of initially strengthened specimen TT1-1I was 17% greater than the repaired specimen TT1-1. Figures 2(b) and 2(c) show the flexural failure pattern of the precracked-repaired (TT1-1) and initially strengthened (TT1-1I) beams, respectively.

In control specimen TS1a, the first flexural crack appeared at approximately 35kN followed by diagonal shear crack with the increase of load at 68kN. The shear crack occurred earlier in comparison to the specimen TT1a from category TT1. As the applied load increased, the shear cracks were proliferated along the bottom of the flange towards the loading point. Beyond this, some flexural cracks from the constant moment zone grew into the flange. The failure mode of the control specimen was controlled by shear at a peak load of 135kN. It can be seen that the ultimate load of the control specimen TS1a was less than that of the TT1a specimen due to the amount of internal transverse steel reinforcement. The failure pattern of the specimen TS1a was similar to the control specimen TT1a (i.e. category TT1). Specimen TS1-1 was precracked similar to the control specimen TS1a. During the preloading phase, the flexural and shear crack formations were almost identical as in the specimen TS1a. Subsequently, the specimen TS1-1 repaired similar to the specimen TT1-1. The new shear cracks were exhibited between the unstrengthened portions of the shear span (i.e. in between the CFRP strip gaps). Due to the increase of load, the CFRP strip was ruptured approximately at 148kN and followed by shear cracks emerging at the supports prior to the failure. This specimen attained a shear enhancement of approximately 40% over the control beam TS1a. The initially strengthened specimen TS1-1I was strengthened with same orientation and spacing of CFRP strips as TS1-1. The flexural crack was observed in the bending zone at approximately 41kN. No diagonal shear cracks were emerged with the increase of load. At last, the specimen failed by flexure at a total load of approximately 121kN. The flexural failure was due to the high longitudinal tensile stress developed at the constant moment zone. The failure occurred under the loading point was probably due to the formation of flexural crack similar to the specimen TS1-1. It was observed that there was no critical shear crack developing along the shear span of the specimen. But the flexural cracks were originated between the unstrengthened portion of the specimen. It must be noted that the ultimate load of the initially strengthened TS1-1I was 10% less than the unstrengthened specimen TS1a. Figure 2(d) shows the flexural failure pattern of the initially strengthened beam TS1-1I. It shows that increasing the external shear reinforcement may not result in a proportional increase in the shear strength but changes the mode of failure shear to flexure. Moreover, the percentage of tensile reinforcement had an influence on the mode of failure of the strengthened specimen. The test results for categories TT1 and TS1 are summarised in Table 3.

