"ACTIVE PROTECTION OF CORRODED STEEL REBAR EMBEDDED IN FRP WRAPPED CONCRETE"

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IN

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CERTIFICATE

This is to certify that the work which is presented in this thesis report entitled "**Active Protection of Corroded Steel Rebar Embedded in FRP Wrapped Concrete**" being submitted by **Nimrat Pal Kaur, Roll No. 800922014** in partial fulfillment of requirements for the award of degree of **MASTERS OF CIVIL ENGINEERING (STRUCTURAL ENGINEERING) at Civil Engineering Department, Thapar University, Patiala,** is a bonafied work carried out by her under the supervision of **Dr. Abhijit Mukherjee**, Director, Thapar University, Patiala and **Dr. Shweta Goyal,** Assistant Professor, Thapar University, Patiala.

The matter embodied in this report has not been submitted in part or full to any other university or institute for the award of any degree.

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ABSTRACT

Reinforced concrete is one of the most commonly used construction materials in civil engineering but its durability problems have been obsessing people. The worst of these problems is caused by corrosion of steel in concrete, inducing the early deterioration of concrete infrastructures. Structural deterioration of reinforced concrete structures affected by corrosion is a gradual process consisting of a few different phases during service life, including corrosion initiation, concrete cracking, excessive deflection and final collapse due to loss of structural strength.

An increasing number of concrete structures are being monitored to enhance their durability. In the last few decades, a number of damage detection techniques such as destructive and non destructive techniques have been developed to analyze the changes in a structure due to corrosion.

A new development in the repair and rehabilitation of RC systems is the use of carbon fiber reinforced polymers (CFRP). These materials have received great attention and their applications to structural repair and retrofit have grown significantly in recent years. CFRP fabrics are largely employed because it offers superior performance such as resistance to corrosion, high stiffness-to-weight ratio, high tensile strength, light weight, high durability and easy installation etc.

The CFRP wraps provide a barrier layer that is expected to impede further corrosion of steel. The FRP sheets, when wrapped around RC members, apply confinement pressure that prevents increase in volume due to rusting. Thus it prevents dislodging of concrete cover. Another important advantage CFRP could be active protection of structures using CFRP wraps as anode. The unique proposition of the present thesis is the use of FRP wraps as anode for active protection. However, it is important to maintain high and uniform electric conductivity of the wrap for effective protection. This thesis investigates carbon FRP (CFRP) composites for active protection of RC structures by using non destructive monitoring techniques.

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CHAPTER 1

INTRODUCTION

1.1 GENERAL

Reinforced concrete (RC) is an extremely popular construction material. It has proven to be successful in terms of both structural performance and durability. Because of the nature and role of concrete in the creation, rehabilitation and regeneration of the infrastructure system of any country, RC plays a very important part in a nation's economic development. Lack of durability of RC structures has thus not only massive economic implications to a nation's well-being, but it is also one of the greatest threats to sustainable growth of concrete and construction industries.

Whatever the source of deterioration and the mechanism of its development, corrosion of embedded reinforcement is recognized as the major problem affecting the durability of concrete structures. It has been found that 40% failure of structures is on account of corrosion of embedded steel in concrete (Sethy, 2005). Therefore corrosion control of steel reinforcement is a subject of paramount importance. Corrosion is a form of damage which is often insidious and hidden until striking at the worst moment of a system operation. The reason of these phenomena is explainable with the mechanism of corrosion. When reinforcement corrodes, the corrosion products generally occupy considerably more volume than the steel. The magnitude of this increase in volume varies approximately 2 or 3 times the volume of the original material. As a result, the corrosion products produce an internal stress that destroys the neighboring concrete under tensile stress.

Maintenance and repair of reinforced concrete structures mainly due to corrosion damage is presently one of the most significant challenges facing the concrete industry. While there are many ways to try and prevent such damage, the optimum control method relies on an early diagnosis of the problems. Reinforcing steel in good quality concrete does not corrode even if sufficient moisture and oxygen are available. This is due to the spontaneous formation of a thin protective oxide film (passive film) on the steel surface in the highly alkaline pore solution of the concrete. When sufficient chloride ions (from deicing salts or from sea water) have penetrated to the reinforcement or when the pH of the pore solution drops to low values due to carbonation, the protective film is destroyed and the reinforcing steel is depassivated.

Although corrosion of steel may not immediately affect the integrity and the ultimate load carrying capacity of a RC structural member, it is the most complex, insidious and destructive form of damage. Once it starts, it is almost impossible to stop the process until eventually the safety, stability and design service life are all drastically reduced with time.

1.2 CORROSION MONITORING OF RC STRUCTURES

Waiting for visible signs of distress to appear on concrete structures is a very expensive method of maintaining a structure. Repair cost by this stage can be astronomical (especially when costs to take the structure off line are included). Therefore corrosion monitoring is necessary as it allows the corrosion to be caught before its onset and opens up much more economical maintenance options such as coating, retrofitting etc. Corrosion measurement employs a variety of techniques to determine how corrosive the environment is and at what rate metal loss is being experienced. Corrosion measurement is the quantitative method by which the effectiveness of corrosion control and prevention techniques can be evaluated and provides the feedback to enable corrosion control and prevention methods to be optimized.

Corrosion monitoring gives a complete picture of the changing condition of a structure with time and there are several methods of monitoring the corrosion of steel reinforcement in concrete for laboratory tests. The more common of these methods are the half cell, linear polarization and AC impedance. The half cell method only predicts the probability of corrosion activity whereas linear polarization and AC impedance are capable of measuring the corrosion rate that occurs in a system. (*Raharinaivo et. al (1986), Bonacci & Maleej (2000), Bertolinia et. al (2004)).*

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 (*Song and Saraswathy, 2007*). New RC structures incorporating one or more of these new strategies are likely to have much longer durable service life than those constructed before.

In the last few decades, a number of damage detection techniques such as destructive and non destructive techniques have been developed to analyze the changes in a structure due to corrosion. Destructive techniques result in accurate measurements and gives specific characteristics of materials by destroying the specimen. Pullout strength, mass loss and compression test are some examples of destructive testing. Non-destructive techniques, on the other hand, monitor the material quality without destroying the specimen. For example, the oil and gas systems deployed in the most remote areas, often at depths never exploited before, or the transmission pipelines traversing the harshest environments on the planet. The inspectability of these systems is very limited and extremely costly. Therefore in many areas of modern engineering, non-destructive evaluation (NDE) techniques have provided valuable and often critical information for the safe operation of the most complex systems. Such usefulness has recently been greatly enhanced by the tremendous advances in computer and communication tools.

Non-destructive techniques such as visual inspection of the surface of the structure are simple and cost-effective technique. However, it relies on the skill of the inspector and cannot provide accurate information on crack depth. Moreover, cracks that have just started to appear may be too small to be visible. Therefore, other non-destructive techniques such as radiography, ultrasonic testing, magnetic particle testing, acoustic emission etc, are necessary to complement visual inspection. The most common non–destructive techniques to monitor corrosion in reinforced concrete structures are given below which are discussed in detail in Chapter 3 (*Song and Saraswathy, 2007*):

- Open circuit potential Measurements
- Surface potential Measurements
- Linear Polarization Resistance Method
- Electrochemical Impedance Spectroscopy
- Half Cell Potential Measurements
- Ultrasonic Pulse Velocity Method
- Impact-echo method
- Acoustic Emission
- Infrared Thermography

Due to the presence of damage in a structure, a number of acoustic/ultrasonic damage detection techniques are developed to analyze the changes of linear properties. Of all the techniques used for monitoring reinforcement corrosion, ultrasonic inspection or ultrasonic testing (UT) is one of the most widely used NDE techniques, which is applied to measure a variety of material characteristics and conditions. Ultrasonic examination is performed using a device that generates an ultrasonic wave with a piezoelectric crystal at a frequency between 0.1 and 25 MHz into the piece being examined and analyzes the return signal. The method consists in measuring the time it takes for the signal to return and the amount and shape of that signal.

1.3 FRPs AND MONITORING OF RETROFITTED ELEMENTS

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) and recent earthquake damages have necessitated the use of strengthening of basic structural components such as slabs, panels, walls, beams and columns. Fiber Reinforced Plastic (FRP) composite wraps, which are commonly used in seismic retrofits have been considered as an effective tool for repairing corrosion damage in concrete. FRP materials have very high strength-to-weight and strength-to-stiffness ratios. They are corrosion resistant and have a low axial coefficient of thermal expansion. The material is ideal for retrofits because it is easy to handle, can conform to the shape of existing elements, and can be applied quickly. Some disadvantages of FRP composites are high initial costs, but is overcomed regarding long-term behavior of the material properties and long-term durability.

Glass and Carbon fibre reinforced polymers (CFRP) sheets have been extensively used in today’s world for retrofitting of existing structures. These are usually bonded to the surface of the concrete structure and are utilized to strengthen existing structures or rehabilitate structures damaged by corrosion.

For strengthening beams, two techniques are adopted. First one is to paste FRP plates to the the tensile face of a beam. This increases the strength of beam, deflection capacity of beam and stiffness (load required to make unit deflection). Alternately, FRP strips can be pasted in 'U' shape around the sides and bottom of a beam, resulting in higher shear resistance. Columns in building can be wrapped with FRP for achieving higher strength and to provide confinement pressure, hence controls further formation of cracks in concrete. It also increases the load carrying capacity of the system.

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 (*Gadve et. al (2008), Bonacci & Maleej (2000), Debaiky et. al (2002)*). However after repair of the corroded structure, it is essential to monitor the structure for further damage.

1.4 FORMAT OF THESIS

The main aim of the study is to monitor the corrosion behavior of RC elements by using NDT techniques and providing active protection by retrofitting with FRP sheets.
The thesis has been divided into five chapters.

