Behavior of Reinforced Concrete Beams Strengthened with CFRP

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Abstract. In recent years, civil engineers and researchers are showing great interest in using the new and advanced methods of repairing, retrofitting, and strengthening of old and ageing reinforced concrete structures. Externally bonding fibre reinforced polymer (FRP) to structural members is an effective method to increase its carrying capacity. This paper is to investigate and improve the understanding, properties of externally RC beams strenghtened with Carbon Fibre Reinforced Polymer (CFRP) sheets. To achieve the aim, two groups of beams were designed according to ACI318-11 and investigated experimentally. The first group consisting of four beams strong in flexure but weak in shear and the second group beams consist of three beams strong in shear but weak in flexure. The beams were strengthened using CFRP externally. The behaviours of the beam specimens under the effect of loads were investigated according to various application of CFRP orientation. According to the results of experiments, effectiveness of the rehabilitation method both on the load carrying capacity and energy absorption capacity were evaluated.

Keywords: FRP, CFRP, Beams, Strengthening, ACI318-11.

1 INTRODUCTION

Reinforced Concrete (RC) is one of the common and most popular building materials in the world. Most structures such as buildings, bridges etc. uses reinforced concrete as their main construction material. Some of these structures or parts of it are not fulfilling their structural functions due to defects on the concrete caused by poor construction practices, corrosion damage, fire damage, accidental damage, or deterioration caused by environmental action. While some reinforced concrete structures need to be upgraded due to design and construction faults and in cases of load increment or damage induced to the structural members by a seismic or other action. In addition, increase in volume of traffic may result to bridge upgrade. Replacing these deficient structures requires huge investments and is not an enticing option, hence strengthening has become the suitable way for improving the load carrying capacity and prolonging their service life. Even though the effectiveness of other techniques are widely accepted, engineers develop a new, better and most promising technique using fibre-reinforced polymer (FRP) which is more advantageous and gained popularity worldwide. FRP is listed as one of the successful technique which is currently interesting to the structural engineers as a modern and promising material in the construction industry (Jumaat et al., 2010).

Khalifa and Nanni (2002), reported that the shear strength of beams is increased by CFRP composite, from the experimental investigations conducted on twelve full-scale reinforced concrete simply supported beams which were designed to fail in shear. Buyukozturk, et. al. (2003) stated that, the failure pattern which demands attention and raises concerns is the sudden brittle manner in which the CFRP plate debonded prior to ultimate failure. Hence, this particular failure pattern deserves further close and critical examination. Almost all the failure that occurred on the tested beams indicates that the FRP was not fully utilized and failure type was changed from ductile to brittle. Such failures may significantly decrease the effectiveness of the strengthening or repair application. A research paper authored by Pham and Al-Mahaidi

(2004) report that retrofitting RC beams with thicker CFRP do not always lead to higher capacity. Fereig et al. (2005), conducted a research on the repair and rehabilitation of reinforced concrete beams using CFRP and GFRP fabrics. Results showed that both GFRP and CFRP regained and improved the ultimate carrying capacity and ductility of the investigated beams, with GFRP showing excellent result compared to CFRP. Siddiqui (2009), published a paper and concluded that the U shaped end anchorage beam has the higher flexural strengthening and inclined strips are effective in improving shear capacity of the beam.

2 EXPERIMENTAL INVESTIGATIONS

2.1 Material properties

2.1.1 Concrete

Ready mixed concrete of grade C30 was used in the research, which was obtained from Near East University Mosque construction site, and was ordered from one of the local supplier. Seven rectangular reinforced concrete beams, three cylindrical specimens and three cube specimens were casted from the same batch of concrete. The curing was made by water spraying for three days, continuously. After three days, formworks were removed and specimens were lifted and placed in curing tank for 28 day with 21 ± 2^0 C temperature and 90% relative humidity. The three cubes and three cylindrical specimens were tested to obtain the 28^{th} day compressive strength of the concrete batch. Table 1 shows the compressive strength obtained.

