FLEXURAL BEHAVIOR OF RC BEAMS STRENGTHENED WITH FRP COMPOSITE SHEETS SUBJECTED TO DIFFERENT LOAD CASES

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KEYWORDS: FRP, strengthening, composites, RC beams, flexure.

ABSTRACT

This study was carried out to experimentally investigate the flexural performance of RC beams strengthened with GFRP and CFRP composite sheets for three cases: strengthening before loading, strengthening while subjected to service loading and strengthening after unloading.. The parameters of study included level of loading and the type of FRP strengthening system. The test program consisted of seven groups of beams. The first group was unstrengthened control group. The remaining six groups were divided into two series, one was strengthened with GFRP sheets, and the other was strengthened with CFRP sheets. Each series consisted of three groups; the first one was strengthened before loading, the second group was loaded to service load, unloaded, repaired with FRP sheet then loaded to failure, and the third group was similar to the second one except that the beam was strengthened while loaded. These beams were tested in flexure and the experimental data on strength and deflection was obtained. The results show that the use of FRP sheets as an external reinforcement to strengthen or repair concrete structural members (uncracked or precracked) is very effective. The test results also reveal that the beams loaded to service load levels, unloaded and then repaired with FRP sheets and those strengthened while loaded behaved in a similar way as those strengthened before loading.

INTRODUCTION

Structures can be damaged due to over-loading, earthquakes, fire, blast loading, mistakes in design calculations, corrosion of reinforcement and improper concrete mix design. All these can lead to unsatisfactory performance with respect to serviceability and ultimate strength. In the past, various techniques were used for strengthening and repair of structural elements. In the recent years, there have been considerable worldwide attentions among engineers for the fiber reinforced polymer (FRP) material in construction industry. These materials have high strength to weight ratio, excellent resistance to corrosion, chemical resistance, non-magnetic, electrically non-conducting, light-weight and twice to four times as strong as steel in tension. It is relatively easy to use, fast, and results in small changes in structural size generally in the order of millimeters. These materials can be applied while the structure in use and therefore it is expected to replace most of previous existing repairs and strengthening techniques.

FRP materials have been successfully used in variety of industries such as aerospace, automotive, and shipbuilding for decades. However, their use in civil engineering applications is relatively new and expected to increase in the near future.

Nowadays, different types and shapes of FRP materials are commercially produced. Carbon, Glass and Aramid are some of the well-known FRP types. They are available in rods, fabrics, and strands and they are also produced in one, two and three-dimensional fabrics. In comparison to steel FRP materials, are still expensive, but due to their superior physical and chemical characteristics, there is an indispensable

and keen tendency towards using FRP to rehabilitate infrastructures Mochizuki et al. (1993). Besides, the labor cost of using and installing FRP materials for repair is only fraction of that needed with steel.

FRP materials offer to the engineer an outstanding combination of properties, such as low weight (therefore they are much easier to handle on site), excellent mechanical strength and stiffness, and the ability of formation in very long lengths. Thus, FRP composite material technique has found wide attractiveness and acceptance among researchers and engineers today in many part of the world.

Several studies have been conducted on the use of Glass or Carbon FRP sheets as flexural strengthening reinforcement of concrete beams (see references). The researchers showed the behavior in terms of load-deflection, load-strain, failure patterns and structural ductility. All beams showed a considerable increase in ultimate load capacity (from 40 to 200%) with a good energy absorption capability.

Most of the experimental studies on the use of fiber reinforced polymers (FRP) as external reinforcement for beams in flexure that are available in the literature were conducted on unloaded beams. Very few studies conducted on beams that were subjected to loading and in some cases they were strengthened after being unloaded. In this study besides the above cases, beams were strengthened while they were subjected to service loads. This will replicate the actual field conditions. Thus, the effectiveness of using FRP in real life will be better evaluated.

The objective of this study was to experimentally investigate the flexural performance of RC beams strengthened with GFRP and CFRP composite sheets in three cases: strengthening before loading, strengthening while subjected to service loading and strengthening after unloading, and in turn, to assess the effectiveness of using composite sheets for flexural strengthening of RC beams in these three load cases.