Fig. 2(a) Shear failure of control beam TT1a

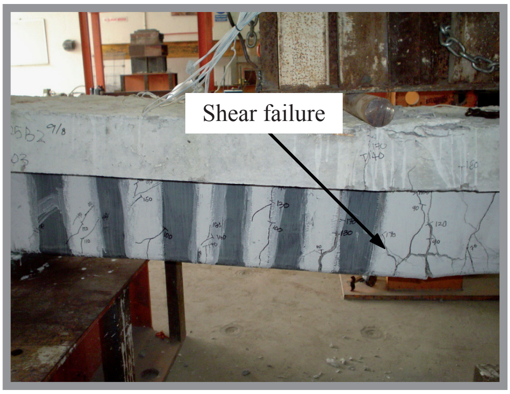


Fig. 2(b) Flexural failure pattern of precracked repaired beam TT1-1

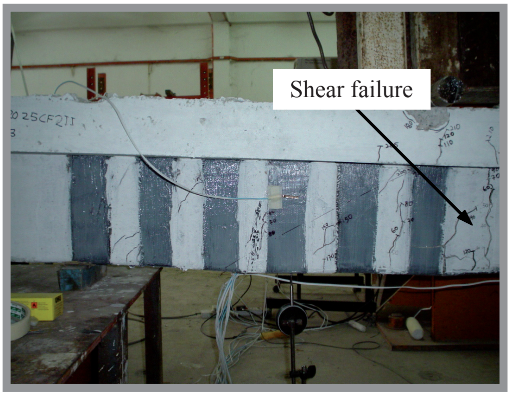


Fig. 2(c) Flexural failure pattern of initially CFRP strengthened beam TT1-1I

Fig. 2(d) Flexural failure pattern of initially CFRP strengthened beam TS1-1I

Categories TT2 and TS2: These categories were subjected to three point bending system with shear span to effective depth ratio of 4.0. In the first cycle of loading, the flexural and shear cracks in the control beam were instigated at 42kN and 81kN and in the reloading phase the beam attained a shear failure at a peak load of 148kN. During reloading, some new diagonal shear cracks formed at the centre of both shear spans. These diagonal shear cracks were widened and propagated as the applied load increased. Specimens TT2-2 and TT2-2I were wrapped at an inclination of 45/135 degree to the longitudinal axis of the beam. However, the external CFRP strip of width 80mm and spacing 150mm c/c was maintained as in categories TS1 and TT1. Moreover, external flexural CFRP reinforcement of width 120mm was also provided along the soffit of the specimen. In beam TT2-2, the flexural and shear cracks were occurred similar to the control beam TT2a (i.e. in precracking phase). After the application of external reinforcement, some new inclined cracks were emerged approximately at 108kN between the unstrengthened portions (i.e. between the CFRP strip gaps). Subsequently, the repaired beam TT2-2 failed in flexural mode (see Figure 2(e)) at a peak load of 201kN with shear enhancement of 36% over the control beam. However, the initially strengthened specimen TT2-2I had also observed a similar failure as specimen TT2-2 at a peak load of 215kN with a increase in shear enhancement of 45% greater than the control beam TT2a. During the application of load, the flexural crack in the specimen TT2-2I was developed similar to the control beam, but the shear cracks were observed emerging in between the CFRP strips at a load of 134kN. Prior to the failure, the inclined CFRP strips ruptured near the mid span. This specimen (i.e. TT2-2I) attained a shear capacity of 7% over the repaired specimen TT2-2. There was no significant shear enhancement in specimen TT2-2I because it had attained flexural failure before it reached the ultimate strength. Figure 2(f) shows the flexural failure pattern of the initially strengthened specimen TT2-2I.

Fig. 2(e) Flexural failure pattern of precracked repaired beam TT2-2

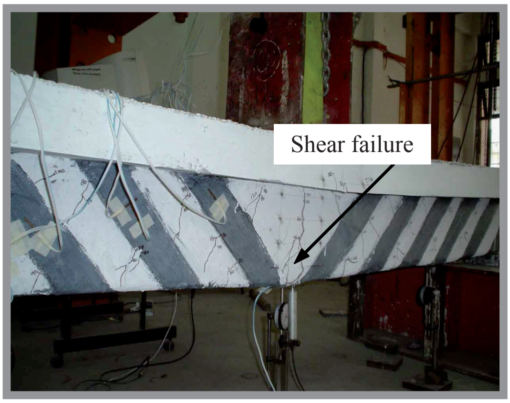


Fig. 2(f) Flexural failure pattern of initially CFRP strengthened beam TT2-I

In Category TS2, the flexural crack in the control beam TS2a initiated at a load of 42kN. But the shear cracks were originated near the centre of both shear spans simultaneously at a load of 68kN. In the second cycle of loading, the previously developed shear cracks were matured along the bottom edge of the flange zone. As the load increased, new shear cracks began to occur near the support at 95kN before the failure of the beam. At the end, the beam was failed in flexure at a peak load of 108kN. The beam TS2-1 was precracked and followed by repairing with vertical CFRP U-strips oriented at 0/90 degree to the longitudinal axis of the beam. Similar to the category TT2, these specimens were also used a strip of 120mm CFRP strip along the soffit. In the precracking phase, the orientation of the flexural and diagonal crack formation in specimen TS2-1 was similar to the control beam TS2a. After repairing the specimen TS2-1, the mode of failure of this specimen was due to flexure at the mid span of the beam (see Figure 2(g)). Due to the application of applied load, the diagonal and web shear cracks were observed at a load of 85kN and 108kN, respectively. The total applied load at ultimate for the specimen TS2-1 was 148kN with a 37% increase in shear enhancement compared to the control beam. However, the initially strengthened beam TS2-1I was strengthened similar to the repaired specimen TS2-1. The flexural crack was initiated similar to the control beam whereas, the diagonal crack was cropped in the unstrengthened portion of beam at a load of 82kN. Increasing the applied load further developed web shear cracks near the support of the specimen. The shear cracks were stopped at the sixty percent of the overall depth whereas the flexural cracks were protruded to the flange of the beam due to the flexural mode of failure. Figure 2(h) depicts the flexural failure with CFRP fracture pattern of the specimen TS2-1I. The obtained failure load (121.44kN) was less than the repaired beam TS2-1, but it was only 12.29% higher than the control beam TS2a. The test results for Categories TT2 and TS2 are summarised in Table 3.