1st chapter is about general introduction about corrosion, its monitoring, FRPs and monitoring of FRP elements.

2nd chapter explains in detail the causes and mechanism of rebar corrosion. Also a brief description on different types of corrosion is been given.

3rd chapter deals with various NDT methods used for monitoring of RC structures. A number of electrochemical rebar corrosion measurement techniques available presently are reviewed to possess with certain advantages and limitations.

4th chapter deals with FRPs and monitoring of retrofitted elements. In this, various types of FRPs their advantages and suitability have been discussed. Also the need for monitoring of retrofitted elements has been mentioned.

5th chapter presents a thorough review of literature on nondestructive monitoring techniques as well as the Ultrasonic guided waves for monitoring rebar corrosion in concrete. Also a thorough review of literature on Fiber Reinforced Plastic (FRP) composite wraps for corrosion protection is also presented.

6th chapter deals with the experimental programme wherein all tests, procedures and measures to be followed during experiments are explained in detail.

7th chapter deals with results and discussions where findings of the experimental programme are explained in detail.

8th chapter is the concluding chapter.

CHAPTER 2

CORROSION PROCESS

This chapter discusses the basics of corrosion and how they apply to steel in concrete.

2.1 INTRODUCTION

Given the widespread use of reinforced concrete in infrastructure, understanding the corrosion of rebar is of major importance. Corrosion of steel reinforcement is the most common durability problem of reinforced concrete structures. Steel in concrete is normally protected from corrosion by a passive film of iron oxides on the steel surface resulting from the natural alkaline environment of the concrete. The passive film is chemically stable in the absence of carbonation and chloride ions (*Bentur et. al (1997), Broomfield (1997)*). The ingress of chloride ions (Cl^-) to the level of the steel reinforcing bars destroys the passive film and initiates corrosion. This makes reinforced concrete structures in coastal areas and/or marine environments vulnerable to damage by corrosion of steel reinforcement. Reinforced concrete infrastructures located in cold environments are also susceptible to corrosion damage due to the use of deicing salts. Once corrosion is initiated, electrochemical reactions occur, leading to the formation of expansive corrosion products that create tensile stresses in the concrete surrounding the corroding steel reinforcing bar. This results in concrete cracking and spalling, which aggravates the progressive damage, thus affecting the durability of the structure.

In this chapter the basic mechanisms of corrosion have been discussed.

2.2 CAUSES OF REBAR CORROSION

It is well known that if bright steel is left unprotected in the atmosphere a brown oxide rust quickly forms and will continue to grow until a scale flakes from the surface. In the concrete structures, reinforcing steel-bars (rebars) normally do not corrode because of a passive film formed on the surface of rebar in concrete of high pH. When chloride concentration at the level of rebar in concrete, however, exceeds the threshold value for corrosion, the passive film is destroyed and corrosion is initiated in rebar. The electro-chemical reaction continues with supplying oxygen and water. Then, due to expansion of corrosion products, corrosion-induced cracks are generated in concrete.

Sound concrete is an ideal environment for steel but the increased use of deicing salts and the increased concentration of carbon dioxide in modern environments principally due to industrial pollution, has resulted in corrosion of the rebar becoming the primary cause of failure of this material. The scale of this problem has reached alarming proportions in various parts of the world.

Carbonation of concrete or penetration of chlorides into the concrete, are the major causes of reinforcement corrosion. Chlorides in concrete either penetrate from the surrounding chloride-bearing environment (such as moisture, oxygen, humidity, temperature, bacterial attack, stray currents, etc.) or contribute from the concrete ingredients (such as concrete quality, w/c ratio, cement content, impurities in the concrete ingredients, presence of surface cracks, etc).

The assessment of the causes and extent of corrosion is carried out using various electrochemical techniques (*Broomfield, 2006*). Prediction of the remaining service life of a corroding reinforced concrete infrastructure is done with the help of empirical models and experimental methods (*Weyers, 1998*).

Following are the two most common contributing factors leading to reinforcement corrosion:

(i) Localized breakdown of the passive film on the steel by chloride ions called chloride attack.

(ii) General breakdown of passivity by neutralization of the concrete, predominantly by reaction with atmospheric carbon dioxide called carbonation.

These major factors along with various other factors that lead to rebar corrosion are explained in detail in the following sections.

2.2.1 Loss of Alkanity due to Chlorides

The passivity provided by the alkaline conditions can also be destroyed by the presence of chloride ions, even though a high level of alkalinity remains in the concrete. The chloride ion can locally de-passivate the metal and promote active metal dissolution. Chlorides react with the calcium aluminate and calcium aluminoferrite in the concrete to form insoluble calcium chloroaluminates and calcium chloroferrites in which the chloride is bound in non-active form. However, the reaction is never complete and some active soluble chloride always remains in equilibrium in the aqueous phase in the concrete. It is this chloride in solution that is free to promote corrosion of the steel. At low levels of chloride in the aqueous phase, the rate of corrosion is very small, but higher concentration increases the risks of corrosion.

2.2.2 Loss of Alkanity due to Carbonation

Carbonation is a result of the interaction of carbon dioxide gas in the atmosphere with the alkaline hydroxides in the concrete. Due to the high alkalinity of the concrete pore water, the steel reinforcing bars are passivated by an iron oxide film (Fe_2O_3) that protects the steel. The passivating layer of hydrated iron oxide is 2–20 nm thick. At this pH value a passive film forms on the steel that reduces the rate of corrosion to a very low and harmless value.

Concrete is permeable and allows the slow ingress of the atmosphere; the acidic gases react with the alkalis (usually calcium, sodium and potassium hydroxides), neutralizing them by forming carbonates and sulphates, and at the same time reducing the pH value. If the carbonated front penetrates sufficiently deeply into the concrete to intersect with the concrete reinforcement interface, protection is lost and, since both oxygen and moisture are available, the steel is likely to corrode. The extent of the advance of the carbonation front depends, to a considerable extent, on the porosity and permeability of the concrete and on the conditions of the exposure.

In the case of carbonation, atmospheric carbon dioxide (CO_2) reacts with pore water alkali according to the generalized reaction,

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O \qquad \ldots\ldots\ldots\ldots\ldots\ldots 2.1$$

It consumes alkalinity and reduces pore water pH to the 8–9 range, where steel is no longer passive.

2.2.3 Cracks due to Mechanical Loading

Cracks in concrete formed as a result of tensile loading, shrinkage, frost attack or other factors allows the ingress of water and oxygen from atmosphere and provide a zone from which the carbonation front can develop. If the crack reaches the surface of rebar the protection can be lost. Due to formation of cracks, debonding of steel and concrete occurs to some extent on each side of the crack, thus removing the alkaline environment and so destroying the protection in the vicinity of the debonding.

2.2.4 Corrosion of Rebar due to Atmospheric Pollution

Most of the times steel reinforcement is exposed to the atmosphere during transportation and storage in the building sites for a long period before their installation in the concrete structures. At any of those stages, steel rebars can be contaminated by chloride ions from windblown salt. This fact leads to the formation of corrosion products on their surface.

2.2.5 Moisture Pathways

If the surface of the concrete is subjected to long-term wetting, the water will eventually reach the level of the reinforcement, either through diffusion through the porous structure of the concrete, or by traveling along cracks in the concrete. Concrete roof decks, by their nature, are meant to be protected from moisture. However, the presence of moisture on roofing systems may result from failure of the roofing membrane, poor detailing of drainage facilities, or lack of maintenance of drainage facilities.

2.2.6 Water-Cement Ratio

Concrete placed with a high water-cement ratio, is more porous due to the presence of excess water in the plastic concrete. The porosity increases the rate of diffusion of water and electrolytes through the concrete and makes the concrete more susceptible to cracking.

2.2.7 Corrosion due to Difference in Environments

Corrosion occurs when two different metals, or metals in different environments, are electrically connected in a moist or damp concrete. This will occur when:

1. Steel reinforcement is in contact with an aluminium conduit.
2. Concrete pore water composition varies between adjacent or along reinforcing bars.
3. There is a variation in alloy composition between or along reinforcing bars.
4. There is a variation in residual/applied stress along or between reinforcing bars.

The aggressiveness of environmental conditions is exacerbated by deicing salts spread on roads and pavements. Deicing salts not only increase pressures within the concrete, but also diminish its ability to withstand them. The application of de-icing agents to a concrete surface covered with ice will cause a substantial drop in temperature at the concrete surface during thawing of the ice. The difference in temperature between the surface area and the interior of the concrete gives rise to a state of internal stresses likely to induce cracking in the region of the outer layer of the concrete.

2.2.8 Low Concrete Tensile Strength

Concrete with low tensile strength facilitates corrosion damage in two ways. First, the concrete develops tension or shrinkage cracks more easily, admitting moisture and oxygen, and in some cases chlorides to the level of the reinforcement. Second, the concrete is more susceptible to developing cracks at the point when the reinforcement begins to corrode.

2.2.9 Electrical Contact with dissimilar metals

Dissimilar metals in contact initiate a flow of electrons that promotes the corrosion of one or the other, by a process known as galvanic corrosion. When two dissimilar metals are in contact with each other, the more active metal will induce corrosion on the less active metal. Such corrosion may induce cracking and damage in the concrete.

2.3 CORROSION MECHANISM OF REBAR

The corrosion of steel reinforcing bars is an electrochemical process that requires a flow of electric current and several chemical reactions.