Table 1. Compressive strength of concrete cylindrical and cube specimens

Specimen	Compressive Strength of cylinder (MPa)	Compressive Strength of cube (MPa)
1	42.06	32.6
2	40.71	35.1
3	39.48	37.2
Average	**40.75**	**35.0**

2.1.2 Steel

S420 deformed bars were used for both longitudinal and transverse reinforcements of all members. Ø10mm and Ø12mm bars were used for longitudinal reinforcements and Ø8mm bars were used for as transverse. The mechanical properties of steel bars under tensile tests were conducted on samples of each diameter. Tensile test was carried out at Near East University, Civil engineering laboratory, using Universal Testing Machine (UTM-4000) 600kN load capacity, with BC 100 control unit to obtain the yield strength, ultimate strength, modulus of elasticity and percentage elongation values of the steel reinforcing bars as shown in Table 2.

Table 2. Mechanical properties of steel reinforcement

Steel Bars diameter (mm)	Ultimate Stress (MPa)	Yield Stress (MPa)	% Elongation	Modulus of Elasticity (GPa)
Ø8	567	446	17.4	210
Ø10	588	456	21.3	208
Ø12	705	551	14.5	210

2.1.3 CFRP material

FRP is a new class of composite material manufactured from fibres and resins which has proven to be efficient and economical for the development and repair of new and deteriorating structures in civil engineering. The CFRP material used is unidirectional sheet with fibres oriented in the one direction only (along the longitudinal axes). The strength of fibre material in longitudinal direction is far greater than that in longitudinal and diagonal directions. For this research, SikaWrap-300C CFRP sheet of 0.17mm thickness was obtained from a local supplier in Nicosia. The CFRP sheet and mechanical properties of the sheet are shown in Fig. 1and Table 3 as obtained from the supplier respectively.

Fig. 1. CFRP sheet used for flexural strengthening

Table 3. Properties of CFRP obtained from supplier

Density of Fibre	$1.8g/cm^3$
Thickness	0.17mm
Tensile Strength	$3900N/mm^2$

Tensile Elastic Modulus of Fibre	230000N/mm^2

2.1.4 Epoxy resins

Epoxy resins are generally used to bond the CFRP on the concrete surface, which can be applied in both shear strengthening and flexural strengthening of beams. Success of the strengthening technique primarily depends on the performance of the epoxy resins used for the bonding. Varieties of epoxy resins are commercially available for usage with wide range of physical and mechanical properties. Epoxy resins are generally available in two parts, a resin and a hardener.
Sikadur-330 epoxy resin (A and B) were used in this research study. Sikadur-330 epoxy resin (A) is the epoxy (white colour) and Sikadur-330 epoxy resin (B) the hardener (grey colour) which were mixed in the ratio 4:1. They were mixed thoroughly with a mixing tool for 10 minutes until the color was a grey and applied on the concrete surface using trowel. The mechanical properties of above mentioned material are given in Table 4. These values were taken from the manufacturer product data sheet.

Table 4. Properties of sikadur-330 obtained from supplier

Density of Mixed Resin	1.31kg/lt
Tensile Strength	30N/mm^2
Flexural Elastic Modulus	3800N/mm^2
Tensile Elastic Modulus	4500N/mm^2
Elongation at Break	0.9%

2.2 Description of the specimens

Beam with section dimension of 300x300mm was initially considered. Using a scale factor of 1:2, (which is a ratio comparing the scaled measurement to the actual measurement) the beams were casted with sectional dimension of 150x150mm. A total of seven reinforced concrete beams were categorized in two groups. The first group consist of four specimens which were designed to be strong in flexure and weak in shear (shear failure) and the second group consist of three specimens designed to be strong in shear and weak in flexure (flexural failure). All beams were strengthened with CFRP strips/sheets externally. In each group, one beam was taken as a control beam. The nomenclature used for different beam configurations are shown in Table 6 for easier identification.

Table 6. Details of test specimens

Group	Specimen Designation	Specimen Description	CFRP Sheet/Strip Layers	Strengthening Orientation
1	CBM1-G1	Control beam	-	-
	SBM1-G1	CFRP was bonded to both sides of the beam perpendicular to longitudinal axis	Strip (1)	Two side bonded
	SBM2-G1	CFRP U-strips were bonded to the beam	Strip (1)	U-bonded
	SBM3-G1	Inclined CFRP strips (45^0) were bonded to both side of the beam, parallel to the shear crack	Strip (1)	45^0 side bonded
2	CBM1-G2	Control beam	-	-
	SBM1-G2	CFRP sheet was bonded to the beam on the tension side	Sheet (1)	Tension face
	SBM2-G2	CFRP sheet was bonded to the beam on the tension side with U-strip end anchorage	Sheet (1)	Tension face

The beams were designed in accordance with American Concrete Institute ACI 318-11, with dimension of 150×150×750 mm. The beams were designed with a concrete cover of 30 mm. Group 1 beams: Strong in flexure and weak in shear were designed with 0.0129 steel ratio and the Group 2 beam: Strong in shear and weak in flexure have a steel ratio of 0.0057. Table 5 shows the parameters used in design calculations.

