Protection and Strengthening of Corroded Prestressing Tendons

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Abstract. As of late, structural deterioration of RC structures affected by corrosion is widely reported. A new evolution in maintenance of RC structures is by cathodic protection by the use of carbon fiber reinforced polymers (CFRP). Using steel bar as a cathode and wrapping of CFRP as anode, which prevents removal of concrete cover and blocks further corrosion of steel. This article presents the utilization of CFRP for the protection of the strand. Series of laboratory trials using cathodic protection systems were performed on pre-stressed concrete structures in order to set up reliable cathodic protection systems. To initiate initial corrosion in the specimens, pre-stressing tendon used as the cathode and CFRP used as the anode while the in the active protection, the impressed charge was passed through the strand. Then, CFRP sheets were bonded by using conductive adhesive to the block samples. Extensively corrosive environment was imposed on the samples for the particular period of time and it was observed that the active protection method is very effectual in slowing down the corrosion of the strand.

Keywords: CFRP, RC Structure, Active Protection, Corrosion.

1. Introduction

The repair is required when the structure has lost its load carrying capacity. This process takes lot of time and if proper action is taken well in advance, then the costly repairs can be avoided. This is possible if the structures are monitored regularly. Therefore, there is a critical need for monitoring of R.C Structures by the use of new and emerging materials and technologies that will facilitate the functionality and efficiency, along with increasing the overall durability and life span of the structures “The more common of these methods are the half-cell potential, linear polarization resistance and AC impedance”[1]. “The half-cell potential method only predicts the probability of corrosion activity whereas linear polarization resistance and AC impedance are capable of measuring the corrosion rate that occurs in a system”[2][3]. “Various techniques for measuring the corrosion rate have been used to detect the corrosion at an early stage, in order to predict residual lives and accordingly decide what preventive or repair systems are to be applied”[4]. “There are various non–destructive techniques to monitor corrosion in reinforced concrete structures.”[5].” The coatings that are investigated by various authors involve alkyd, epoxy polyamide and polyester polymeric films”[6]. “The FRP sheets are being used for repair, strengthening and retrofitting of structural components due to their low weight, ease of handling and
rapid implementation. Also, FRP wrapped samples have shown substantially higher resistance to corrosion” [7] [8] [9]. “Concrete structures that are subjected to repeated service loads, weathering or chemical attack may display surface-breaking cracks. These cracks may eventually lead to failure of the structure as they extend from the surface into the material, or take a role in the corrosion of reinforcement in concrete” [10]. “It can be concluded here that recent developments in the field of FRPs have resulted in a highly efficient construction material. FRPs are being used increasingly to rehabilitate corrosion affected structures” [11]. “FRP plates can compensate the loss of longitudinal reinforcement in beams, slabs and columns. FRP sheets are wrapped around beams and columns to rehabilitate them from the loss of shear capacity and confinement due to corrosion of links or stirrups” [12]. The efficiency of FRPs in enhancement of bending and shear” [13]. “Degradation of steel reinforcements due to corrosion cracking of concrete due to weathering, rapidly changing traffic needs (both in terms of intensity and load levels)” [14] and “recent earthquake damages have necessitated the use of strengthening of basic structural components such as slabs, panels, walls, beams and columns” [15]. “Various researchers have reported that retrofitting by FRP wraps slows down the rate of corrosion thereby preventing the structure from damage” [16]. “Fibers can be formed from a wide range of amorphous and crystalline materials but in the construction industry the three fibers which are generally used in structural systems” [17]. “Organic coatings are effectively applied for the corrosion protection of metals, due partly to the role they play as a physical barrier between the metal surface and the corrosive environment” [18]. However, “all polymers are osmotic to potentially corrosive species such as oxygen, water and ions” [19]. The coatings that are investigated by various authors involve alkyd, epoxy polyamide and polyester polymeric films” [20][21]. “Establishing structures potential map, according to ASTM C876-91,[22] is the most commonly applied electrochemical technique for diagnosing the corrosion risk of reinforced concrete structures” [23]. “It can be concluded here that recent developments in the field of FRPs have resulted in a highly efficient construction material” [24]. “FRPs are being used increasingly to rehabilitate corrosion affected structures” [25]. FRP plates can compensate the loss of longitudinal reinforcement in beams, slabs and columns” [26]. “FRP sheets are wrapped around beams and columns to rehabilitate them from the loss of shear capacity and confinement due to corrosion of links or stirrups” [27]. “The efficiency of FRPs in enhancement of bending” and “capacities of flexure elements and enhancement of confinement of concrete in compression elements has been well established” [28].