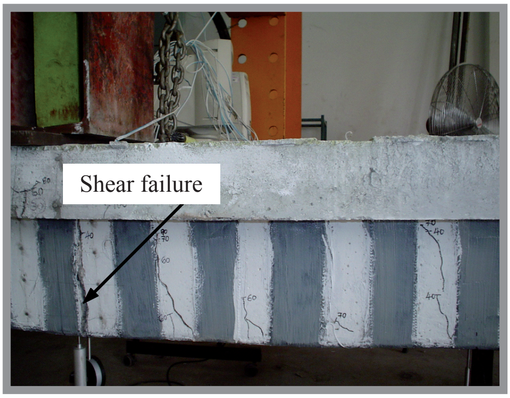


Fig. 2(g) Flexural failure pattern of precracked repaired beam TS2-1

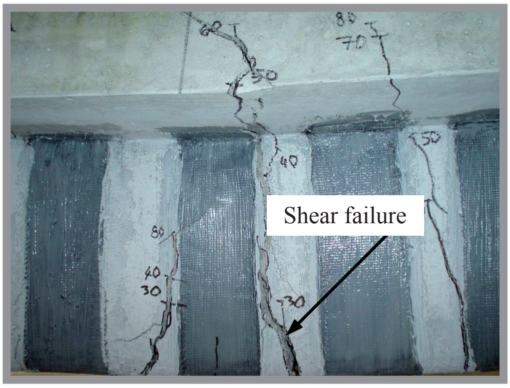


Fig. 2(h) Flexural failure pattern of initially CFRP strengthened beam TS2-1I

Some key observations of categories TT1, TS1, TT2, and TS2 are listed below:

- Experimental results show that the precracked-repaired and initially strengthened beams in categories TT1 & TS1 and TT2 & TS2 achieved a gain in shear enhancement ranging from 38% to 61% and 13% to 45% respectively over the control beam.
- The shear enhancement in the initially strengthened specimens (i.e. non precracked) was very little as compared to the precracked-repaired beams. However, the specimens TS1-1I and TS2-2I were attained less shear enhancement when compared to the precracked-repaired specimens TS1-1 and TS2-1, respectively. The shear enhancement of the initially strengthened specimen TT2-2I was only 7% greater than the precracked-repaired beam TT2-2. It shows that there was no significant difference between the precracked-repaired and initially strengthened specimens. It was found that the application of CFRP strips in the precracked-repaired beams attained better performance as compared to the non-precracked beams (i.e. initially strengthened beam).
- It was observed from the experimental investigation, the amount and distribution of cracks in the initially strengthened specimens was more than the precracked-repaired specimens. It shows that the CFRP became active after the formation of crack.
- All the precracked-repaired beams and non-precracked (i.e. initially strengthened beam) were failed in premature flexural failure, however no debonding failure was observed in any of the beams. This is probably due to the presence of the secondary fibres (0 or 135 degree) in the CFRP strips acting as restraint. It can be concluded that the bi-directional CFRP strip technique controls the debonding of CFRP strip failure from the bonded concrete surface.
- For instance, the CFRP shear contribution of the specimens TT1-1 and TT1-1I in the category TT1 were 28% and 66% greater as compared to the specimens TS1-1 and TS1-2 (i.e. category TS1a) respectively. It shows that shear enhancement of the strengthened specimens was influenced by internal tensile reinforcement as well.
- The experimental results of the strengthened specimens reveal that increasing the amount of internal and external CFRP shear reinforcement may not proportionally increase the shear capacity but changes the mode of failure shear to flexure due to the presence of excessive amount of shear reinforcement.

Table 3: Summary of test results for T-beams

SPECIMEN	Ult. Failure load (kN)	Contribution of CFRP strip (kN)	% of Shear enhancement	Mode of failure
TT1a (C)	174.65	---	---	Shear
TT1-1 (P-R)	241.16	66.51	>38.08	Flexural
TT1-1I (I)	281.08	106.43	>60.94	
TS1a (C)	134.74	---	---	Shear
TS1-1 (P-R)	187.98	53.24	>39.51	Flexural
TS1-1I (I)	121.44	---	---	
TT2a (C)	148.04	---	---	Shear
TT2-2 (P-R)	201.26	53.22	>35.95	Flexural
TT2-2I (I)	214.56	66.52	>44.93	
TS2a (C)	108.14	---	---	
TS2-1 (P-R)	148.04	39.90	>36.90	Flexural
TS2-1I (I)	121.44	13.30	>12.29	