Table 5. Summary of Group 1 and Group 2 beam design

Beam	b (mm)	h (mm)	d (mm)	f_c(MPa)	f_y(MPa)	A_s (mm^2)	ρ	ρ_{eff}
Group 1	150	150	116	30	420	226.2	0.0129	0.0102
Group 2	150	150	117	30	420	157	0.0089	0.0062

2.3 Reinforcement details

A total of seven reinforced concrete beams were casted in two groups. Group 1 containing four beams and Group 2 containing 3 beams.
Group 1 beams had a cross-section of 150×150mm and a span of 750mm. As the beam of Group 1 were made strong in flexure, reinforced with 2Ø12mm steel bars at bottom part of the beam, with Ø8mm stirrups at 200mm spacing. A Ø8mm steel bar was used at the upper part of the beam to tie up the stirrups as shown in Fig. 2 and Fig. 3.

Fig. 2. Internal reinforcement of Group 1 beams

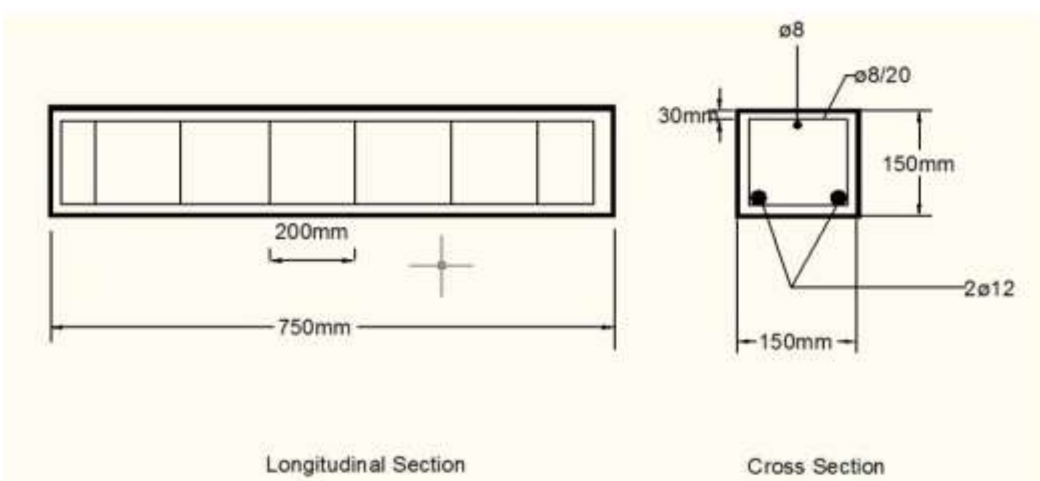

Fig. 3. Detail of Group 1 beam

Group 2 beams had a cross-section of 150×150mm and a span of 750mm. As the beam of Group 2 were made weak in flexure, reinforced with 2Ø10mm steel bars at bottom part of the beam, with Ø8mm stirrups at 100mm spacing. A Ø8mm steel bar was used at the upper part of the beam to tie up the stirrups as shown in Fig. 4 and Fig. 5.

