

Flexural Strengthening of Pre-cracked Corroded RC Beams using CFRP Sheets

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Abstract - Corrosion of steel reinforcing bars is inevitable. Despite the stringent provisions specified by most of existing building codes, corrosion is still being reported in reinforced concrete (RC) structures due to the continuous exposure to harsh environments, proximity to sea-shores, and the use of deicing salt. The transfer of water, oxygen, and aggressive agents such as carbon dioxide and chloride into concrete leads to corrosion and consequently to concrete cracking, spalling, and deterioration. In this project corroded RC beam were strengthened with CFRP sheets. Corrosion was induced to pre-cracked RC beams using accelerated corrosion process. Effect of corrosion on RC beams in terms of flexural behaviour and the influence of various parameters such as thickness of CFRP sheet, beam width to sheet width ratio and bond length on the ultimate load of the strengthened beams were studied. Finally analytical evaluations on the ultimate load capacity of strengthened beams were done and compared with the experimental results.

Key Words: RC Beam, Corrosion, Pre-Cracking, CFRP, Accelerated corrosion process, Strength.

1. INTRODUCTION

Steel corrosion is one of the main causes of deterioration in reinforced concrete (RC) structures, which leads to the cracking and spalling of concrete cover, the reduction in cross section of steel bars, and the weakening of the bond and anchorage of steel bars in concrete. The corrosion damage significantly affects the serviceability and durability of RC structures. As the corrosion damage on RC structures increases, the repair and strengthening of these structures is becoming a major cost of construction activities.

Corrosion of steel reinforcement is associated to chloride ingress or/and carbonation in severe or aggressive environments and constitutes the most common form of steel deterioration. Chloride and carbonation induced corrosion phenomena are significantly different, also in terms of cross area reduction. The damage of corrosion in reinforced concrete (RC) structures is considered by reduction in the cross sectional area of steel reinforcement, steel properties such as yield and ultimate strength and ductility and leads to premature failure. It also leads to

losses of bond between concrete and steel bars, cracking and spalling of concrete cover. Damage and residual capacity assessment as well as suitable repair and strengthening of deficient reinforced concrete members are urgent for most existing structures. Therefore, research on corroded members has increased remarkably in recent years.

The use of fiber reinforced polymers (FRP) to retrofit and rehabilitate concrete structures is rapidly becoming a popular new technology. The advantages of using composite materials for retrofitting, as, opposed to steel plate bonding or jacketing, are that FRP are light weight, have a high tensile strength, and possess a high resistance to acids and bases making them essentially non-corrosive. The use of externally bonded carbon fiber reinforced polymers (CFRP) sheets for flexure and shear strengthening of reinforced concrete structures has been investigated extensively [6, 10, 15].

Corroded beams were repaired by bonding carbon fiber reinforced polymer (CFRP) sheets to the tension side to restore the strength loss due to corrosion. Different strengthening schemes were used to repair the damaged beams. Test results showed detrimental effect of corrosion on strength as well as the bond between steel reinforcement and the surrounding concrete. Corroded beams showed lower stiffness and strength than control (uncorroded) beams [1, 8]. However, strength of damaged beams due to corrosion was restored to the undamaged state when strengthened with CFRP sheets. On the other hand, the ultimate deflection of strengthened beams was less than ultimate deflection of un-strengthened beams.

2. EXPERIMENTAL INVESTIGATION

2.1 Material Properties

As per IS 10262:2009, M25 grade mix was designed to prepare the test specimens. Different trials were carried out to determine the design mix. The mix design proportion, compressive strength are shown in Table 1. Table 2 shows the mechanical properties of CFRP sheet used.

All beams were tested under three-point bending. The tests were conducted with a Universal testing machine. All specimens were simply supported and were subjected to three-point loading. The midspan deflection of the beam was taken using dial gauge.