5.2 LOAD DISPLACEMENT PROFILE

Figures 3(a) and 3(b) show the applied load versus mid deflection for specimens in categories TT1 & TS1 and TT2 & TS2, respectively. In precracked-repaired and initially strengthened beams, the load was initially carried by concrete (i.e. before first crack) and followed by the contribution of the longitudinal reinforcement after the initiation and propagation of flexural cracks. Subsequently, the steel stirrups and CFRP reinforcement began to carry the load after the formation of shear crack. All the precracked-repaired and initially strengthened specimens were failed in flexure and thus increased the ductility of the beams. It can also be seen in Figures 3(a) and 3(b); the load deflection curves of the precracked-repaired and initially strengthened beams in categories TT1, TS1, TT2, and TS2 were similar with respect to their control beam. This trend was due to the effect of internal steel stirrups however, in the investigation of CFRP wrapped rectangular beams [14], they found that there was significant difference was attained in the precracked-repaired and initially strengthened beams due to the absence of internal shear reinforcement.

The stiffness of the precracked-repaired and initially strengthened beams in categories TT1 & TT2 was greater as compared to the categories TS1 & TS2, respectively. Perhaps, this was attributed to the percentage of longitudinal tensile reinforcement ratio. The initial stiffness of the precracked-repaired and initially strengthened beams in categories TT1 and TS1 were almost similar prior to the formation of crack in concrete. Afterwards, there was a deviation in displacement curves for strengthened specimens in category TS1 due to the decrease in amount of tensile reinforcement. Similar trend was also observed in the CFRP strengthened specimens from categories TT2 and TS2. From this, it was concluded that the stiffness of the strengthened specimen increased with the increase in amount of tensile reinforcement. It was also observed that the mid deflections in subgroups TT2 and TS2 were more when compared to the subgroups TT1 and TS2 for the same load. Table 4 shows the mid deflection values of the strengthened specimens. The CFRP strengthened beams had smaller deflection value than the control beam for the same load. But the deflection at failure load of the strengthened beams was greater in comparison to the control specimen.

Table 4. Summary of mid deflection values of the CFRP strengthened T beams

Specimen	Ultimate Load (kN)	Maximum Deflection (mm)	Corresponding Deflection @ peak load of control beam (mm)
TT1a (c)	174.65	10.83	---
TT1-1(P-R)	241.16	17.70	7.88
TT1-1I (I)	281.08	20.02	8.03
TS1a (c)	134.74	11.54	---
TS1-1 (P-R)	197.98	12.97	8.36
TS1-1I (I)	121.44	19.90	---
TT2a (c)	148.04	10.29	---
TT2-2 (P-R)	201.25	13.79	8.76
TT2-2I (I)	214.56	16.02	9.20
TS2a (c)	108.14	9.41	---
TS2-1 (P-R)	148.04	14.22	10.33
TS2-1I (I)	121.44	12.67	10.72

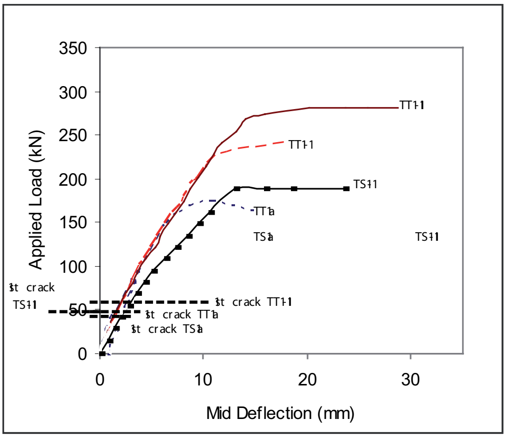


Fig. 3(a) Load-Mid Deflection curves for precracked-repaired and initially strengthened T-beams in categories TT1 and TS1

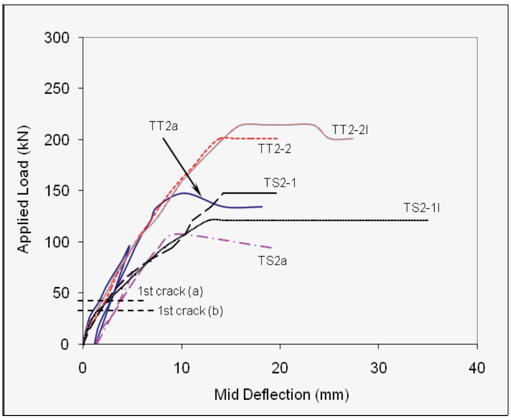


Fig. 3(b) Load-Mid Deflection curves for precracked-repaired and initially strengthened T-beams in categories TT2 and TS2