Fig. 4. Internal reinforcement of Group 2 beams

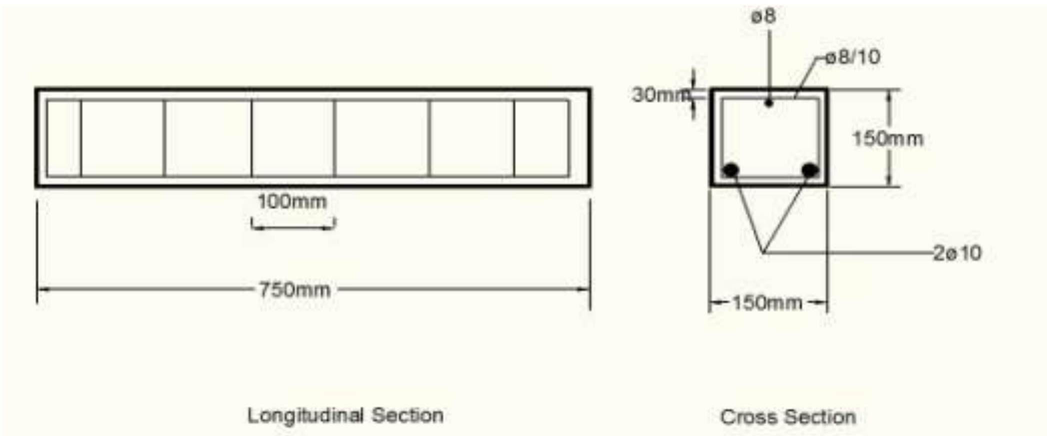

Fig. 5. Detail of Group 2 beams

2.4 Epoxy application

All the faces of the specimen, where CFRP is to be applied, were first smoothened with scratch paper. Finally, the specimens were cleaned from dust by using air blower and brushes to obtain a clean surface. CFRP strips/sheets were cut beforehand into prescribed sizes using appropriate scissors. Sikadur-330 epoxy resin mixture of about 2 mm thick was applied on the surface of the concrete beams where the CFRP strips/sheets were positioned. Using a roller, the strips/sheets were squeezed against the surface to assure that there was no void between the strip/sheet and the concrete surface. All CFRP strips/sheets used in strengthening were of unidirectional SikaWrap-300C. After strengthening, the specimens were left undisturbed in the laboratory for 3 day before testing to make sure that the epoxy had enough time to cure.

2.5 Wrapping orientation

SBM1-G1 beam which was designed to be strong in flexure was externally bonded with CFRP strips both sides of the beam, perpendicular to the longitudinal axis. The strips were bonded perpendicular at an angle of 90^0 to the longitudinal axis of the beam with 80mm center to center spacing as shown in Fig.6. In the second scheme, SBM2-G1 beam specimen was designed to fail in shear. U shape CFRP strips were used to strengthen the beam in shear. The strips were bonded perpendicular at an angle of 90^0 to the major axis (longitudinal) of the beam with 80mm center to center spacing as shown in Fig. 7. In the third scheme, SBM3-G1 beam specimen was designed to fail in shear. The beam was strengthened with SikaWrap-300C unidirectional CFRP strips bonded on both two sides. The strips were bonded at an angle of 45^0 to the major axis (longitudinal) of the beam and parallel to the expected diagonal shear failure at 80mm center to center spacing as shown in Fig. 8.