The three essential components of a galvanic corrosion cell are:

- Anode
- Cathode
- Electrolyte

The anode is the location on a steel reinforcing bar where corrosion is taking place and metal is being lost. At the anode, iron atoms lose electrons to become iron ions (Fe^{+2}). This oxidation reaction is referred to as the anodic reaction. The cathode is the location on a steel reinforcing bar where metal is not consumed. At the cathode, oxygen in the presence of water, accepts electrons to form hydroxyl ions (OH^-). This reduction reaction is referred to as the cathodic reaction. The electrolyte is the medium that facilitates the flow of electrons (electric current) between the anode and the cathode. Concrete, when exposed to wet and dry cycles, has sufficient conductivity to serve as an electrolyte. **Fig. 2.1** illustrates the corrosion cell for a steel reinforcing bar embedded in concrete where the anode and the cathode are on the same steel reinforcing bar.

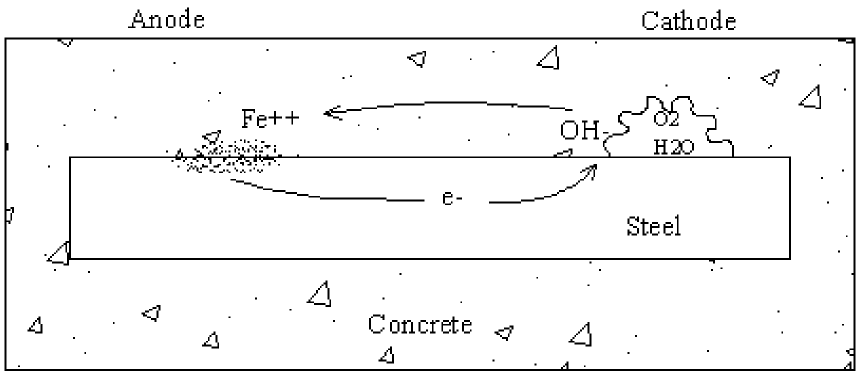


Fig. 2.1 Corrosion Cell in Reinforced Concrete (Gadve et al. 2010)

The corrosion of steel in concrete in the presence of oxygen but without chlorides takes place in several steps:

At the anode, iron is oxidized to the ferrous state and releases electrons

$$Fe \rightarrow Fe^{++} + 2e^{-} \tag{2.2}$$

These electrons migrate to the cathode where they combine with water and oxygen to form hydroxyl ions

$$2e^{-} + H_2O + \frac{1}{2}O_2 \rightarrow 2OH^{-} \tag{2.3}$$

The hydroxyl ions combine with the ferrous ions to form ferrous hydroxide

$$Fe^{++} + 2OH^{-} \rightarrow Fe(OH)_2 \tag{2.4}$$

In the presence of water and oxygen, the ferrous hydroxide is further oxidized to form Fe_2O_3

$$\begin{aligned} &4Fe(OH)_2 + O_2 + H_2O \rightarrow 4Fe(OH)_3 \\ &2Fe(OH)_3 \rightarrow Fe_2O_3.2H_2O \end{aligned} \tag{2.5}$$

Both the anodic and cathodic reactions are necessary for the corrosion process to occur and they need to take place simultaneously. The anode and cathode can be located next to each other or can be separated. When they are located next to each other, i.e., on microscopic scale, the resulting corrosion cell is referred to as a microcell. When they are separated by some finite distance, the resulting corrosion cell is referred to as macro cell as illustrated in **Fig. 2.2**.

Corrosion of steel reinforcing bars embedded in concrete may be due to a combination of macro cells and micro cells.

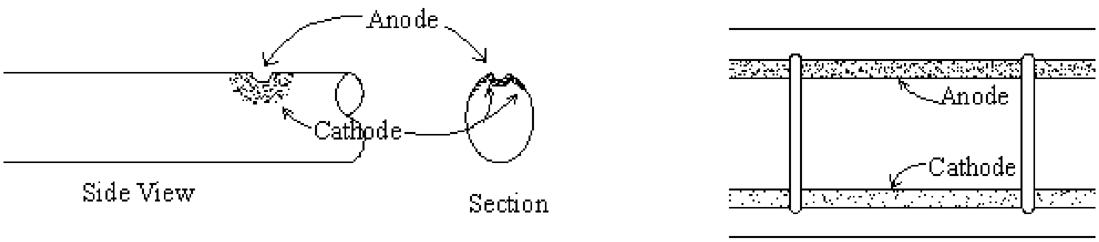


Fig. 2.2 Micro cell and Macro cell (Gadve et al. 2010)

The corrosion products resulting from the corrosion of steel reinforcing bars occupy a volume five to ten times that of the original steel. This increase in volume induces stresses in the concrete that result in cracks, delaminations and spalls. If left untreated, the process continues which further accelerates the corrosion process by providing an easy pathway for water and chlorides to reach the steel until the concrete becomes structurally unsound as shown in **Fig 2.3.**

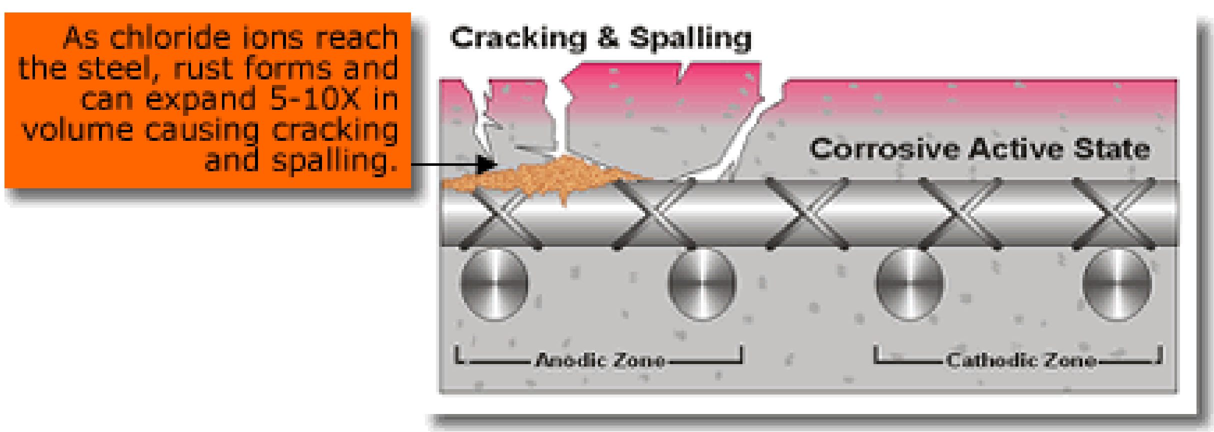


Fig.2.3 Cracking and spalling of concrete due to penetration of chloride ions

The minimum chloride ion concentration needed to initiate corrosion of steel reinforcing bars is also called the chloride threshold. Although the concept of chloride threshold is generally accepted, there is little agreement on what the threshold value is. Several factors influence the chloride threshold value: the composition of the concrete (resistivity), the amount of moisture present, and the atmospheric conditions (temperature and humidity). The threshold concentration depends on the pH level and the concentration of oxygen. When chlorides are uniformly distributed, higher concentrations are needed to initiate corrosion. Regardless of what concentration of chloride ions is needed to initiate corrosion, an increase in the chloride ion concentration increases the probability that corrosion of steel reinforcing bars will occur.

2.4 CLOSING REMARKS

This chapter discusses the theory of corrosion mechanism and causes of rebar. The various factors and effect of corrosion process are well discussed. It is concluded that the two most important causes of rebar are the ingress of chloride ions and carbon dioxide to the steel surface. To obtain maximum information about the corrosion state of rebar in a particular structure, various non destructive monitoring techniques are necessary so as to provide an effective repair or rehabilitation system such as coating, retrofitting, corrosion inhibitors etc. Next chapter provides information regarding various non destructive monitoring techniques in detail.

CHAPTER 3

NDT TECHNIQUES FOR MONITORING OF RC STRUCTURES

3.1 INTRODUCTION

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 (*Broomfield, 2006*). It is therefore essential to be able to assess the condition of concrete structures, and more specifically, to estimate the depth of surface breaking cracks. Non-destructive techniques (NDT) are suitable candidates to reach this goal as compared to partially destructive tests because they allow for in-situ inspection with high spatial resolution, whereas tests performed on drilled cores may only be performed on a limited number of measurement points. Also, NDT will not affect the integrity of structure, as is possible with drilling cores.

3.2 IMPORTANCE AND NEED OF NON-DESTRUCTIVE TESTING

It is often necessary to test concrete structures after the concrete has hardened to determine whether the structure is suitable for its designed use. Ideally such testing should be done without damaging the element. The tests available for checking integrity of the element range from the completely non-destructive, where there is no damage to the element, through those where the concrete surface is slightly damaged, to partially destructive tests, such as core tests and pullout and pull off tests, where the surface has to be repaired after the test.

The corrosion of reinforcements has resulted to be one of the most frequent causes of premature failure of RC element. Corrosion is an insidious process, often difficult to recognize until deterioration is well advanced. When left unchecked, corrosion will propagate in the structure and ultimately lead to damage. Monitoring the corrosion rate, assuming the uniform corrosion and the loss in diameter decreases linear with the corrosion rate, allows calculating the remaining load carrying capacity and the safety of the structure. There are several methods of measuring true, instantaneous rate of corrosion, based on non-destructive testing. Non-destructive testing can be applied to both old and new structures. For new structures, the principal applications are likely to be for quality control or the resolution of doubts about the quality of materials or construction. The testing of existing structures is usually related to an assessment of structural integrity or adequacy. Non-destructive testing can be used in the situations as a preliminary to subsequent coring. Typical situations where non-destructive testing may be useful are, as follows:

- quality control of pre-cast units or construction in situ.
- removing uncertainties about the acceptability of the material supplied owing to apparent non-compliance with specifications.
- confirming or negating doubts concerning the workmanship involved in batching, mixing, placing, compacting or curing of concrete.
- monitoring of strength development in relation to formwork removal, prestressing, load application or similar purposes.
- location and determination of the extent of cracks, voids, honeycombing and similar defects within a concrete structure.
- determining the concrete uniformity, possibly preliminary to core cutting, load testing or other more expensive or disruptive tests.
- determining the position and condition of reinforcement.
- increasing the confidence level of a smaller number of destructive tests.