2. Methodology:
Following chapter represents experimental setup to evaluate the effectiveness of using FRPs for Active Protection of R.C Structures. The effectiveness is monitored by the electrochemical techniques namely Half-cell Potential and LPR measurements. The objective of this present investigation is to explore the efficacy on FRP used in structural repairs that are damaged by corrosion. Since the structure is repaired after it has been damaged by corrosion, therefore experimental program necessitates creation of conditions where corrosion has already set in prior to FRP intervention. Corrosion is a process that requires several years and decades to set in. Preparation of samples that emulate the field conditions would be a long procedure. Their performance needs to be monitored over several years. Therefore, it is prudent to devise a pilot test that introduces rapid corrosion and provides quick results to enable us to identify the promising areas of further long-term investigations. In the present work the rapid corrosion is done by impressed current technique. The detailed experimental procedure involves the following steps:

- As per IS specifications, the basic properties of cement, fine aggregates, coarse aggregates and steel tendons are considered.
- Taking tendon of diameter 12.7 mm and cutting the tendons to required length 600 mm and cleaning it with Hexane Reagent solution.
- Then Coating the length of 150 mm of the pre-stressing tendons from both ends with epoxy paint so as to protect that portion of tendon from corrosion, no current will pass through that portion due to epoxy coating.
• Preparation of nine blocks of size 300 x 300 x 60 mm using M30 grade of concrete with pre-stressing tendons placed.
• Further subjecting the block specimens to accelerated corrosion by impressed current technique, having initial 5 mV voltage.
• Retrofitting of corroded slab specimens is done and further Active Protection of strand is done by supplying applied current of 10mA. Three different Protections is provided namely: During corrosion initiation, At the time of outset of crack and 2 days after the outset of crack.

2.1. Materials
Pre-stressing tendons, coarse aggregates, fine aggregates, cement, water, are the primary materials used in the preparation of sample required for the investigation.

2.1.1. Pre-stressing Tendons
Tendon of nominal diameter 12.7 mm and of length 600 mm were used as a standard size. Table 12. Shows the properties of 12.7 mm diameter strand as provided by the company. Using hexane reagent solution, the tendons are cleaned with sand paper and use petrol for cleaning to remove unwanted particles from the tendons. Until it was placed in concrete, the white shining surface was kept in the laboratory.

2.1.2. Coarse Aggregate
Two different sizes of crushed aggregates: 10 mm and 20 mm were used in this study for coarse aggregates. To remove dust and dirt, the aggregates are washed and are dried. As per IS: 383-1970, the tests were performed on aggregates. Table 1, table 2 and table 3 consist of the results of various tests conducted on coarse Aggregates.

2.1.3. Fine Aggregate
For the laboratory work fine aggregates of grade III is used. As per IS 383-1870, the Sieve Analysis is carried out. Table 7 and Table 8 shows the sieve analysis and physical properties of fine aggregates respectively.