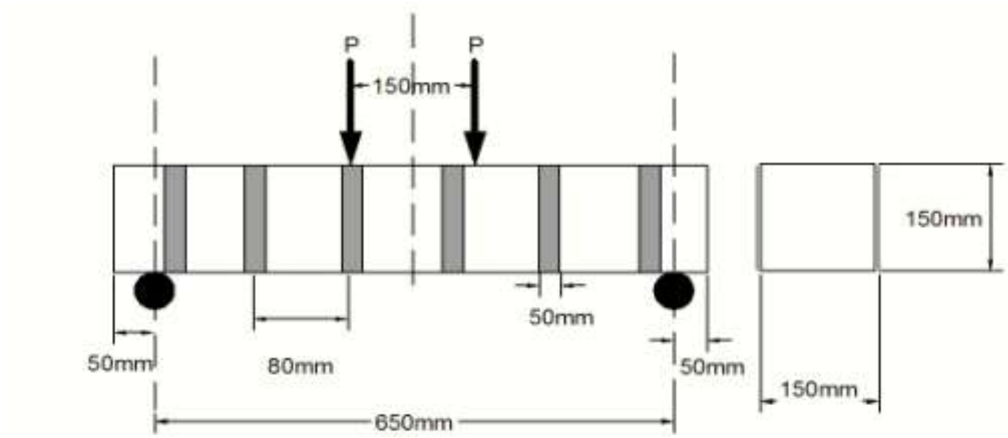

Fig. 6. Schematic representation of SBM1-G1 beam

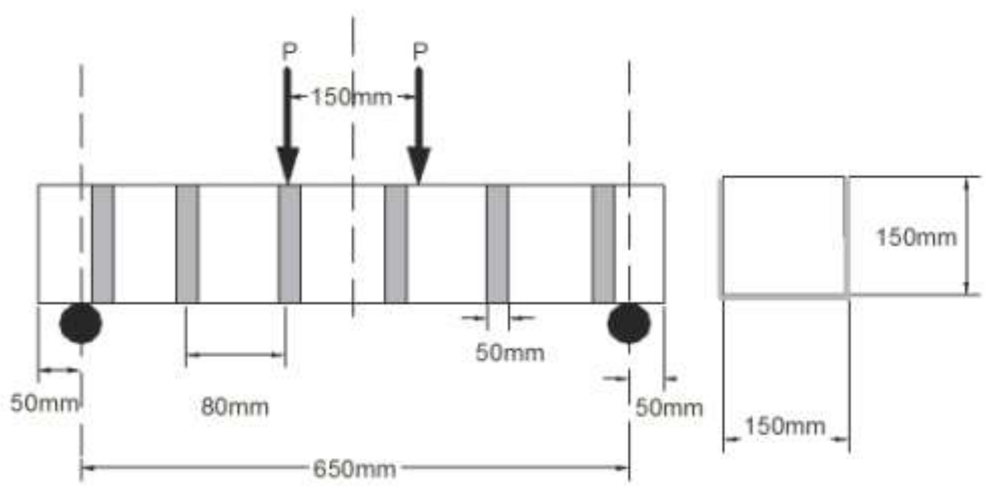

Fig. 7. Schematic representation of SBM2-G1 beam

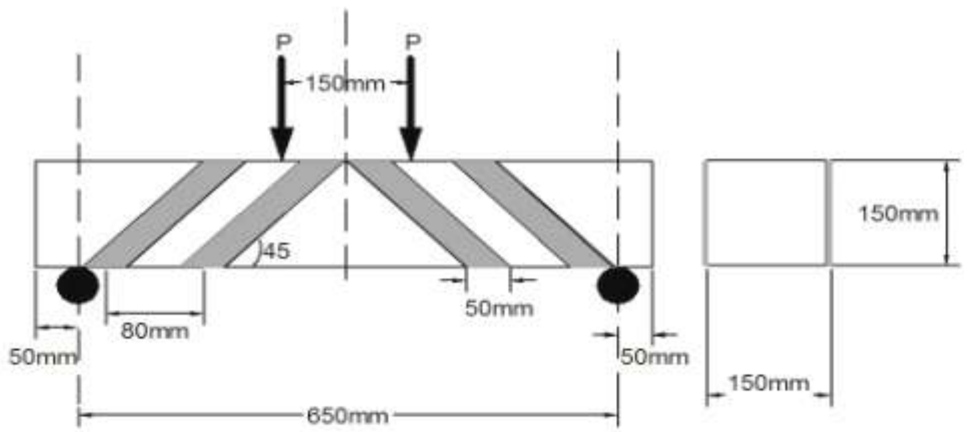

Fig. 8. Schematic representation of SBM3-G1 beam

In the second group, first scheme, SBM1-G2 of Group 2 beams that was designed to be strong in shear and weak in flexure, was externally bonded with SikaWrap-300C unidirectional CFRP sheet at bottom part of the beam in order to strengthen the beam in flexure. The sheet is orientated parallel to the major axis (longitudinal) of the beam as shown in Fig. 9. The sheet at the tension side is bonded parallel to the major axis (longitudinal) of the beam as shown in Fig. 10. The second scheme, SBM2-G2 beam specimen was designed to fail in flexure. SikaWrap -300C unidirectional CFRP sheet bonded on the tension side (bottom of the beam) in single layer and CFRP U-strips were bonded at the ends of the beam to prevent any possible debonding of sheet as shown in Fig. 11.