3.3 BASIC METHODS FOR NDT OF RC STRUCTURES

Although a number of different non-destructive testing methods have been developed, but the common methods with some typical applications that have been adopted for non-destructive testing of RC strctures are explained in the following sections.

- **Visual inspection**, which is an essential precursor to any intended non-destructive test. An experienced civil or structural engineer may be able to establish the possible cause(s) of damage to a concrete structure and hence identify which of the various NDT methods available could be most useful for any further investigation of the problem.

- **Half-cell electrical** potential method, used to detect the corrosion potential of reinforcing bars in concrete.

- **Linear Polarization Resistance (LPR)**, used to estimate the corrosion rate of steel in concrete.
- **Schmidt/rebound hammer test,** used to evaluate the surface hardness of concrete.
- **Carbonation depth measurement test**, used to determine whether moisture has reached the depth of the reinforcing bars and hence corrosion may be occurring.
- **Permeability test**, used to measure the flow of water through the concrete.
- **Penetration resistance or Windsor probe test,** used to measure the surface hardness and hence the strength of the surface and near surface layers of the concrete.
- **Covermeter testing**, used to measure the distance of steel reinforcing bars beneath the surface of the concrete and also possibly to measure the diameter of the reinforcing bars.
- **Radiographic testing** used to detect voids in the concrete.
- **Ultrasonic pulse velocity testing**, mainly used to measure the sound velocity of concrete and hence the compressive strength of the concrete.
- **Impact echo testing**, used to detect voids, delamination and other anomalies in concrete.
- **Ground penetrating radar or impulse radar testing,** used to detect the position of reinforcing bars or stressing ducts.
- **Infrared thermography**, used to detect voids, delamination and other anomalies in concrete and also detect water entry points in buildings.

3.3.1 Half-cell electrical potential method

It is used to detect the corrosion potential of reinforcing bars in concrete. The method of half-cell potential measurements normally involves measuring the potential of an embedded reinforcing bar relative to a reference half-cell placed on the concrete surface. The half-cell is usually a copper/copper sulphate or silver/silver chloride cell but other combinations are also possible.

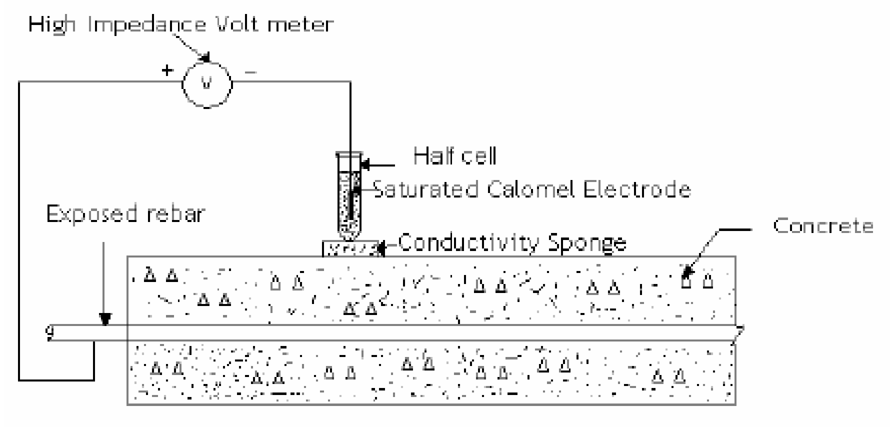


Fig-3.1 Half-cell electrical potential method (*Song and Saraswathy, 2007*)

The concrete functions as an electrolyte and the risk of corrosion of the reinforcement in the immediate region of the test location may be related empirically to the measured potential difference. ASTM C876 - 91 gives a Standard Test Method for Half-Cell Potentials of uncoated reinforcing steel in concrete. The limitation of this method is that it cannot indicate the actual corrosion rate and it may also require to drill a small hole to enable electrical contact with the reinforcement in the member under examination.

The ASTM interpretation of half-cell potential readings (SCE) is as follows:

Open circuit potential (OCP) values	Corrosion condition
< -426 Mv	Severe corrosion, corrosion induced cracking may occur
< -276 Mv	High risk, 90% probability of corrosion
-126 to -275 Mv	Intermediate risk, corrosion activity in uncertain
0 to -125 mV	Low risk, 10% probability of corrosion

3.3.2 Linear Polarization Resistance (LPR)

It is used to estimate the corrosion rate of steel in concrete. LPR has been widely used in the laboratory and is now being applied in structures. The basic principle of LPR is to measure the corrosion current which gives an indication of how quickly a known area of steel is corroding. The amount of steel loss during the corrosion process can be measured to a certain degree of accuracy by means of the measurement of the electrical current generated by anodic reaction and consumed by the cathodic reaction. **Fig 3.2** shows the LPR arrangement.

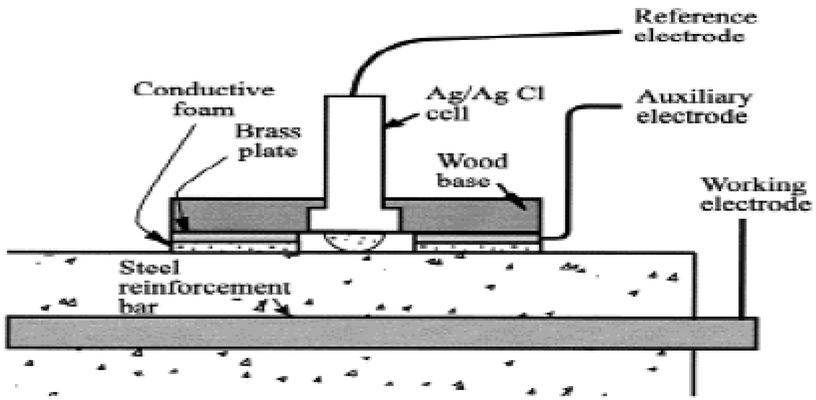


Fig-3.2 Linear Polarization Resistance method (*Song and Saraswathy, 2007*)

There is a direct relationship between the measured corrosion current and the mass of steel consumed by Faraday's Law. Corrosion current can be derived indirectly through half-cell potential measurement through the following expression given by Stern-Geary:

$$I_{corr} = \frac{B}{R_p} \qquad \text{………… (3.1)}$$

Where I_{corr} is the change in current (µA /cm^2),

B is a constant relating to the electrochemical characteristics of steel in concrete,

Rp is the polarization resistance expressed as $Rp = \frac{\text{(change in potential)}}{\text{(applied current)}}$

It deserves emphasis that this linear relationship is only valid when the potential change is kept less than 20mV. LPR measurement is very useful in finding the true condition of corrosion in a structure although it is slow compared with the half-cell potential test.

3.3.3 Ultrasonic pulse velocity testing

It is mainly used to measure the sound velocity of concrete and hence the compressive strength of the concrete. A pulse of longitudinal vibrations is produced by an electro-acoustical transducer, which is held in contact with one surface of the concrete under test. Ultrasonic examination is performed using a device that generates an ultrasonic wave with a piezoelectric crystal at a frequency between 0.1 and 25 MHz into the piece being examined and analyzes the return signal. The method is based on the measurement of time it takes for the signal to return and the amount and shape of that signal as shown in **Fig.3.3**.

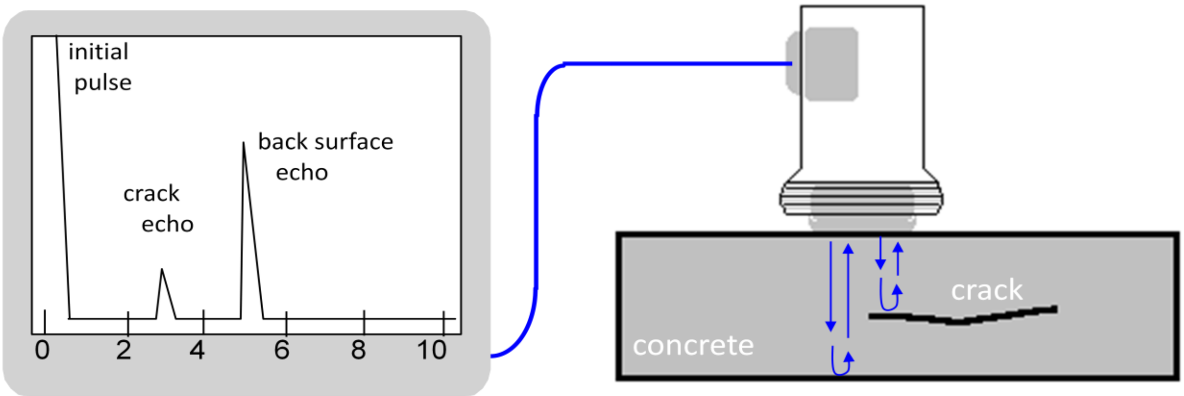


Fig. 3.3 Ultrasonic Pulse Velocity Signal

The two most common methods of ultrasonic testing are:-

1. Pulse echo method

In the pulse-echo method, a piezoelectric transducer with its longitudinal axis located perpendicular to and mounted on or near the surface of the test material is used to transmit and receive ultrasonic energy. The ultrasonic waves are reflected by the opposite face of the material or by discontinuities, layers, voids, or inclusions in the material, and received by the same transducer where the reflected energy is converted into an electrical signal. **Fig.3.4** shows the principle of pulse echo method of inspection. The electrical signal is computer processed for display on a video monitor or TV screen. The display can show the relative thickness of the material, depth into the material where flaws are located, (with proper scanning hardware and software), and where the flaws are located in the X-Y plane.