Table-1 Mix Proportion

Grade	Mix Proportion				Comp. Strength (N/mm ²)	
	Cement (kg)	Fine Aggregate (kg)	Coarse Aggregate (kg)	w/c	7 th day	28 th day
M25	1.55	2.57	4.36	0.4	21.11	31.8

Table -2: Properties of CFRP sheet

Sl. No.	Parameter	Value
1	Tensile Strength	4000 MPa
2	Density	1.8 g/cc
3	Elongation	1.7 %
4	Elastic modulus	230 GPa

2.2 Experimental Setup

The experimental setup used for testing of RC beam specimen is three point flexure test. The RC beam specimens are laid horizontally over two points of contact (lower support) and then a force is applied to the top of the beam through a single point of contact until the specimen fails. The maximum recorded force is the flexural strength of the specimen. When a specimen is placed under flexural loading all three fundamental stresses are present: tensile, compressive and shear and so the flexural properties of a specimen are the result of the combined effect of all three stresses as well as (though to a lesser extent) the geometry of the specimen and the rate of the load applied. Fig -1 shows the schematic diagram of three point loading test performed in RC beams.

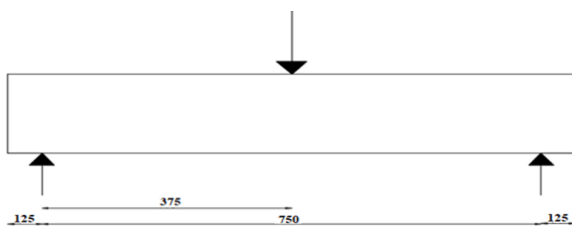


Fig -1: Three-Point Loading Experimental Setup

2.3 Beam Specimen Configuration

A total of 8 RC beam specimens were casted and tested, two of the beams were casted as control beams, of which one beam was neither corroded nor strengthened while the other beam was corroded using accelerated corrosion technique without any strengthening, all other beams were corroded, then strengthened in flexure with CFRP sheets at the soffit of the RC beam. The cross sectional dimensions of the specimens were 120 mm X 140 mm with a clear cover of 25 mm at the top and bottom of the beam. The length of the specimens was 1000 mm, with 750 mm as the

effective span and a shear span of 375 mm. Two numbers of 8mm diameter bars were provided as tension reinforcement, two numbers of 6 mm diameter bars were provided as compression reinforcement. Enough shear reinforcement was provided in an amount calculated to ensure that the beams would fail in flexural (i.e.: 6mm diameter bar at 80 mm c/c spacing). Fig -2 and Fig -3 shows the detailing of RC control beam and strengthened beam specimen.

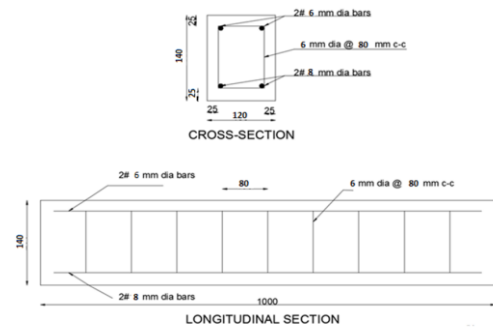


Fig -2: Detailing of Control Beam

The designation UCB stands for uncorroded control beam, CCB stands for corroded control beam and CFRP strengthened beam was designated as for example 700L 60W 0.75T, where L stands for length of CFRP sheet i.e.: 700mm, W stands for width of CFRP sheet i.e.: 60mm, T stands for thickness of the CFRP sheet i.e.: 0.75 mm.

Pre-cracking load was applied to all beams before applying corrosion to them. Pre-cracking load was selected by finding the first crack load of uncorroded control beam. It was obtained as 16 kN. Hence each beam was loaded with 16 kN to induce crack in them. Cracking of the beam can accelerate the corrosion process.