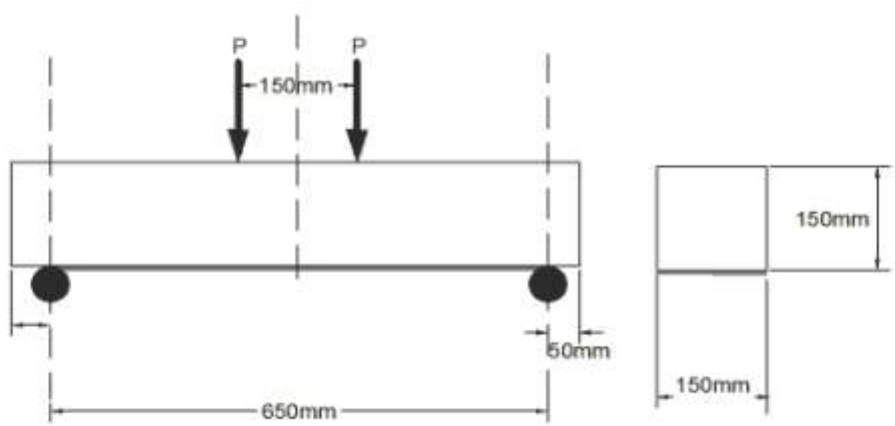

Fig. 9. Schematic representation of SBM1-G2 beam

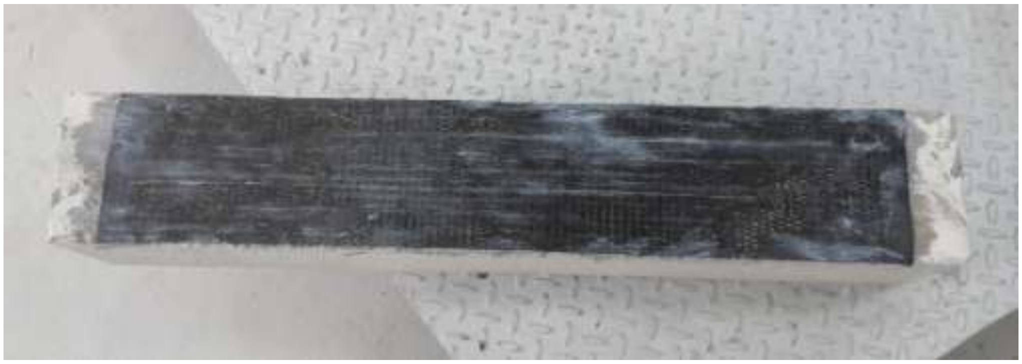

Fig. 10. SBM1-G2 beam

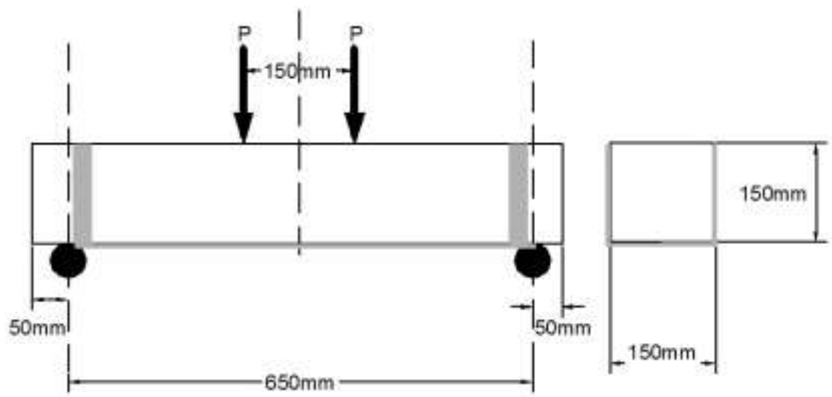

Fig. 11. Schematic representation of SBM2-G2 beam

3 EXPERIMENTAL PROCEDURE

The experimental research was carried out at Near East University, Department of Civil Engineering, CE laboratory, Nicosia, Turkish Republic of Northern Cyprus. A total of seven reinforced concrete beams were tested with similar loading. All the beams were tested using Automatic Flexural Testing Machine (UTC-4620) with 200kN load capacity. The beams were tested as simply supported with two points loading placed at equal distance from the supports. The loads was applied at a constant pace rate of 0.2MPa/s until failure occurred on the specimens as shown in Fig. 12.