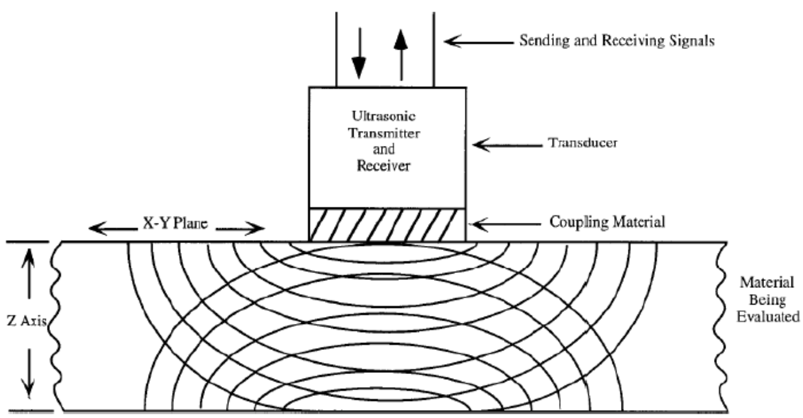


Fig.3.4 Principle of pulse echo method of inspection (*Vermani et al. 2008*)

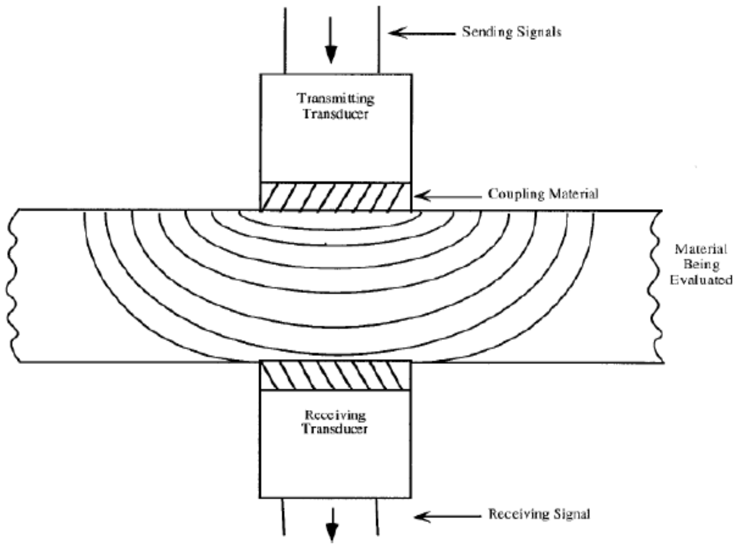


Fig.3.5 Principle of through transmission of ultrasonic testing (*Vermani et al. 2008*)

2. Through transmission method

In the through-transmission method, an ultrasonic transmitter is used on one side of the material while a detector is placed on the opposite side. One unit acts as transmitter and the other unit as receiver. The beam from the transmitter T travels through the material to its opposite surface where the receiving transducer R is placed. **Fig 3.5** shows the principle of through transmission method of testing. Scanning of the material using this method will result in the location of defects, flaws and inclusions in the X-Y plane.

3.4 CLOSING REMARKS

In this chapter various NDT methods for corrosion monitoring of RC structures are reviewed ans it is observed that each method possess certain advantages and limitations. It is observed that non-destructive techniques can be used effectively for investigation and evaluating the actual condition of the structures but the choice of a particular NDT method depends upon the property of concrete to be observed such as strength, corrosion, crack monitoring etc. In the present study half cell potential, LPR and Ultrasonic pulse velocity measurements are taken in order to study the effect of corrosion on steel rebar.

CHAPTER 4

FIBRE REINFORCED POLYMER (FRP) AND RETROFITTING

4.1 INTRODUCTION

Retrofitting of existing infrastructure is bound to increase all over the world. This is because of deterioration of structural strength of existing infrastructure (due to age and environmental attacks),up-grading of various design codes(due to better understanding of various design concepts in due course of time) and higher load carrying capacity demand (due to present day increased service needs) etc. For years, civil engineers have been in search for alternatives to steels and alloys to combat the high costs of repair and maintenance of structures damaged by corrosion and heavy use. Since 1940s, composite materials, formed by the combination of two or more distinct materials in a microscopic scale, have gained increasing popularity in the engineering field. Fiber Reinforced Polymer (FRP) is a relatively new class of composite material manufactured from fibers and resins and has proven efficient and economical for the development and repair of new and deteriorating structures in civil engineering. Wide spread utilization of FRP's in construction is hampered by lack of long-term durability and performance data in tropical environment.

4.2 NEED OF RETROFITTING IN RC STRUCTURES

Over the last 50 years, the strengths of various types of concrete have increased from the low levels of 15-20 MPa to values in the range of 40-70 MPa. Retrofitting of concrete structures has become an increasingly dominant use of the material in structural engineering applications. Such uses include increasing the load capacity of existing structures (such as existing parking garages) that were designed to tolerate far lower service loads. Other uses include seismic retrofitting, and repair of damaged concrete structures. Repair and rehabilitation work for concrete structures can broadly be classified into two categories:

- repair in which damage due to deterioration and cracking is corrected to restore the original structural shape, and

- repair which is necessary to strengthen the structural capacity of members whose load carrying capacity is either inadequate or whose strength has been severely impaired due to sustained damage.

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) and recent earthquake damages have necessitated the use of strengthening of basic structural components such as slabs, panels, walls, beams and columns. Various researchers have reported that retrofitting by FRP wraps slows down the rate of corrosion thereby preventing the structure from damage (*Kutarba and Hamilton (2007), Spainhour et al. (2008), Bonacci and Maalej (2000)*).

(a) Corrosion damage to a concrete beam (b) FRP on a bridge structure

Fig.4.1 (a) Corrosion damage to a concrete beam, (b) FRP on a bridge structure (*Kutarba and Hamilton (2007)*.

Retrofitting of reinforced concrete beams or columns in which the steel reinforcement has been damaged by corrosion is one area of particular interest in marine environments and in locations where deicing salts are used. **Figure 4.1 (a)** shows the two-fold result of severe corrosion damage to a concrete beam. **Figure 4.1 (b)** shows the application of FRP on a bridge structure. The bridge girder was strengthened for flexure and shear using a wet lay-up system *(Kutarba and Hamilton (2007)).*

4.3 WHAT ARE FRPs ?

Fibre-reinforced polymer commonly known as FRPs represents a class of materials that falls into a category referred to as composite materials. Composite materials consist of two or more materials that retain their respective chemical and physical characteristics when combined together. FRPs are commonly used in the aerospace, automotive, marine, and construction industries. Fibre-reinforced polymer is a composite material made of a polymer matrix reinforced with fibres. The fibres are usually glass, carbon, or aramid, while the polymer is usually an epoxy, vinylester or polyester thermosetting plastic. Fibres can be formed from a wide range of amorphous and crystalline materials but in the construction industry the three fibres which are generally used in structural systems are *(Hollaway and Head, 2001).*

- the glass fibre (the E-glass fibre, the S-glass fibre and the Z-glass fibre),
- the aramid fibre (the aromatic polyamides, Kevlar 49 fibre) and
- the carbon fibre (the ultra high-modulus fibre, the high-modulus fibre and the high-strength fibre).

The primary function of fibre reinforcement is to carry load along the length of the fibre and to provide strength and stiffness in one direction. FRP composites are different from traditional construction materials like steel or aluminium. FRP composites are anisotropic (properties apparent in the direction of applied load) whereas steel or aluminium is isotropic (uniform properties in all directions, independent of applied load). Therefore FRP composites properties are directional, i.e. the best mechanical properties are in the direction of the fibre placement.

However like other materials FRPs are also bounded to have defects and can decay during the service life. Defects in composites may be due to several factors including improper design, fabrication and manufacturing and air voids. During manufacturing of FRPs due to poor workmanship some defects may occur which may adversely affect the fiber matrix adhesion properties, resulting in debonding at the fiber/matrix interfaces, micro-cracking in the matrix, fiber fragmentation, continuous cracks and several other phenomena that may actually degrade the mechanical property of the composites. So assessment of cracks in FRP and monitoring of delamination in FRP is also required.

4.4 SUITABILITY OF FRP FOR USES IN STRUCTURAL ENGINEERING

Externally bonded fibre-reinforced polymers (FRPs) in the form of continuous carbon (C), glass (G) or aramid (A) fibres bonded together in a matrix made of epoxy, vinylester or polyester, have been employed extensively throughout the world in numerous rehabilitation applications of reinforced concrete or masonry structures. The high strength-to-weight ratio, immunity to corrosion and easy handling and installation has made FRP jackets the material of choice in an increasingly large number of projects where increased strength or inelastic deformation capacity must be achieved for seismic retrofitting, despite the relatively high material costs.

Since its first applications in Europe and Japan in the 1980s, use of bonded repair and retrofit of concrete structures with fiber reinforced polymer (FRP) systems has progressively increased to the extent that today it counts for at least 25 Innovative Bridge Research and Construction (IBRC) projects in the United States, in addition to numerous projects independently undertaken by state departments of transportation (DOTs) and countries.

Fibre reinforced polymer (FRP) composite system into construction is a promising alternative for the rehabilitation of weakened and deficient concrete members. Fibre Reinforced Polymer Composites, originally developed for the aerospace industry, show immense potential as a material that can be used in civil infrastructure. The strength properties of FRPs collectively make up one of the primary reasons for which civil engineers select them in the design of structures. A material's strength is governed by its ability to sustain a load without excessive deformation or failure. When an FRP specimen is tested in axial tension, the applied force per unit cross-sectional area (stress) is proportional to the ratio of change in a specimen's length to its original length (strain). When the applied load is removed, FRP returns to its original shape or length. In other words, FRP responds linear-elastically to axial stress.