2.1.4. Cement
In the present investigation, Portland Pozzolana cement (PPC) was used. The cement is of grey color with a light greenish shade and having no any hard lumps.

| S.No. | Characteristic          | Value of 20 mm | Value of 10 mm |
|-------|-------------------------|----------------|----------------|
| 1     | Type                    | Crushed        | Crushed        |
| 2     | Total Water absorption  | 0.64%          | 0.56%          |
| 3     | Finess Modulus          | 8.625          | 6.833          |
| 4     | Specific gravity        | 2.66           | 2.63           |
Table 2. Sieve Analysis of Coarse Aggregate (20 mm size)

| S. No. | Sieve Size | Mass Retained | Percentage Retained | Cumulative Percentage Retained | Percentage Passing |
|--------|------------|---------------|---------------------|---------------------------------|--------------------|
| 1      | PAN        | 0.02          | 0.56                | 99.98                           | -                  |
| 2      | 4.75 mm    | 0.1           | 2.83                | 99.42                           | 0.58               |
| 3      | 10 mm      | 3.28          | 92.91               | 96.59                           | 3.41               |
| 4      | 20 mm      | 0.13          | 3.68                | 3.68                            | 96.32              |

Total Mass taken = 3.53 Kg
Fineness Modulus = 6.99

Table 3. Sieve Analysis of Coarse Aggregate (10 mm)

| S. No. | Sieve Size | Mass Retained | Percentage Retained | Cumulative Percentage Retained | Percentage Passing |
|--------|------------|---------------|---------------------|---------------------------------|--------------------|
| 1      | PAN        | 0.1           | 7.09                | 99.99                           | -                  |
| 2      | 4.75 mm    | 0.61          | 43.26               | 92.9                            | 7.1                |
| 3      | 10 mm      | 0.7           | 49.64               | 49.64                           | 50.36              |
| 4      | 20 mm      | 0             | 0                   | 0                               | 100                |

Total Mass taken = 1.41 Kg
Fineness Modulus = 6.42

Table 4. Physical properties of Fine Aggregate

| S. No. | Characteristic | Value |
|--------|----------------|-------|
| 1      | Water absorption | 2.465 |
| 2      | Specific gravity | 2.567 |
| 3      | Bulk Density    | Loose-1.48 g/cc |
|        |                 | Compacted - 1.6 g/cc |
| 4      | Fineness Modulus | 2.465 |
| 5      | Gravity Zone    | Zone III |

Table 5. Sieve analysis of Fine Aggregate

| S. No. | Sieve Size | Mass Retained (gm) | Percentage Passing (%) |
|--------|------------|--------------------|------------------------|
| 1      | PAN        | 59                 | 94.1                   |
| 2      | 150 μ      | 306                | 69.4                   |
| 3      | 300 μ      | 289.5              | 71.05                  |
| 4      | 600 μ      | 107.5              | 89.25                  |
| 5      | 1.18 mm    | 163.5              | 83.65                  |
| 6      | 2.36 mm    | 49                 | 95.1                   |
| 7      | 4.75 mm    | 12.5               | 98.75                  |
| 8      | 10 mm      | 0                  | 100                    |

Total Weight taken = 1000 gm,
Fineness Modulus of Fine Aggregate = 2.465
2.1.5. Water
For casting the specimens, fresh and clean tap water was used in the present study. As per Indian standard, the water was relatively exempt from organic matter, sugar, chloride, silt, oil and acidic material.

2.1.6. CFRP Materials
Carbon FRP sheets has been used which are commercially available world over was used in present investigation. The Unidirectional CFRP sheets used for wrapping and protecting the corroded samples of cross section (300 x 0.1176) mm. From the BASF construction chemicals and building systems, the CFRP sheets are taken.

2.1.7. Adhesive
Manufacturer recommends the compatible epoxy system that is the adhesive used for (Zerokor 21 AD) for bonding FRP sheets with concrete.

2.2. Concrete Mix Design
By using fine aggregate and crushed stone coarse aggregate of size 20 mm and 10 mm and Portland pozzolana cement (PPC), M30 concrete mix is prepared. As per IS Guidelines, the mix was designed. 1:2.36:3.72 is the ratio of cement: sand: coarse aggregate. 0.43 was the water-cement ratio and 36 MPa was the compressive strength of concrete after 28 days.