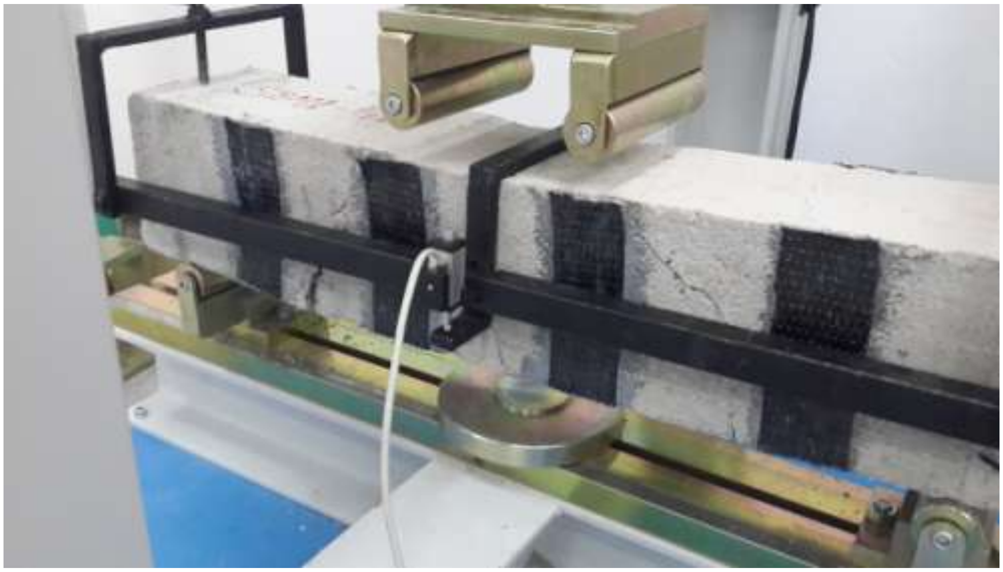

Fig. 12. View of SBM3-G1 on automatic flexural testing machine (UTC-4620) 200kN

4 TEST RESULTS AND DISCUSSIONS

4.1 Experimental observations of Group 1 beams

The control beam was designed as strong in flexure and weak in shear and failed due to diagonal tension failure as expected. The failure was observed from one support and started as a thin hair-like crack close to the support which widened gradually and propagated upward at approximately 45^o inclined to the longitudinal axis. This failure is pure diagonal tension failure and occurred sudden as seen in Fig. 13. SBM1-G1 showed an increase in ultimate capacity compared to the control beam. The failure observed in both sides of the beam was due to concrete crushing close to the CFRP strips and some flexural crack at the mid-span of the beam. The ultimate load capacity of SBM2-G1 was 94.69kN which showed an increase in ultimate capacity compared to the control beam. The failure observed in both sides of the beam was due to concrete crushing close to the CFRP strips and some flexural crack and the failure was almost sudden. The ultimate load capacity of SBM3-G1 was 81.85kN which showed an increase in ultimate capacity compared to the control beam. The failure observed in both sides of the beam was due to concrete bursting close to the CFRP inclined strips and some flexural crack that started from the center and bottom of the beam to almost the center of the beam. The CFRP strips were not detached from the concrete.

Fig. 13. Failure in CBM1-G1

4.2 Summary of the experimental observations of Group 1 beams

Generally all the strengthened beams in Group 1 showed an increase in ultimate capacity compared to the control beam as showed in both Table 7 and Table 8. The U-strip strengthened beam has the highest increase and 45^0 wrapped beams lowest. It shows that wrapping beams with 45^0 strips parallel to the diagonal tension failure increase the ultimate strength less that the 90^0 this is because the CFRP did not arrest the propagated diagonal tension crack.

Table 7. Results of Group 1 beams

Group	Beam Designation	Ultimate load (kN)
1	CBM1-G1	74.20
	SBM1-G1	84.03
	SBM2-G1	94.69
	SBM3-G1	81.85

Table 8. Comparison of control beam with strengthened beams (Group 1)

Group	Beam Designation	Ultimate load (kN)	Ultimate capacity increase compared control beam	% increase compared to control beam
1	CBM1-G1	74.20	-	-
	SBM1-G1	84.03	9.83	13.25
	SBM2-G1	94.69	20.49	27.61
	SBM3-G1	81.85	7.65	10.31

4.3 Experimental observations of Group 2 beams

The control beam was designed as strong in shear and weak in flexure. CBM1-G2 failed due to flexural failure as expected and crushing of concrete at the position of applied load. The flexural failure was observed at the mid-span of the beam and started as thin hair-like flexural cracks, which widened as it propagated to the top of the beam as shown in Fig. 14. The change in the position of the neutral axis was easily and clearly observed at the mid-span due to maximum deflection that occurred at the position. SBM1-G2 showed an increase in ultimate capacity compared to the control beam. The failure observed due to debonding of CFRP from the end followed by shear compression failure. SBM2-G2 was 100.6kN which showed a significant increase in ultimate capacity compared to the control beam. Bursting of concrete was observed together with shear compression failure. No debonding occurred, this improvement was due to U-strips attached to the end of the CFRP.