Among FRPs high strength properties, the most relevant features include

- Excellent durability and corrosion resistance.
- High strength-to-weight ratio.
- A member composed of FRP can support larger live loads since its dead weight does not contribute significantly to the loads that it must bear.
- Ease of installation.
- Versatility.
- Anti-seismic behavior.
- Electromagnetic neutrality.
- Excellent fatigue behavior and fire resistance.

One of the most common uses for FRP involves the repair, rehabilitation and retrofitting of damaged or deteriorating structures as shown in **Fig. 4.2 (a), (b).** Several companies across the world are beginning to wrap damaged bridge piers to prevent collapse and steel-reinforced columns to improve the structural integrity and to prevent buckling of the reinforcement. Architects have also discovered many applications for which FRP can be used. These include structures such as siding/cladding, roofing, flooring and partitions.

(a) (b)

Fig.4.2 (a). Externally bonded carbon fiber reinforced polymer (FRP) composites strengthen openings in concrete for new mechanical systems in a building being adapted for a new use.

(b) Seismic retrofitting of column-beam joints of Aigaleo football stadium in Athens, Greece, using CFRP fabrics with steel anchorages.

4.5 TYPES OF FRPs

In civil engineering three types of fibres dominate. These are carbon, glass, and aramid fibres and the composite is often named by the reinforcing fibre, e.g. CFRP for Carbon Fibre Reinforced Polymer. They have different properties. For strengthening purposes carbon fibres are the most suitable. All fibres have generally higher stress capacity than the ordinary steel and are linear elastic until failure. The most important properties that differ between the fibre types are stiffness and tensile strain.

4.5.1 Carbon Fibre Reinforced Polymer (CFRP)

Carbon fibre reinforced polymer, is a material consisting of extremely thin fibers about 0.005–0.010 mm in diameter and composed mostly of carbon atoms. The carbon atoms are bonded together in microscopic crystals that are more or less aligned parallel to the long axis of the fiber. The crystal alignment makes the fiber very strong for its size. Several thousand carbon fibers are twisted together to form a yarn, which may be used by itself or woven into a fabric **(Fig.4.3).** Carbon fiber are combined with a plastic resin and wound or molded to form composite materials such as carbon fiber reinforced plastic to provide a high strength-to-weight ratio material. The properties of carbon fiber such as high tensile strength, low weight, and low thermal expansion make it very popular in aerospace, civil engineering, military, and motorsports, along with other competition sports. However, it is relatively expensive when compared to similar materials such as fiberglass or plastic.

Fig.4.3 Carbon fiber sheet

4.5.2 Glass Fibre Reinforced Polymer (GFRP)

GFRP is a lightweight, strong material with very many uses, including boats, automobiles, water tanks, roofing, pipes and cladding. The plastic matrix may be epoxy, a thermosetting plastic (most often polyester or vinylester) or thermoplastic. Glass fibres are basically made by mixing silica sand, limestone, folic acid and other minor ingredients. The mix is heated until it melts at about 1260°C. The molten glass is then allowed to flow through fine holes in a platinum plate. The glass strands are cooled, gathered and wound. The fibres are drawn to increase the directional strength. The fibres are then woven into various forms for use in composites **(Fig.4.4).** GFRP sheets are also being increasingly used in rehabilitation and retrofitting of concrete structures as an alternative to steel in concrete due to their high strength-to-weight ratio, corrosion resistance, ease of handling , temperature resistance and application at site.

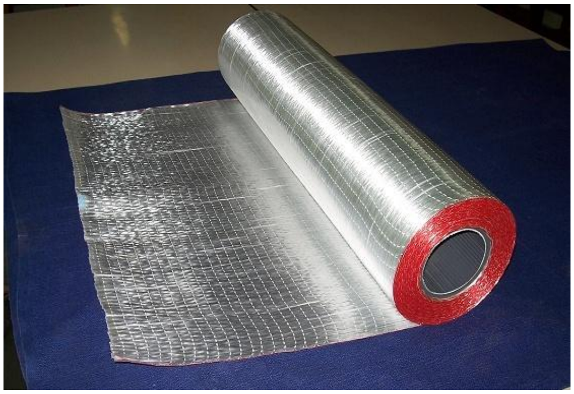


Fig.4.4 Glass fiber sheet

4.5.3 Aramid Fibre Reinforced Polymers (AFRP)

Aramid is the short form for aromatic polyamide. Aramid fibers are most commonly known Kevlar, Nomex and Technora. Aramids are generally prepared by the reaction between an amine group and a carboxylic acid halide group, commonly this occurs when an aromatic polyamide is spun from a liquid concentration of sulfuric acid into a crystallized fibre. Fibres are then spun into larger threads in order to weave into large ropes or woven fabrics **(Fig. 4.5).** Aramid has high fracture energy and is therefore used for helmets and bullet-proof garments. Aramid fibres are sensitive to elevated temperatures, moisture and ultraviolet radiation and therefore not widely used in civil engineering applications.

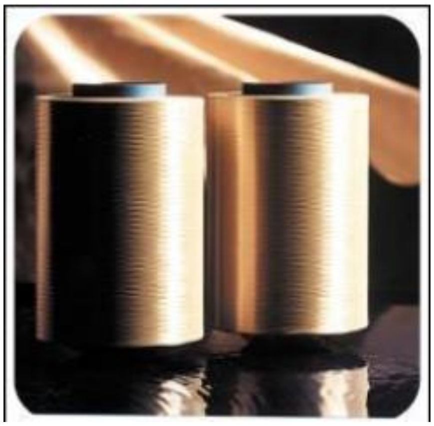


Fig.4.5 Aramid fiber sheet

4.6 Properties of CFRP

- Carbon fibre reinforced polymer (CFRP) is alkali resistant.
- Carbon fibre reinforced polymers (CFRP) are resistant to corrosion; hence they are used for corrosion control and rehabilitation of reinforced concrete structures.
- Carbon fibre reinforced polymer composite has low thermal conductivity.
- CFRP composites have high strength to weight ratio and hence it eliminates requirements of heavy construction equipment and supporting structures.
- CFRP composites are available in rolls of very long length. Therefore, they need very few joints, avoiding laps and splices, and its transportation is also very easy.
- CFRP composites have a short curing time. Therefore, the application takes a shorter time. This reduces the project duration and down time of the structure to a great extent.
- Application of CFRP composites does not require bulky and dusty materials in a large quantity; therefore, the site remains tidier.
- CFRP composites possess high ultimate strain; therefore, they offer ductility to the structure and they are suitable for earthquake resistant applications.
- CFRP composites have high fatigue resistance. So they do not degrade, which easily alleviates the requirement of frequent maintenance.
- CFRP composites are bad conductor of electricity and are non-magnetic.

4.7 Suitability of CFRP in Civil Engineering

The main impetus for development of carbon fibres has come from the aerospace industry with its need for a material with combination of high strength, high stiffness and low weight. Recently, civil engineers and construction industry have begun to realize that this material (CFRP) have potential to provide remedies for many problems associated with the deterioration and strengthening of infrastructure. Effective use of carbon fibre reinforced polymer could significantly increase the life of structures, minimizing the maintenance requirements.

Studied in an academic context as to its potential benefits in construction, it has also proved itself cost-effective in a number of field applications strengthening concrete, masonry, steel, cast iron, and timber structures.

Civil structural applications of fiber reinforced polymer (FRP) composites include both new constructions as well as existing structures. CFRP is widely used to strengthen concrete structures that have lost reinforcing steel mass due to corrosion and concrete deterioration because CFRP possess good rigidity, high strength, low density, corrosion resistance, vibration resistance, high ultimate strain, high fatigue resistance, and low thermal conductivity. In addition the FRP materials that are electrically conductive can be designed to offer active protection as well. The conductive FRP wrap-around can be used as anodes and the reinforcements can act as cathode to impede the corrosion of steel.

Carbon fibre reinforced polymer (CFRP) is currently used worldwide to retrofit and repair structurally deficient infrastructures such as bridges and buildings. Retrofitting has become the increasingly dominant use of the material in civil engineering, and applications include increasing the load capacity of old structures (such as bridges) that were designed to tolerate far lower service loads than they are experiencing today, seismic retrofitting, and repair of damaged structures. **Fig.4.6** shows retrofitting by FRP sheets. When reinforced concrete (RC) members are strengthened with externally bonded CFRP, the bond between the CFRP and RC substrate significantly affects the members load carrying capacity.

Fig.4.6 Retrofitting of beam by FRP Sheets

CFRP can also be applied to enhance shear strength of reinforced concrete by wrapping fabrics or fibers around the section to be strengthened. Wrapping around sections (such as bridge or building columns) can also enhance the ductility of the section, greatly increasing the resistance to collapse under earthquake loading. Such 'seismic retrofit' is the major application in earthquake-prone areas, since it is much more economic than alternative methods. If a column is circular (or nearly so) an increase in axial capacity is also achieved by wrapping. In this application, the confinement of the CFRP wrap enhances the compressive strength of the concrete. The advantages of CFRP over steel, namely its light weight and corrosion resistance, should enable the material to be used for niche applications such as in offshore environments. When used as a replacement for steel, CFRP bars could be used to reinforce concrete structures, however the applications are not common.

4.8 CLOSING REMARKS

It can be concluded that recent developments in the field of FRPs have resulted in its use as a highly efficient construction material. CFRPs are being used increasingly to rehabilitate corrosion affected structures. CFRP wraps provide a barrier layer that impedes further corrosion of steel and prevents the increase in volume of RC members due to rusting by applying confinement pressure, thereby preventing dislodging of concrete cover.