EXPERIMENTAL PROGRAM

Beam Details

A total 14 beams were designed and cast. Two beams were used as control specimens with no strengthening. The remaining 12 specimens were divided into two series. The first series (6 beams) was used to evaluate the effectiveness of the GFRP sheets in strengthening beams for flexure under different loading and unloading conditions. The second series (6 beams) was similar to the first series but were strengthened with CFRP sheets. The 6 beams in each series were divided into three groups. The first group consists of two beams that were strengthened with FRP sheets before loading. The second groups consists of two beams that were loaded to service load, unloaded, then repaired with FRP sheet and then reloaded again until failure. The third group was similar to the second group except that the beams were strengthened while the service load was applied on them. Details of these groups are shown in Table 1.

The test span was 1350 mm and the cross section was 200 ×150mm for all beams. All beams were reinforced with 2ϕ10 mm steel bars in the tension side (bottom) and 2ϕ6 mm in compression side (top), and ϕ6 mm steel stirrups @ 75 mm center to center. Figure 1 shows the beam setup and its cross section.

Test Setup

The test span of all beams was 1350 mm. The beams were tested simply supported, subjected to two point loads symmetrically placed at equal distance (100 mm) from the centerline of the beam. This means that the shear span for all specimens was 575 mm. The beams were tested using a load jack. The mid-span deflections were monitored using linear variable displacement transducer (LVDT) whereas the strains in the longitudinal steel bars at mid-span were recorded using electrical strain gages. The loads were applied continuously and recorded, along with the readings of the corresponding LVDT and strain gages, using a data acquisition system. A schematic diagram of test set-up is shown in Fig 1.

Table 1 Details of beam groups.

Group	Strengthened/ Unstrengthened	Description	No. of Specimens
NO-FRP	Unstrengthened	Beams represent the control group (No Strengthening).	2
G-SBL	Strengthened With GFRP Sheets	Beams were strengthened with GFRP before loading	2
G-SAU		Beams were loaded to service load, unloaded, strengthened with GFRP then reloaded until failure.	2
G-SWL		Beams were loaded to service, strengthened with GFRP while loaded, then continue loading until failure.	2
C-SBL	Strengthened With CFRP Sheets	Beams were strengthened with GFRP before loading	2
C-SAU		Beams were loaded to service load, unloaded, strengthened with GFRP then reloaded until failure.	2
C-SWL		Beams were loaded to service, strengthened with GFRP while loaded, then continue loading until failure.	2
Total			14

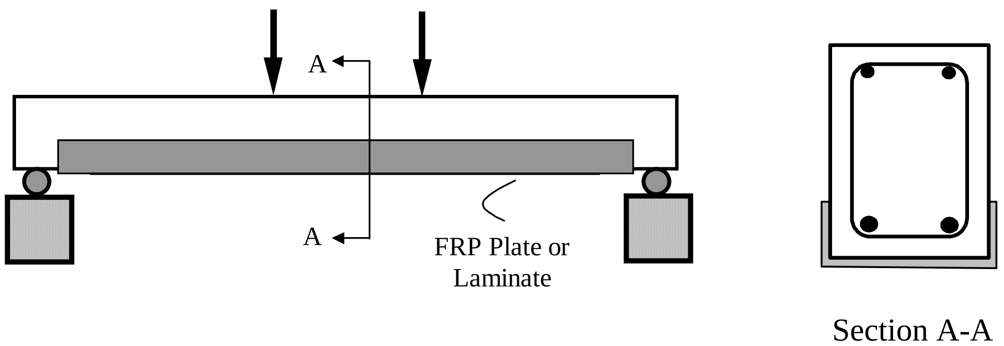

Fig. 1 Beam set-up and its cross-section.

Material Properties

Concrete

The concrete used to cast the beam specimens was provided by a local concrete batch-plan. The compressive strength of concrete f'_c was determined by testing concrete cylinders for all beams at the day of testing (99 days after casting). The compressive strength of concrete was 40.1 MPa as the average of spray concrete cylinders.