Fig. 14. Failure in CBM1-G2

4.4 Summary of the experimental observations of Group 2 beams

Generally all the strengthened beams in Group 2 showed an increase in ultimate capacity compared to the control beam as showed in both Table 9 and Table 10. The strengthened beams show an increase in ultimate strength compared to the control beam. With tension side plus U-strip end anchorage wrapping showing the highest increase. The addition of end U-strip also eliminates the effect of debonding as in the SBM1-G2. Experiment conducted by Siddiqui (2009), showed that end anchorages increase the load carrying capacity. It also was stated that tension side bonding of CFRP sheets with U-shaped end anchorages is very effective in flexural strengthening of RC beams as this scheme not only increases the flexural capacity substantially, but also maintains sufficient deformation capacity.

Table 9. Results of Group 2 beams

Group	**Beam Designation**	**Ultimate load (kN)**
2	CBM1-G2	85.31
	SBM1-G2	94.78
	SBM2-G2	100.60

Table 10. Comparison of control beam with strengthened beams (Group 2)

Group	**Beam Designation**	**Ultimate load (KN)**	**Ultimate capacity increase compared control beam**	**% increase compared to control beam**
2	CBM1-G2	85.31	-	
	SBM1-G2	94.78	9.47	11.11
	SBM2-G2	100.60	15.29	17.92

4.5 Energy absorption capacity

To ascertain the damage caused by loading a structure, engineers use energy absorption as an important parameter. Energy absorption is obtained to evaluate the strength of a structure or structural member after impact of loading. In this research, one cylindrical specimen was wrapped using a single layer of CFRP sheet as shown in Fig. 15 and was compared with the average compressive strength of cylindrical specimens that were not wrapped (the specimens used to obtain compressive strength). The compressive strength of the wrapped specimen was 45.9MPa. This shows an increase of 12.64% compared to the average of unwrapped specimens where the compressive strength was 40.75MPa. The failure of the wrapped specimen was observed to be sudden after the ultimate load, which was due to the rupture of CFRP from the concrete cylinder. Increase in compressive strength of the wrapped specimen, indicates that CFRP can be used to reduce the damage of compression members.

Figure 15. Failure of wrapped cylindrical specimen

5 CONCLUSIONS

According to the research experiment conducted, the following conclusions and key findings can be drawn on the basis of the results.

- The failure mode in Group 1 control beam was due to flexural failure, while Group 2 control beam failed due to diagonal tension (shear failure) as expected. Change in failure mode was observed in all the strengthened beams compared to the control beam for both groups and are more brittle.
- It was observed in all strengthened beams that the ultimate capacity of CFRP was not reached. All the failures in the strengthened beams are either due to debonding of CFRP from the surface, rupture or crushing of the concrete around the CFRP. Concentration of stress near the CFRP end was the cause of the failure.
- Strengthened beams showed an increase in ultimate capacity and stiffness compared to the control beams in each group.
- The most undesirable mode of failure is due to diagonal tension failure which caused failure without reaching the yield strength capacity of the reinforcements. By applying the CFRP U-strip scheme, the effectiveness and efficiency was observed with 27.61% increase with respect to the control beam.

- In Group 1, SBM1-G1 showed a greater ultimate capacity compared to SBM3-G1, so bonding CFRP strips at 45^0 inclined to the longitudinal axis and parallel to the shear failure (diagonal tension failure) is not as effective as bonding at 90^0 to the longitudinal axis.
- In seismic regions, CFRP can be applied on compression members to increase their absorption capacity. In this experiment, the tested cylinder wrapped with 1 layer of CFRP showed an increase in compressive strength of 12.64% with respect to the control.

Generally, the recent and new effective technique of CFRP strengthening can be used in reinforced structures including bridges, high rised buildings, etc. to increase the ultimate carrying capacity without increase in the overall weight of the system. The most effective and efficient orientation is applying CFRP as U-strips with 27.61% increase with respect to the control beam in shear strengthening. For flexural strengthening, applying the sheet in the tension face with U-strip end anchorage was the most effective.

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