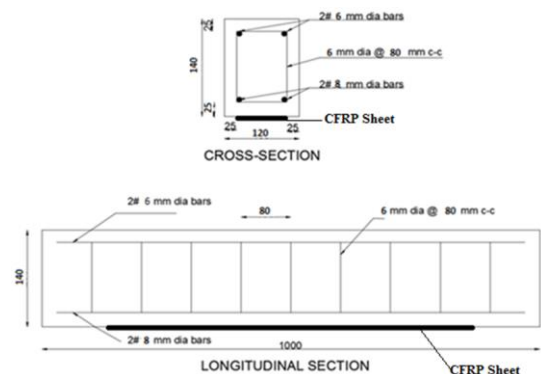


Fig -3: Detailing of Strengthened Beam

2.4 Test Setup for Accelerated Corrosion Process

Set-ups used for inducing reinforcement corrosion through accelerated corrosion process consist of a DC power source, a counter electrode, and an electrolyte (Fig-4). The positive terminal of the DC power source is connected to the steel bars (anode) and the negative terminal is connected to the counter electrode (cathode). The current is impressed from counter electrode to the

rebars through concrete with the help of the electrolyte (normally sodium chloride solution).

In this work, accelerated corrosion process is achieved by using 24 volt 2A DC power supply, 5% NaCl solution as electrolyte and stainless steel plate as cathode (Fig-5).

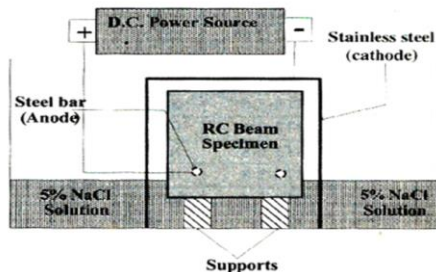


Fig -4: Schematic diagram of Accelerated Corrosion Test Set up



Fig -5: Corroded beams in the test set up

The specification of RC beam specimens is given in Table-4.

Table-4: Specification of RC Beams

Sl.No:	Notation	Dimension of CFRP sheet [Length x Width x Thickness](All dimensions are in mm)
1	UCB	—
2	CCB	—
3	700L60W1.5T	700X60X1.5
4	600L60W1.5T	600X60X1.5
5	500L60W1.5T	500X60X1.5
6	700L60W0.75T	700X60X0.75
7	700L100W1.5T	700X100X1.5

2.5 Preparation of RC Beam Specimens

All beams which have to be strengthened are corroded, after application of pre-cracking load, using accelerated corrosion process. After corroding the beams, they are strengthened using CFRP sheets. Strengthening requires careful observation and preparation of the beam. After the beam specimens were corroded for 8 days they

were ready for structural strengthening. The basic procedures carried out in strengthening the RC beam specimens are described in the following steps.

- The surface of concrete requires special preparation for proper bonding between the concrete and strengthening material is used. All dust, laitance, grease, curing compounds, foreign particles, disintegrated materials and other bond inhibiting materials must be removed from the bonding surfaces. The concrete surface has to be clean and sound.
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- The epoxy used for bonding CFRP with the beam is Araldite. It is available in many different types of packs, the most common containing two different tubes, one each for the resin and the hardener. Clean both the surfaces to be bonded. Take equal quantities (by volume) of resin and hardener of Adralite Standard. Mix the resin and hardener until it forms a uniform colour. Apply a thin coat of the mixture on both the surfaces. Join the surfaces and apply pressure using tape, clamps or band. Remove the pressure after 6-8 hours. Full strength is achieved in 24 hours.

Fig-6 to Fig- 8 shows the procedures of strengthening of RC corroded beams



Fig-6: Application of Epoxy



Fig-7: Bonding CFRP



Fig-8: Strengthened beams

3. RESULTS AND DISCUSSIONS

The corroded beams were strengthened in flexure by bonding CFRP sheets on the soffit of the beam. The main test variables were the thickness of the CFRP sheet (0.75mm and 1.5 mm), the width of the CFRP sheet (60 and 100mm), and bond length (500, 600 and 700 mm). Results are expressed in terms of their deflection and ultimate load-carrying capacity.

3.1 Load Carrying Capacity and Failure Mode

Table 5 provides the results obtained from the experimental tests carried out on one control beam and 5 CFRP strengthened corroded RC beams. The addition of the strengthening material to the corroded RC beams caused superior load-carrying capacity and reduced ultimate deflection. The average increment of the ultimate load-carrying capacity was 65%, compared to that of the corroded control beam. The corresponding yield load-carrying capacity of the beams significantly improved after strengthening. The yield point was determined by the stiffness variation in the load-deflection curve. This enhanced ultimate load-carrying capacity shows the superior performance of the strengthened beams compared with that of the corroded control beam.