Steel

The yield strength of steel bars used in this experimental program was determined by performing the tensile test on two specimens of each bar diameter. The average tensile strength of steel bars was found to be 412 MPa and 322 MPa for 10 and 6 mm bars, respectively.

FRP Composite Sheets

The properties of the GFRP and CFRP composite sheets which were externally bonded to the beams using epoxy matrix are given in Table 5.

Table 2 Properties of FRP sheets.

Type	Modulus of Elasticity, E_f (MPa)	Tensile Strength, f_{fu} (MPa)	Design Thickness (mm), t_f
GFRP	26200	540	1.00
CFRP	75100	930	1.19

Preparation of Test Specimens

Ready-Mix concrete was used to cast the beam specimens. Six of 150 × 300 mm cylinders were cast to determine the compressive strength of the concrete. The test specimens were subjected to intermittent spraying of water twice a day for two weeks and then left to dry for two more weeks. On the ninty-nine day after casting, the process of attaching the external GFRP & CFRP sheets started. The following procedure was used to attach the sheets:

Surface Treatment Phase

The surface of the beam where the sheet to be attached at, was first sand-blasted to be able to develop a sound bond and withstand the imposed stresses. The process included smoothing out the unevenness in the surface, repair the damage and rounding the corner of the concrete. After that, the surface of the concrete was cleaned with acetone several times until the washcloth no longer had blackness. At this point the sheets were also wiped with acetone to remove dust or any adhered substances.

Attaching the FRP's

After preparing the concrete surfaces and wiping out the sheets, the epoxy was applied to the FRP sheet and then attached to the concrete surface. Any excess of epoxy was squeezed out by pressing the sheets to the concrete.

The specimens were then kept in the laboratory under control conditions (25C° ± 2 and 30% relative humidity) for 2 days, and then tested.

Table 3 Summary of load-deflection of GFRP beams.

Beam designation	Service Stage	Yield Stage		Ultimate Stage	
	Load at Δ_{ser} (kN)	P_y (kN)	Δ_y (mm)	P_u (kN)	Δ_u (mm)
(1)	(2)	(3)	(4)	(5)	(6)
NO-FRP	20	27	3.4	53.1	25.9
G-SBL	29	46	4.4	82.3	15.2
G-SAU	33	45	3.6	85.1	15.3
G-SWL	29	43	3.5	81.8	13.6

Average deflection of control beams at service load (Δ_{ser}) =2.4 mm

Table 4 Summary of load-deflection of CFRP beams.

Beam designation	Service Stage	Yield Stage		Ultimate Stage	
	Load at Δ_{ser} (kN)	P_y (kN)	Δ_y (mm)	P_u (kN)	Δ_u (mm)
(1)	(2)	(3)	(4)	(5)	(6)
NO-FRP	20	27	3.4	53.1	25.9
C-SBL	36.5	61.3	4.5	92.5	8.7
C-SAU	33	57	4.3	100.7	9.1
C-SWL	29	49	3.4	85.4	8.9

Average deflection of control beams at service load (Δ_{ser}) =2.4 mm

TEST RESULTS AND DISCUSSION

The flexural test results which include the values of loads at service, yield and ultimate levels for the GFRP and CFRP groups are given in Tables 3 and 4, respectively. It should, however, be indicated that:

- The service load value of the control beams was calculated at 35- 40 % of the ultimate load with a corresponding deflection of Δ_{ser} = 2.4 mm.

- Deflection (Δ_{ser}) was used as a reference value to compare the deflection of all strengthened beams at service loads. The values obtained are given in column (2) of Tables 3 and 4.

- Yield load is the load at which steel started to yield. The yield strain for control unstrengthened beams was 2065 microns and the corresponding deflections Δ_y is given in column (4) of the same tables.

In each of the above values, increases of service, yield and ultimate loads for the strengthened/repaired beams over unstrengthened ones were computed as the ratio of the difference in the values for strengthened beams over unstrengthened beams (control beams) and tabulated in Tables 5 and 6, for GFRP & CFRP strengthened groups, respectively. The values are expressed as the ratio percentage of the gain relative to the unstrengthened.