2.3. Preparation of Specimen
Specimens were blocks of size 300 x 300 x 60 mm with the tendons placed at the center. To prepare the specimens the tendons were pre-conditioned and then blocks were cast. The detailed procedure is explained in the following section:

2.3.1. Preparation and Pre-conditioning of Pre-stressing Strands
In the present work, Pre-stressing Strands of nominal size 12.7 mm diameter was used. Firstly, required length of 600 was attained by cutting the strands. To remove any surface scale, each strand is then wire brushed. Strands are thoroughly cleaned by using Hexane reagent solution and Petrol and allowed to air dry for removal of unwanted impurities from the surface. As similar as specified in ASTM G 109[3] the strand specimen was prepared. Each strand was weighed to 0.1 gm.

2.3.2. Block Specimen Preparation:
For the preparation of sample, slab mould with pre stressing tendons positioned homocentrically was cast. A lubricating agent was applied in the interior of slab mould for the easy removal of slab. For the protrusion of 150 mm lengths of tendons outside the sample strands were embedded in concrete. Concrete mix is poured and vibration was provided for the proper compaction after the positioning of tendons. For the excursion of voids vibration was done properly. After 24 hours, the sample was then detached from the mould. Curing of the sample is done for 28 days.

2.3.3 Inducing Corrosion
In present study impressed current method is used. By immersion into Sodium Chloride corrosion can be induced. For the rapid induction of corrosion impressing anodic current method can be used. The sample was submerged in Sodium Chloride solution and direct charge was passed. To provide even distribution of NaCl solution, mats are placed over the tops. The strand was used as an anode. In order to cover electrical continuity was utilized as cathode.

2.4. Techniques for monitoring corrosion
For the monitoring of corrosion in the different samples two method were used in the present study. Two methods were half-cell measurement method and LPR method as one method will only provide the risk of corrosion and the other method will indicate the rate of immediate corrosion.
2.4.1. Half Cell Measurement
In this investigation, by using half-cell potential, all the sample was observed daily by placing the electrode on top surface of the concrete where saturated calomel will be used as electrode. ASTM Standard C 876 recommends this procedure. In order to completely depolarize it, the electricity supply was turned off an hour before observing the half-cell values. For the period of 30-day experimental test, there was a need replace the dripping salt water daily, cleaning of electrodes. Probability was that at the time of measurement, No pre-stressing strand corrosion was occurring in the area if the potential value is more positive than -200mV, strand corrosion starts occurring when potential value is more negative than -426mV.

2.4.2. Measurement of Linear Polarization Resistance (LPR)
For measuring the localized corrosion, Electrochemical LPR technique was especially good. For precise location of strands guard ring that is supplied with the field machine was used in LPR measurements on concrete surfaces. Front panel is connected via cables to the guard rings. Cu/CuSO4 reference electrode was incorporated into the Guard Ring. Before performing the test, NaCl solution was used to make the conducting sponge wet and for the proper electrical contact to guard ring. Wetted sponge was then placed below the Guard ring assembly.

2.5. Active Protection
Active Protection is a method in which ceasing rebar corrosion in chloride contaminated concrete is the main aim. Around the strand, the alkalinity of the concrete is restored and a favorable environment for the of strand passivation is revamped. The method where the pre stressing strand functions as cathode and external surface of the concrete wrapped by carbon fiber reinforced polymer sheets functions as anode.

2.6. Corrosion of wrapped specimen
Objectives of present work were to evaluate the effect of impressed current for the active protection. An initial exposure was applied before wrapping to simulate corrosion deteriorated structures. The exposure time was adjusted so as to have three damage levels i.e. onset of corrosion, 2 days after beginning of detectable crack and beginning of detectable crack. After corrosion, FRP sheets were used to wrap the specimens and a 10-mA constant anodic current was provided with tendon (cathode) and CFRP sheet (anode). The sample for Active Protection, in which carbon fiber ribbon are connected to the positive terminal and the pre stressing strand is connected to the negative terminal. For a period of 30 days, monitoring of corrosion was done by using half-cell potential and LPR measurements. For comparison, three specimens are kept under passive protection in which they are corroded to the levels explained earlier and then wrapped with CFRP Sheets. No current is applied between the sheet and the tendon. The monitoring procedure is similar to the one explained earlier.