Table 5: Test Results

Sl No	Beam ID	P _u (kN)	u (mm)	% increase in ultimate load w.r.t CCB (%)
1	UCB	33.0	15	-
2	CCB	12.4	17	-
3	700L 60W 0.75T	19.4	7	56.5
4	600L 60W 0.75T	18.4	10	48.4
5	500L 60W 0.75T	18.2	12	46.8
6	700L 60W 1.5T	20	6.5	61.3
7	700L 100W 1.5T	26	6	109.7

The failure modes of all beams are shown in Figs 9-14. The behaviour of the control beams under loading was typical flexural and all failed due to concrete crushing after steel yield mechanism. The failure modes of all strengthened beams are found to be very close to each other.



Fig-9: 500L 60W 0.75T



Fig-10: 700L 100W 1.5T



Fig-11: 600L 60W 0.75T



Fig-12: 700L 60W 0.75T



Fig-13: 700L 60W 1.5T

3.2 Effect of Strengthening on Deflection

The deflection and reduction of deflection due to strengthening by CFRP sheet at failure load of CCB (12.4 kN) and ultimate failure load is shown in Table 6.

Table -6: Reduction in Deflection due to CFRP Strengthening

Sl. No.	Beam	Deflection (mm)	Reduction % over CCB
1	UCB	15	—
2	CCB	17	—
3	700L 60W 0.75T	7	58.82
4	600L 60W 0.75 T	10	41.17
5	500L 60W 0.75T	12	29.41
6	700L 60W 1.5T	6.5	61.76
7	700L 100W 1.5T	6	64.71

The deflection of the strengthened beams was reduced compared to control beam. This indicates that the strengthened specimens have good elastic stiffness when compared to control beams.

3.3 Effect of Bond Length

The bond length greatly influenced the flexural performance of the strengthened beam. As the bond length decreases the ultimate load also decreases. Effect of bond length is studied in beams 700L 60W 0.75T, 600L 60W 0.75T and 500L 60W 0.75T. From experiment it is clear that as the bond length increases, ultimate deflection at the midspan of the strengthened beam decreases considerably. For a bond length of 700mm there is a percentage decrease of 58.82% in ultimate deflection over corroded control beam. For 600L 60W 0.75T and 500L 60W 0.75T the deflection reduced to 41.17 and 29.41% respectively. Ultimate load of 700L 60W 0.75T is increased to 56.5% over control beam.

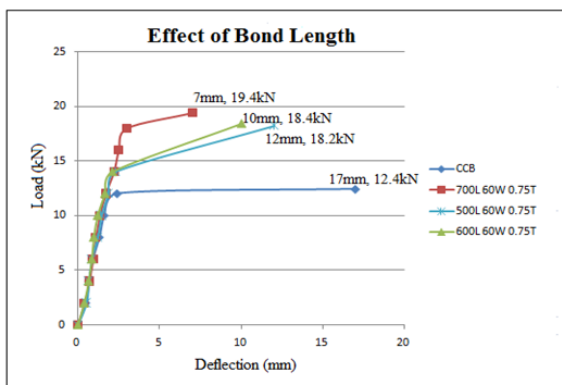


Fig-14: Effect of bond length

While the ultimate loads for lower bond lengths are much less compared with 700L 60W 0.75T (Fig-14). Thus bond length is an important parameter in terms of ultimate load and deflection. Therefore as the bond length increases, ultimate load increases and deflection gets reduced.

3.4 Effect of thickness of CFRP sheets

Thickness of CFRP sheet is also an important parameter which influences the ultimate load of the strengthened beam. Two beams i.e, 700L 60W 0.75T and 700L 60W 1.5T are used for studying the effect of thickness. 700L 60W 0.75T beam shown an ultimate load of 19.4kN and 700L 60W 1.5T has an ultimate load of 20kN. From the results obtained it is clear that the ultimate load increases with increase in thickness of CFRP sheet. There is an overall increase 0.6kN in the ultimate load of 700L 60W 1.5T over the beam strengthened with one layer of CFRP i.e. 700L 60W 0.75T (Fig-15). Ultimate load increases as the thickness increases but it cannot be increased more than a limit since the problem of debonding can happen on higher thickness of the sheets.