Table 5 Summary of increase in strength of GFRP beams.

Beam designation	Service Stage		Yield Stage		Ultimate Stage	
	Load at Δ_{ser} (kN)	GAIN %	P_y (kN)	GAIN %	P_u (kN)	GAIN %
NO-FRP	20	__	27	__	53.1	__
G-SBL	29	45	46	70	82.3	55
G-SAU	33	65	45	67	85.1	60
G-SWL	29	45	43	59	81.8	54

Table 6 Summary of increase in strength of CFRP beams.

Beam designation	Service Stage		Yield Stage		Ultimate Stage	
	Load at Δ_{ser} (kN)	GAIN %	P_y (kN)	GAIN %	P_u (kN)	GAIN %
NO-FRP	20	__	27	__	53.1	__
C-SBL	36.5	83	61.3	127	92.5	74
C-SAU	33	65	57	111	100.7	90
C-SWL	29	45	49	81	85.4	61

<u>Load Deflection Relationships</u>
The average load-deflection relationships for GFRP and CFRP strengthened groups of beams are plotted in Figs. 3 and 4, respectively, along with the control unstrengthened group. The values of the loads at service, yield and ultimate levels are given in Tables 5 and 6, for GFRP and CFRP groups, respectively.

Control Beams (No-FRP group)
As shown in Table 3 and Fig 3 the values of load at service, yield and ultimate levels for unstrengthened beams are 20 kN, 27.0 kN, and 53.1 kN, respectively.

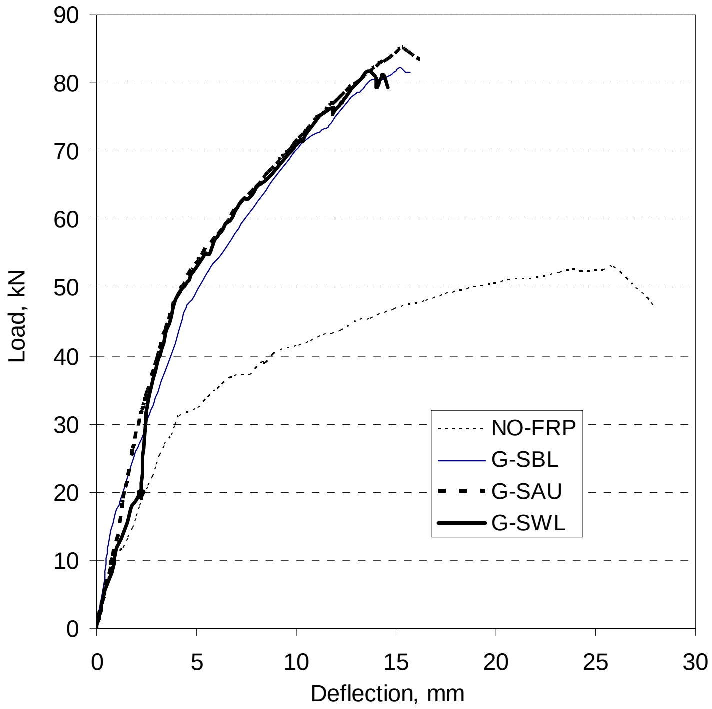

Fig. 3 The GFRP strengthened beams along with the control (unstrengthened) beam.