3. Result & Discussion
Analysis of Structure (bearing from corrosion of the strand) was performed. It is important to observe the various change in the corroded structure with time to time. The main aim of this investigation is to look over the potency of the Carbon Fiber Reinforced Polymer composites. These CFRP’S were used with active protection to restore or maintain the corroded reinforced slabs.

3.1. Measurements of Half Cell Potential
Half-cell potential (Ecorr) was noted everyday of tendons in all the samples throughout the period of work. As a reference electrode, saturated calomel electrode was utilized. The specimens should be depolarized before taking the Half Cell Potential reading, to estimate the electrochemical signals accurately. The current is interrupted for one hour to attain this objective, before to the computation of the half-cell potential. During active corrosion protection the main purpose of the present work is to explore the effect of applied charge and passive corrosion protection on behaviour of slabs. 10 mA (40
μA/cm²) of current are chosen for this objective for all 6 slabs. During the test period, Fig. 1 shows variation of half-cell potential for three block specimens subjected to passive protection. Fig. 2, Fig. 3, Fig. 4, shows the effect of half-cell potential during the test duration for six block specimens subjected to active protection.

The applied electrochemical technique for identifying the risk of corrosion in the RC structures is establishing structures potential map, according to ASTM C876-91. When the open circuit voltage was less than -426 mV (SCE), possibility of corrosion in rebar placed in concrete was more than 90% recommended by ASTM C876-91. In the beginning stages of speeding up corrosion, the corrosion threshold values i.e -426 mV was more than the half-cell potential values, which shows that corrosion had not started yet. After that the observations kept on reducing to the more negative value showing depassivation of strand, until it attained a stage of critical corrosion. For all specimens, this rate of fall was nearly uniform. Longitudinal cracks start to be seen along the length of the strand with the passage of time.

Bursting stresses in the concrete is caused by the evolution of corrosion along the strand. This implies that the corrosion damages the structural capacity of the element and strand cross section. More critical and dangerous situation occurred if the occurrence of longitudinal cracking was not repaired. This was the reason that the retrofitting of slabs was needed at this stage. Observation from the investigation of the results shows sudden fall in half-cell potential of the strand sample after a certain interval of time. This implies that a definite amount of chloride had attained the pre-stressing strand will lead to the initiation of the corrosion as it had become anodic.

However, the half-cell value starts increases slowly, after issuing active protection in specimens of six slabs. After this, FRP performs as a hindrance for the chlorides and slows down the performance of the corrosion. However, the Ecorr will require more time to reach passive stage as the value of specimens was still in the of active corrosion stage. Therefore, long-term testing was needed on specimens that had been adequately repaired, in order to fully assess the efficacy of FRP composite wrap in the prevention of corrosion. Moreover, after providing Passive Protection in another 3 slab specimens i.e., after wrapping with FRP sheet only without allowing Impressed current to pass through slabs, shows that FRP did give out the purpose as a productive barrier to corrosion activity, but passive protection provide extremely slow recovery from corrosion. The half-cell potential values slowly reach to less negative potential in the case of passive protection by FRPs.

From above two protection methods, it can be concluded that Active protection provide sufficient and adequate recovery from Corrosion on slabs, while Passive protection with FRP sheets arrest the further corrosion but did not recover much from corrosion as compared to Active protection.

3.2. Corrosion Rate by LPR Technique

The values observed from corrosion current density (Icorr) indicates the continuation of corrosion in the propagation phase, that’s why LPR measurements were required. This method is more reliable than Half-cell method as Half-cell method indicates only probability of corrosion initiation in slabs.

Fig. 5 shows variation in corrosion current density (Icorr) during the test period for three block specimens subjected to passive protection by LPR method. Fig. 5 – 8 shows variation in corrosion current density (Icorr) during the test period for six block specimens subjected to active protection at the beginning of crack and two days after crack, beginning t of corrosion respectively, by LPR method.