5.3 STRAIN IN DISCRETE CFRP STRIPS AND CONCRETE SURFACE

Graphs of applied load versus strain in CFRP strips and concrete surface of precracked-repaired and initially strengthened beams in categories TT1, TS1, TT2, and TS2 are shown in Figure 4. The strains in CFRP strips are not only measured to investigate the distribution of strain in the precracked-repaired and initially strengthened beams but it also assists to understand the behaviour of strain in the strengthened system. The position of strain gauges of the strengthened specimens is shown in Figure 4. The strain gauges were placed across the depth of the beam. The rate of strain value in concrete surface of the precracked-repaired and initially strengthened beams was higher when the beams experienced a shear crack in the unstrengthened portion of beams. On the other hand, the strains in fibre strips were minimal prior to the initiation of diagonal crack, however, in the later stage, the rate of strain values were significantly increased thus representing the effectiveness of the CFRP strip resisting in shear. It can be seen from the figures, the magnitude of the horizontal fibres strain in the CFRP strip was relatively less than the vertical fibre strain. This study confirms that the vertical or inclined fibres (i.e. 90 or 45 degree) were carrying the load like internal steel stirrups, however the fibres oriented perpendicular to the vertical or inclined fibres (i.e. 0 or 135 degree) were probably acting as restraint to control the debonding of CFRP strip from the concrete surface. The observed fibre strains were different across the cross section of the web. However, the strain gauge located near the mid height of cross section attained a maximum value in comparison to other locations.