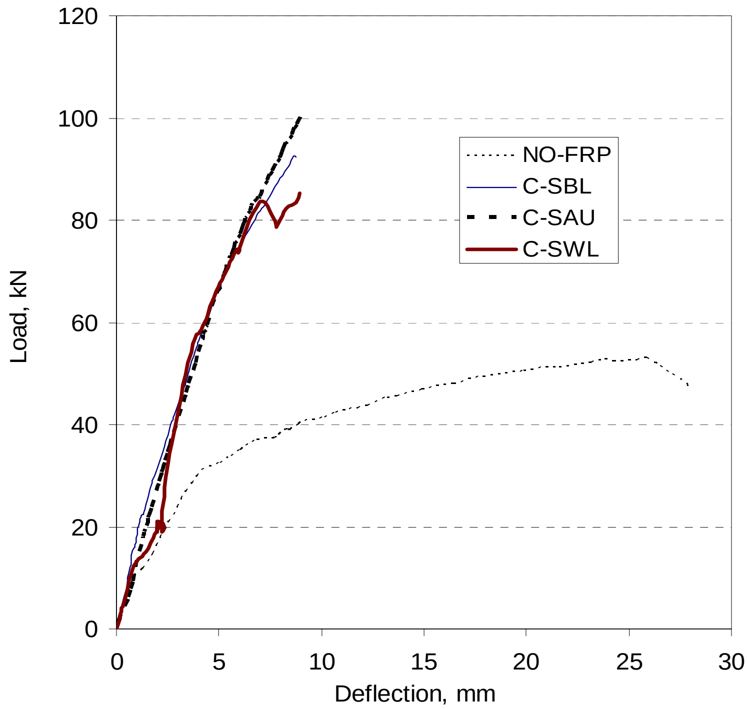

Fig. 4 The CFRP strengthened beams along with the control (unstrengthened) beam.

Beams Strengthened Before Loading (G-SBL and C-SBL)

For G-SBL beams, as shown in Table 5, the loads at service, yield and ultimate levels are 29 kN, 46 kN and 82.3 kN, respectively, with an increase of 45%, 70%, and 55% respectively, over the corresponding values for the control unstrengthened beams. For C-SBL beams, as shown in Table 6, the loads at service, yield and ultimate levels are 36.5 kN, 61.3 kN and 92.5, respectively, with an increase of 83%, 127%, and 74% respectively, over the corresponding values for the control unstrengthened beams. Increase in the service load, (45% for G-SBL group and 83% for C-SBL group) may be attributed to the fact that strengthening with FRP sheet increases the flexural stiffness (increase of flexural rigidity of the cross section due to sheeting). This can be observed in Figs. 3 and 4.

Beams Strengthened after Unloading (G-SAU and C-SAU)

The beams G-SAU and C-SAU which were loaded to service load (20 kN), unloaded, strengthened with FRP sheet, then reloaded, also showed similar increase in service, yield and ultimate loads. For G-SAU beams, as shown in Table 5, the loads at yield and ultimate levels are 45 kN and 85.1 kN, respectively, with an increase of 67%, and 60% respectively, over the corresponding values for the control unstrengthened beams. For C-SAU beams, as shown in Table 6, the loads at yield and ultimate levels are 57 kN and 100.7 kN, respectively, with an increase of 111%, and 90% respectively, over the corresponding values for the control unstrengthened beams.

Increases in the ultimate loads for G-SAU and C-SAU beams are slightly higher than the increase in the ultimate loads for G-SBL and C-SBL beams. The gain in strength may be attributed to the fact that some of the glue (epoxy) used to bond the GFRP or CFRP sheets seeped and filled the preloading cracks and thus added some extra strength. Furthermore, the ductility is also slightly higher as will be seen later.

Beams Strengthened While Loaded (G-SWL and C-SWL)

The beams (G-SWL & C-SWL) loaded to service load (20 kN), unloaded, strengthened with FRP sheet, then reloaded, also showed similar increase in service, yield and ultimate loads. For G-SWL beam, as shown in Table 5, the load at ultimate level is 81.8 kN, with an increase of 54% over the corresponding value for the control unstrengthened beam. For C-SWL beam, as shown in Table 6, the load at ultimate level is 85.4 kN, with an increase of 61 %, over the corresponding value for the control unstrengthened beam.

Ductility of Tested Beams

The ductility of a beam can be defined as its ability to sustain inelastic deformation without loss in load carrying capacity, prior to failure. It is usually calculated for conventional reinforced concrete structures as the ratio of curvature, deflection, or rotation at ultimate to the corresponding value at yielding of steel. In the case of beams strengthened with FRP sheets, there is usually no clear yield point. However, it was shown that deflection and energy based on tension steel yielding can be used as a criterion of ductility to evaluate comparative structural performance of plate bonded RC beams (Triantafillou and Plevris 1992). In this study ductility based on deflection is used for comparison between strengthened & unstrengthened beams. The ductility index is defined is:

$$\mu_{DS} = \frac{mid\text{-}span\ deflection\ at\ ultimate\ load\ (\Delta_u)}{mid\text{-}span\ deflection\ at\ service\ load\ (\Delta_{ser})} \qquad (1)$$

Or,

$$\mu_{Dy} = \frac{mid\text{-}span\ deflection\ at\ ultimate\ load\ (\Delta_u)}{mid\text{-}span\ deflection\ at\ yielding\ of\ steel\ (\Delta_y)} \qquad (2)$$

The values of ductility indices based on deflection are shown in Tables 7 and 8.