CHAPTER 5

LITERATURE REVIEW

5.1 GENERAL

This chapter presents a thorough review of literature on nondestructive monitoring techniques as well as the Ultrasonic guided waves for monitoring rebar corrosion in concrete and it is observed that corrosion monitoring is necessary as it allows the corrosion to be caught before its onset and opens up much more economical maintenance options such as coating, retrofitting etc. Also a thorough review of literature on Fiber Reinforced Plastic (FRP) composite wraps for corrosion protection is presented as FRP wraps have proved to slow down the rate of corrosion and prevents the structure from corrosion damage in chloride contaminated concrete.

5.2 LITERATURE REVIEW ON ELECTROCHEMICAL TECHNIQUES

Angst et al. (2009) studied linear polarization method (LPR) and Electrochemical impedance spectroscopy (EIS) for detecting active corrosion and stated that the most accurate technique to detect depassivation of the steel is the measurement of the linear polarization resistance, which is inversely proportional with the corrosion current as described by the Stern–Geary-equation. By applying the Stern–Geary-equation and assuming Tafel slopes the corrosion rate can then be calculated.

Bhattacharjee et al. (2009) illustrated the findings of an experimental investigation carried out on large number of specimens for evaluating the performance of different types of rebar in chloride contaminated concrete made with different types of cement through different corrosion rate techniques. Corrosion rate were obtained by linear polarization resistance (LPR) technique with guard ring arrangement and AC impedance spectroscopy.

Bhavneet et al. (2010) used two non-destructive techniques namely electrochemical LPR measurement and ultrasonic guided waves for determining the corrosion initiation and progression. It was concluded that electrochemical measurements are effective only in monitoring corrosion initiation and are not useful to measure corrosion progression whereas ultrasonic guided waves are effective for both monitoring and progression of corrosion.

Broomfield et al. (2002) applied corrosion monitoring techniques to monitor durability in new constructions, and as well as on existing structures to evaluate rehabilitation strategies such as corrosion inhibitor applications and patch repairs. Corrosion monitoring systems include linear polarization, concrete resistivity and half cell potential measurements. The author concluded that this monitoring system is very effective to access the condition of new and rehabilitated structures well in time.

Goueygou et al. (2008) experimentally studied the effectiveness of two non-destructive testing techniques: the measurement of electrical resistivity and the transmission of ultrasonic surface waves, to detect the width and depth of crack pattern. Rectangular concrete slabs reinforced with 10 mm bar and 25 mm cover the test specimens were cast. A major crack was induced in the middle of the specimen using a three point bending setup. Electrical resistivity measurements were made with a four probe square device and Ultrasonic Rayleigh wave technique was used to measure pulse velocity, phase velocity and peak attenuation. The test results showed that, both techniques were able to detect the presence of a main crack in the middle of the specimen but the secondary cracks around the main crack and the depth of the crack were detected only by ultrasonic technique.

Jung et al. (2002) investigated the feasibility of detecting internal defects (cracks, honeycombs, inclusions) in reinforced concrete beams using ultrasonic guided waves (Lamb waves). Experiments were carried out on full-scale beam specimens. The experimental results showed that it Lamb waves were able to detect the presence of cracks because in lamb wave method the defect detection does not depend on the reflection of waves from defects but on how the waves interact with them. The author also concluded that the lamb wave technique gives stronger differences in ultrasonic signal strengths from defective and defective free regions in comparison to the conventional ultrasonic methods.

Koleva et al. (2006) tested small scale cylindrical RC specimen to investigate the corrosion behaviour of steel in concrete. Steady direct current was applied to reinforcement steel (cathode) for corrosion prevention and protection. A cylindrical titanium mesh served as counter electrode and saturated calomel electrode (SCE) as reference electrode. The specimens were monitored using LPR and EIS techniques. Tafel plots were used to find the electrochemical parameters such as polarization resistance (Rp), corrosion potential (E_{corr}) and corrosion current density (I_{corr}).

The corrosion current density was estimated by Stern–Geary equation. Test results indicated that the corrosion current density decreased significantly for protected specimens.

Li et al. (2006) studied the application of steel thin film electrical resistance (TFER) sensor for in situ corrosion monitoring. For this, the sensing element of the sensor was designed to have a multiple-line pattern, in order to study the sensitivity of TFER to various corrosive environments, and the feasibility to detect the localized feature of corrosion. The polarization resistance (Rp) of thin films and bulk steel were measured by the linear polarization resistance (LPR) method in order to investigate the difference in corrosion behavior of thin films and bulk steel. The test results showed that the corrosion behavior of bulk steel could be successfully predicted using the steel thin film electrical resistance (TFER) sensor. Moreover, the TFER sensor with the multiple-line pattern showed the enhanced sensitivity to localized corrosion phenomena. The TFER sensor can also be applied to atmospheric conditions where it is difficult to apply an electrochemical method because of the absence of a proper electrolyte in dry cycles. In summary, the TFER sensor could be a reliable tool for corrosion monitoring in a wide range of industries.

Montemor et al. (2003) presented an overview on the state-of-the-art of the most important aspects of the corrosion process initiated by chlorides, its development and monitoring techniques. The determination of a critical level, above which serious problems can occur, has been one of the main goals of investigation. The use of electrochemical techniques such as polarisation resistance, electrochemical impedance, galvanostatic pulse and potential measurements have shown to be powerful tools.

Park et al. (2003) tried to establish the suitability of the type of sensor system to evaluate the corrosion behavior of rebar. For this, a correlation was developed between sensor output and corrosion rate of reinforcing steel in a concrete environment by using two galvanic sensor systems. Non destructive methods such as open-circuit potential, linear polarization resistance (LPR) measurement and electrochemical impedance spectroscopy (EIS) were used for current measurements and the test results indicated that the steel/copper sensor is a reliable nondestructive method of determining actual corrosion rate in a concrete environment. However, steel/stainless steel sensor is not suitable for detecting corrosion damage of reinforcing steel due to the low galvanic current output.

Poursaee et al. (2010) experimentally carried out study using potentiostatic transient technique to determine the corrosion density of steel rebars. The effect of the Stern–Geary constant (B) on the corrosion rate of steel bar in concrete was also discussed. Half cell potential and conventional LPR techniques were used to compare the results with potentiostatic transient technique for cracked specimens (active state) and specimens with no crack (passive state), respectively. Concrete specimens with 10mm carbon steel bar with exposed length 400mm were cast. Transverse and longitudinal cracks were developed in the specimen and the specimens were alternately exposed to 2-week periods with ponding well solution (3 wt.% chloride (NaCl) solution) and then 2 weeks without solution.

Half-cell potential of the rebars was monitored by measuring the potential of the steel bar against $Cu/Cu(SO_4)$ reference electrode, and for the potentiostatic transient test, ±20 mV versus the E_{corr} was applied to the steel bars. For LPR measurements stainless steel was used as counter electrode and saturated calomel electrode (SCE) as reference electrode. Test results showed that by having more active corrosion, the corrosion rates determined using the conventional LPR show more fluctuations and discrepancies as compared to the actual corrosion rate (mass loss) while the values obtained from the potentiostatic transient method show less fluctuations and are very close to the actual values. It was concluded that the value of B is necessary for LPR measurements whereas potentiostatic transient technique is simple and relatively fast technique to calculate the corrosion current density of steel rebars without knowing the value of B.

Pradhan et al. (2010) experimentally investigated the various corrosion parameters that specify the possibility and the magnitude of corrosion in concrete through different electrochemical corrosion tests namely potential measurement, corrosion rate measurement and potentiodynamic polarization test. The performance of concrete both in internal chloride and external chloride exposure conditions was studied. From the results it was observed that, dropped half-cell potential value obtained from external chloride exposure mostly lie in the active zone. In addition it was observed that there was significant difference in corrosion current values obtained from both internal and external chloride exposure conditions. Through this work it was confirmed that the critical chloride level leading to corrosion initiation was not a unique value and varies with steel type, cement type, and w/c ratio.

Sakr (2005) carried out an experimental study to investigate the effect of different percentage (from 2% to 10%) of tricalcium-aluminate (C_3A) in cement on corrosion of reinforcing steel bars when subjected to chloride and/or sulphate media using different electrochemical techniques namely; half-cell potential measurement, impressed voltage method and impressed current method. The corrosion rate was calculated using Faraday's law. It was observed that increasing the percent of C_3A from 2% to 10% decreases the corrosion of reinforcing steel immersed in 5% NaCl solution and optimum percentage of C_3A to control corrosion of reinforcing steel in both chloride and sulphate containing media is 6%. The test results showed that each electrochemical technique provided some but not all information about the corrosion resistance of steel bars embedded in cement in exposed to aggressive media.

Sathiyanarayanan et al. (2006) studied the performance of galvanostatic pulse technique for monitoring the corrosion of steel in concrete. Corrosion rate values obtained by weight loss method and LPR techniques were compared with the values obtained from galvanostatic pulse technique for steel reinforced in M15, M20, M30 and M35 grade concrete containing 0-5% Nacl. Concrete cubes reinforced with 5 mm steel rod exposing a length of 50 mm were cast. The conventional three electrode assembly consisting of stainless steel (counter electrode), saturated calomel (reference electrode) and reinforcing steel (working electrode), was used for both LPR and galvanostatic pulse measurements. The corrosion rate from mass loss was calculated by using the following relationship

$$\text{Corrosion rate (mmpy)} = \frac{87.6 \times \text{mass loss (mg)}}{\text{Area (cm}^2\text{)} \times \text{Time (h)} \times \text{Density}}$$

The test results indicated that the corrosion rate values of steel in concrete are dependent on the strength as well as the percentage of chloride present in the concrete. On increasing the strength from M15 to M35, the corrosion rates decreased for a given chloride concentrations. Further it was found that the corrosion rates obtained by the galvanostatic pulse method and weight loss method agree well in most of the studied system. However, the corrosion rate values obtained by the LPR method were found to be one order lower than that of the actual corrosion rates for steel in concrete in the presence of chloride due to the inclusion of resistance of the concrete in the measured Rp values. Therefore galvanostatic pulse technique were found to give more reliable results about the state of reinforcing steel in concrete and the rate of corrosion.