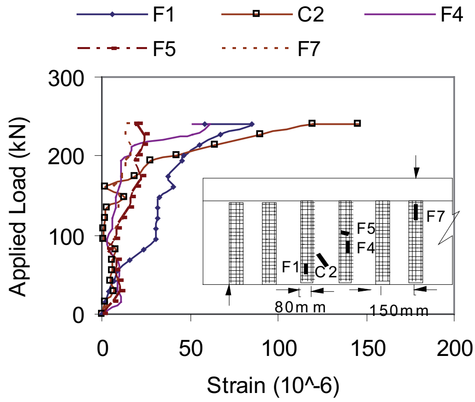


Fig. 4(a) TT1-1

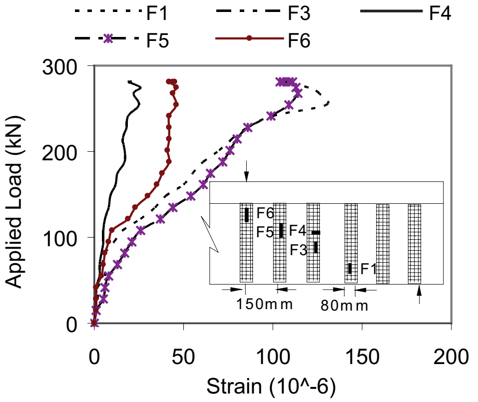


Fig. 4(b) TT1-1I

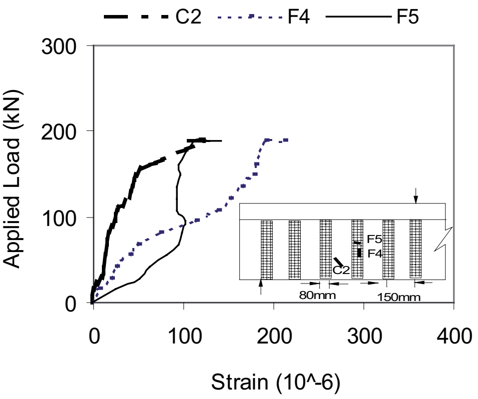


Fig. 4(c) TS1-1

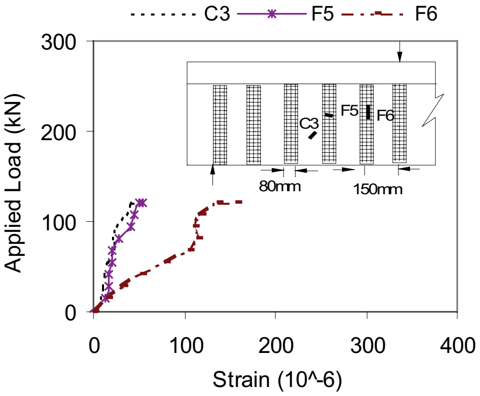


Fig. 4(d) TS1-1I

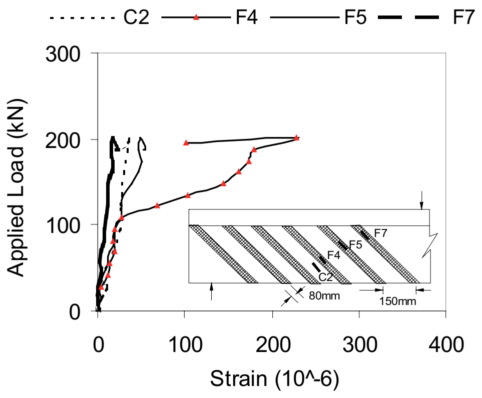


Fig. 4(e) TT2-2

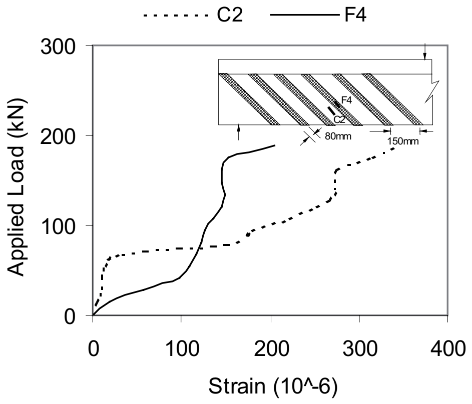


Fig. 4(f) TT2-2I

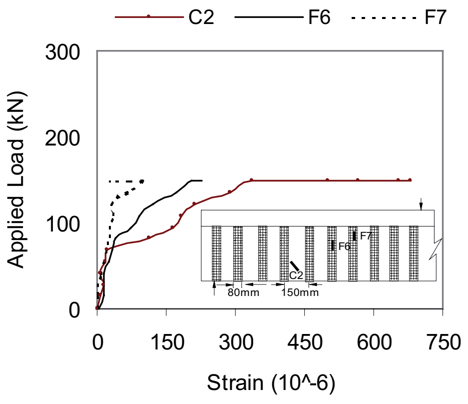


Fig. 4(g) TS2-1

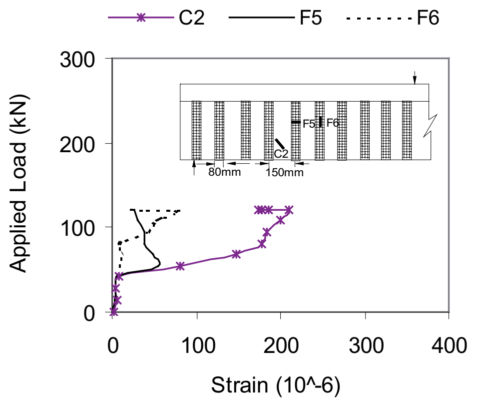


Fig. 4(h) TS2-1I

Fig. 4 Load versus strain in CFRP strip and concrete surface for precracked-repaired and initially strengthened beams

6. CONCLUSIONS

This paper presents the experimental results of the T-beams bonded externally with bi-directional CFRP fabric strips. Following conclusions are drawn based on the experimental investigation:

1. Experimental investigation shows that the increase in shear enhancement in the precracked-repaired and initially strengthened beams ranged between 13% and 61% over the control beam.
2. It was found that the application of CFRP strips in the precracked-repaired beams attained better performance as compared to the non-precracked beams (i.e. initially strengthened beam).
3. All the precracked-repaired beams and non-precracked (i.e. initially strengthened beam) were failed in premature flexural failure, however no

debonding failure was observed in any of the beams. This is probably due to the presence of the secondary fibres (0 or 135 degree) in the CFRP strips acting as restraint. It can be concluded that the bi-directional CFRP strip technique controls the debonding of CFRP strip failure from the bonded concrete surface.

4. Results also show that shear enhancement of the precracked-repaired and initially strengthened specimens were influenced by internal tensile reinforcement as well.
5. The experimental results of the precracked-repaired and initially strengthened specimens reveal that increasing the amount of internal and external CFRP shear reinforcement may not proportionally increase the shear capacity but changes the mode of failure shear to flexure due to the presence of excessive amount of shear reinforcement.

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