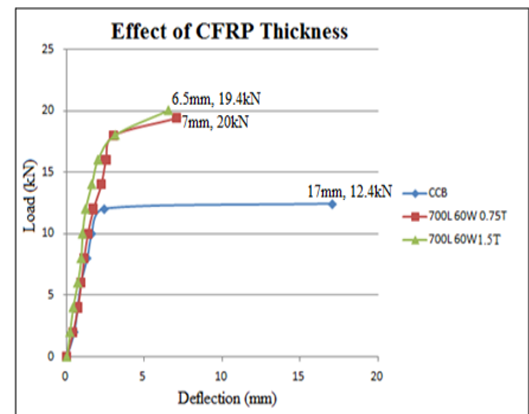


Fig-15: Thickness of CFRP sheet

3.5 Effect of width of CFRP sheets

Width of the CFRP sheet is varied to study its influence on ultimate load and deflection of the strengthened beam. Two beams i.e, 700L 60W 1.5T and 700L 100W 1.5T are used for studying the effect of width of CFRP sheets. It is observed from the experiment that as the width of CFRP sheet increases load carrying capacity of the beam also gets increased. For 700L 60W 1.5T beam ultimate load is 20kN and deflection is 6.5mm and for 700L 100W 1.5T beam ultimate load is 26kN and deflection is 6mm. There is a large increment in the load carrying capacity. Therefore width of CFRP sheet is the most important parameter. From the entire test results, maximum ultimate load is obtained for 700L 100W 1.5T (Fig-16).

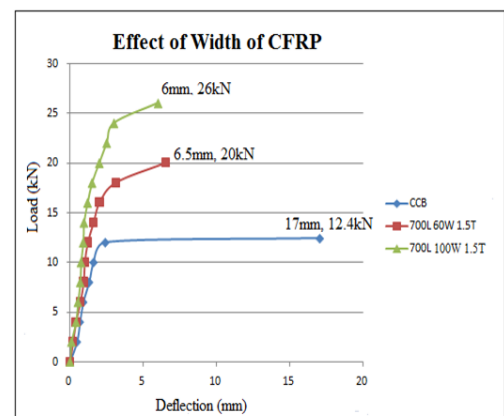


Fig-16: Effect of width of CFRP

4. CONCLUSIONS

The following major conclusions are drawn based on the experimental studies carried out under this investigation.

- The use of CFRP sheets for strengthening corroded RC beams is capable of maintaining structural integrity

- and increasing the ultimate strength of these beams to a level above the ultimate strength of the control beam.
- The use of CFRP sheets for strengthening RC beams decreased the ultimate deflection of these beams to a level below the control beam.
 - The bond length greatly influenced the flexural performance of the strengthened beam and it is clear that as the bond length increases, ultimate deflection at the midspan of the strengthened beam decreases considerably. For a bond length of 700mm there is a percentage decrease of 58.82% in ultimate deflection over corroded control beam.
 - Ultimate load of 700L 60W 0.75T is increased to 56.5% over control beam. While the ultimate loads for lower bond lengths are much less compared with 700L 60W 0.75T.
 - Thickness of CFRP sheet is also an important parameter which influences the ultimate load of the strengthened beam. 700L 60W 0.75T beam shown an ultimate load of 19.4kN and 700L 60W 1.5T has an ultimate load of 20kN and it is clear that the ultimate load increases with increase in thickness of CFRP sheet. There is an overall increase 0.6kN in the ultimate load of 700L 60W 1.5T over the beam strengthened with one layer of CFRP i.e. 700L 60W 0.75T.
 - Ultimate load increases as the thickness increases but it cannot be increased more than a limit since the problem of debonding can happen on higher thickness of the sheets.
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 - It is observed from the experiment that as the width of CFRP sheet increases load carrying capacity of the beam also gets increased. Therefore width of CFRP sheet is the most important parameter.

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