Table 7 The Ductility index of GFRP group.

Beam designation	Deflections		Deflection ductility index	
	Δ_y (mm)	Δ_u (mm)	μ_{DS}	μ_{Dy}
NO-FRP	3.4	25.9	10.8	7.6
G-SBL	4.4	15.2	6.3	3.5
G-SAU	3.6	15.3	6.4	4.3
G-SWL	3.5	13.6	5.7	3.9

Average deflection of control beams at service load (Δ_{ser}) =2.4 mm

Table 8 The Ductility index of CFRP group.

Beam designation	Deflections		Deflection ductility index	
	Δ_y (mm)	Δ_u (mm)	μ_{DS}	μ_{Dy}
NO-FRP	3.4	25.9	10.8	7.6
C-SBL	4.5	8.7	3.6	1.9
C-SAU	4.3	9.1	3.8	2.1
C-SWL	3.4	8.9	3.7	2.6

Average deflection of control beams at service load (Δ_{ser}) =2.4 mm

The results clearly indicate that the control beams are more ductile than the repaired beams with FRP sheets. It can be also noted that the values of ductility indices are reduced as the stiffness of the beam increased due to the bonded FRP sheets. Furthermore, the ductility of the beams strengthened or repaired with GFRP sheets are higher than that of the corresponding beams strengthened or repaired with CFRP sheets. This may be ascribed to the higher ultimate strain of GFRP with respect to that of CFRP. Also the ductility of (precracked) beams is slightly higher than that of strengthened (uncracked) beam for the same type of FRP sheets used.

Failure Mode

Normally four flexural failure modes are possible with the FRP externally strengthened reinforced concrete beams: 1) rupture of the FRP laminates on the bottom of the beam; 2) crushing of the concrete at the top of the beam, 3) delamination of the FRP laminate and 4) cohesive failure in which FRP laminate separates with part of concrete attached to it. This is assuming adequate shear strength of any tested beams and proper and adequate adhesion of the FRP laminates. These failure modes occur after considerable flexural cracking and vertical deflection and may, or may not proceeded by the development of yielding of the reinforcing steel rebars.

The beams of the control specimens, failed by crushing of concrete after yielding of longitudinal steel bars and the occurrence of many flexural cracks. All the strengthened beams tested in this study failed due to the fourth mode, i.e, cohesive failure, as shown in Fig. 5. It started with some flexural cracking and yielding of steel reinforcement followed by cohesive failure at the tension side of the beam near the supports at the end of the FRP laminate. Separation of FRP with part of concrete attached to it indicates that there is an excellent bond between FRP laminates and concrete surface.

Fig. 5 The failure pattern of the strengthened beams.

CONCLUSIONS

In order to evaluate the effectiveness of using FRP composite material (GFRP and CFRP) to strengthen uncracked and precracked RC beams, a series of RC beams were designed, cast, strengthened before and after loading and then tested to failure.

From the results of this study, the following conclusions can be drawn:

i. The test results indicate that a significant gain in flexural strength can be achieved by bonding FRP sheets to the tension face of RC beams.

ii. Beams loaded to s*ervice* load level, *unloaded,* repaired with FRP sheets performed in a similar way as those strengthened before loading.

iii. Beams loaded to s*ervice* load level, repaired with FRP sheets *while loaded* performed in a similar way as those strengthened before loading.

iv. The use of FRP sheets as an external reinforcement to strengthen or repair concrete structural members (uncracked or precracked) proved to be very efficient and developed enough ductility.

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