By LPR method Icorr is determined indicates that the corrosion current density (Icorr) enhanced with days subjected to voltage due to enhancement in amount of chloride around the strands in all the samples. Value of Icorr hike as the corrosion advances in the slabs. Due to the concentration of chlorides (NaCl), the depassivation of layer appeared around the strand. From the Fig. 5 – 8, it is concluded that the Icorr values was between 7 – 10 μA/cm² during the acceleration process, which shows that there was less corrosion. It indicates moderate corrosion if the exposure value Icorrwere increasing upto 25 μA/cm². Further as the exposure value enhanced, It indicates major corrosion and crack was observed if Icorr reaches 35 μA/cm². However, after active protection the risk of corrosion was lessen from high to moderate as the value of Icorr starts decreasing.
During Passive Protection provided to slab specimen wrapped only with FRP Sheets subjected to different stages of corrosion namely (i) beginning of corrosion, (ii) beginning of detectable crack and (iii) two days after beginning of visible crack, values of corrosion current density are constant after protection or are decreasing at very slow rate, with the values remaining almost at the same level at which protection was provided. One the other hand active protection lowers the corrosion current at the faster rate. However, the final Icorr values have not yet stabilized after 30 days of monitoring and the specimens are to be protected and monitored further. Table 6 shows Corrosion condition at different values of Icorr. On comparing further, the protection of tendon with the protection of rebar [27], it is observed that the rebar are protected more effectively as compared to tendons. In rebars, the Icorr values came in very low corrosion stage within 30 days, as opposed to tendons, in which Icorr values are still in moderate corrosion stages.

The investigation results indicate that although the corrosion rate decreased by wrapping the CFRP sheet by both active protection and passive protection. However, for decreasing the corrosion rate, active protection is very effective. However, eliminate the corrosion activity completely, long term monitoring is required.

Table 6. Corrosion condition at different values of Current Density

| S. No. | Icorr (μA/cm²) | Corrosion Condition               |
|--------|----------------|-----------------------------------|
| 1      | 7-10           | Low Corrosion                     |
| 2      | Upto 25        | Moderate Corrosion                |
| 3      | 35             | Major Corrosion with crack        |
**Figure 1.** Passive and Corrosion Protection given on block specimen at three stages of corrosion by Half-cell potential.

**Figure 2.** Active and Corrosion Protection given on block specimen at onset of Corrosion by Half-Cell Measurement.
Figure 3. Corrosion and Active Protection given on block specimen at the onset of visible Cracks

Figure 4. Corrosion and Active Protection of Block Specimen Two days after crack

Figure 5. Corrosion and Passive Protection at the beginning of corrosion on slab-1

Figure 6. Corrosion and Active Protection at the beginning of detectable crack on slab-2
Figure 5. Corrosion and Passive Protection provided on block specimen at Three Stages of corrosion by LPR Method.

Figure 6. Corrosion and Active Protection provided on block specimen at onset of corrosion by LPR Method.
Figure 7. Corrosion and Active Protection provided on block specimen at the time of visible crack by LPR Method.

Figure 8. Corrosion and Active Protection provided on block specimen, Two days after crack by LPR Method.

4. Conclusion

The results which are acquired from the tests, performed in this work concluded that:

- By using tendon as cathode and carbon wrap as anode; Carbon fibre reinforced polymer can be employed effectively in issuing active protection.
- In words of corrosion protection and prevention, the protection current can alter the material structure to favourable trend.
- The rate of corrosion in concrete block specimens decreases in the active protection when came in contact with an extreme chloride environment to a larger level.
- LPR method is more authentic method used for monitoring when compared with half-cell method.
- Actively Protected block specimen’s shows better corrosion protection with time irrespective of time of wrapping as compared to passively protected block specimen.
- Corrosion behaviour of pre stressing strands efficiently measured by LPR and Half-Cell.
Though, one single method is enough for giving all particulars about corrosion behaviour and hence both the electrochemical techniques are used simultaneously for the better results.

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