Shah et al. (2010) carried out an experimental study to compare nonlinear ultrasound (NLU) method and acoustic emission (AE) technique in nondestructive evaluation of concrete, damaged under axial compression loading. The sensitivity of both methods in assessing concrete damages was also examined. Cubic concrete specimens were produced using different w/c ratios (40%, 50%, and 60%). Three specimens at each w/c ratio were used for AE monitoring and three specimens for NLU evaluation. In AE testing technique four sensors were used to listen to the wide range of events under various loading and unloading cycles. The NLU evaluation was based upon measuring the change in fundamental amplitude with increasing damage and output power level. It was observed that the AE activity and the NLU amplitude were quite sensitive to change in the applied loading events and w/c ratios. Test results indicated that the increase in AE events was higher for high w/c concrete as compared to low w/c one. Attenuation also increased with increase in damage. The AE index showed greater sensitivity to concrete damages over NLU method. It was concluded that NLU parameter is an easy measure of assessing concrete damages than AE technique.

So et al. (2008) investigated galvanostatic pulse transient technique to evaluate the corrosion of steel in concrete and compared it with conventional LPR method. Galvanostatic pulse transient measurements were conducted on a number of short sections of steel bar embedded in concrete. Stern-Geary equation was used for LPR measurements. The electrochemical potential transient response was analyzed to obtain separate equivalent electronic components, comprising a series of resistances and capacitances, whose values are dependent on the corrosion condition of the reinforcing steel. The corrosion rate was evaluated from a summation of the separate resistive components and compared with corrosion rate determined from taking a conventional LPR on the same specimens. The results obtained showed that the galvanostatic pulse transient technique enables the separate components of the polarization resistance to be resolved, which offers significant advantages over the LPR method and provides a more conservative evaluation of the ongoing rate of corrosion.

Song et al. (2007) reviewed all the electrochemical and non destructive techniques from the point of view of corrosion assessment and their application to bridges, buildings and other civil engineering structures.

5.3 LITERATURE REVIEW ON ULTRASONIC TECHNIQUES

Goueygou et al. (2008) experimentally studied the effectiveness of the transmission of ultrasonic surface waves, to detect the width and depth of crack pattern. Rectangular concrete slabs reinforced with 10 mm bar and 25 mm cover the test specimens were cast. A major crack was induced in the middle of the specimen using a three point bending setup. Ultrasonic Rayleigh wave technique was used to measure pulse velocity, phase velocity and peak attenuation. The test results showed that, Rayleigh wave technique is a good method for measuring the depth of the crack as these were detected only by ultrasonic technique.

Kundu et al. (2003) studied the feasibility of detecting interface degradation and separation of steel bars in concrete beams using lamb waves. The lamb wave can propagate a long distance along the reinforcing steel bars embedded in concrete and is sensitive to the interface bonding condition between steel rebar and concrete. This investigation showed that the lamb wave inspection technique is an efficient and effective tool for health monitoring of reinforced concrete structures.

Jung et al. (2002) investigated the feasibility of detecting internal defects (cracks, honeycombs, and inclusions) in reinforced concrete (RC) beams using ultrasonic guided waves. Experiments were carried out on full-scale beams. It is shown that for RC beam inspections, the guided wave technique was better than the conventional stress wave techniques.

Lin et al (2003) described a simple device to determine the time of impact and to demonstrate its efficiency in measuring the depth of surface-opening cracks in concrete. The device comprises a conducting impact device, a sensing film, and an auxiliary circuit. With the device, stress waves are generated and the time of impact is detected so that the evaluation work needs only a single receiver. Laboratory studies were carried out on concrete specimens containing cracks with depths of 0.158 and 0.9 m. Experimental results show that this device can accurately measure the depth of surface-opening cracks in concrete. The advantages of using the new device include reduction in instrument cost and ease of operation because only one receiver is needed for a test.

Mahmoud et al. (2010) studied the use of surface acoustic waves (SAWs) for non-destructive structural health monitoring of concrete specimens externally bonded with carbon fiber-reinforced polymer (CFRP) composites and subjected to accelerated aging conditions. The surface waves are generated and received at the external face of the CFRP using narrow-band transducers with a 110-kHz center frequency. Both experimental testing and signal processing schemes of ultrasonic wave propagation through the CFRP substrate were described. Results indicated a marked decrease in measured ultrasonic parameters over time indicating a possible debonding or deterioration in the samples. It was concluded that this non-destructive technique could provide the basis for an accurate and cost-effective method for structural health monitoring of concrete structures retrofitted with CFRP composites.

Raisutis et al. (2007) analysed the possibilities of NDT technique based on application of ultrasonic guided waves. CFRP rods that are used for aerospace applications and are defective with multiple delaminations were used for the study. By numerical modeling and experiments it was demonstrated that guided waves can be applied for inspection of small diameter carbon fibre reinforced plastic rods used in the manufacturing of the longer on reinforcement of the light weight gliders. The presence of delamination type defects can be detected as essential reduction of the amplitude or complete disappearance of the leaky waves over a defected zone. It was shown that delamination type defects are not obstacles for ultrasonic guided waves and do not stop propagation of guided wave mode, but just converts it in to the modes which do not generate leaky waves. Due to this fact not only single defect, but even series of defects can be detected.

Sharma et al. (2010) studied towards development of a damage detection methodology. An attempt has been made by first developing a damage monitoring technique for steel bars in air. It has been done by utilizing ultrasonic guided waves. Experimentally, both pulse transmission and pulse echo techniques have been adopted and the time of flight and signal attenuation have been observed to locate and quantify the damage accurately. An efficient numerical technique, the spectral element method, has been used for numerical modelling of the problem. The numerical results have been validated with the experimental observations.

Vermani et al. (2008) studied that in the area of non destructive testing, ultrasonic testing using wave propagation is an emerging field. Ultrasonic testing uses transmission of high frequency sound waves into a material to detect imperfections or to locate changes in material properties. The most commonly used ultrasonic testing technique is pulse echo and through transmission wherein sound is introduced into a test object and reflections (echoes) are returned to a receiver from internal imperfections. This report presents the use of above two techniques to detect the damage in reinforcing steel bars.

Shah et al. (2010) investigated the correlation between acoustic emission and nonlinear ultrasonic techniques in assessing damage growth in concrete. The NLU evaluation is based on measuring the change in fundamental amplitude with increasing damage and output power level. It was observed that Acoustic emission (AE) technique is well suited for detecting actual damage in structures whereas NLU amplitude attenuation is examined to be used as a useful measure of damage growth in concrete.

5.4 LITERATURE REVIEW ON MONITORING OF STRUCTURES RETROFITTED WITH FRP

Bonacci and Maalej (2000) carried out an experimental program to provide a realistic assessment of the potential of using FRP materials in the repair and strengthening of reinforced concrete flexural members exposed to a corrosive environment. A total of seven specimens (270 x400 x 4350 mm) were tested. Four of the seven RC beams were reinforced externally with one or two layers of CFRP composite. Some specimens were tested under monotonic loading and other specimens were tested under sustained loading. CFRP external reinforcement increased beam load carrying capacities by 10–35% and reduced deflection by 10–32% with respect to the control specimen. The results showed that the use of FRP sheets for strengthening corroded reinforced concrete beams is an efficient technique that can maintain structural integrity and enhance the behavior of such beams.

Belarbi and Bae (2007) tested small scale cylindrical RC specimens wrapped with CFRP sheets to investigate the effect of corrosion. The specimens were exposed to three stages of accelerated corrosion process in addition to impressed constant voltage. The three stages included wet and dry cycle, dry condition and again wet and dry cycle. It was observed that the average corrosion rate increased during wet and dry cycles as compared to dry condition in both unwrapped and wrapped samples. Therefore, it was concluded that even if the external corrosion sources were removed (the second stage, dry condition,), the corrosion of steel reinforcement in CFRP wrapped columns may continue to occur since the evaporation of the entrapped moisture is inhibited.

Badawi and Soudki (2005) studied the effect of carbon fiber-reinforced polymer (CFRP) confinement on the cracking damage induced by impressed current-accelerated corrosion of reinforced concrete beams. The investigation was carried out for two different corrosion configurations, namely uniform and shear-span corrosion at three different degrees of corrosion. Uniform corrosion along the whole length of the beams and shear-span corrosion at 900 mm from each beam end were considered. The different degrees of corrosion were achieved using an accelerated corrosion technique with an impressed current. It was concluded that CFRP laminate confinement reduces corrosion expansion by up to 70% and slows the rate of corrosion through decreasing the corrosion mass loss by up to 35%. It also reduced the reduced the corrosion mass loss in the post repaired beams by 35 and 33% for the shear-span and uniform corrosion beams, respectively, compared to the unwrapped corroded beams.

Debaiky et al. (2002) discussed the use of carbon fiber-reinforced polymer CRP wraps as a rehabilitation technique for corroded reinforced concrete columns. Two groups of cylindrical RC specimens were subjected to either an aggressive environment or impressed current (galvanostatic) corrosion. Part of each group was wrapped before the corrosion initiation. The wrapping consisted of one or two layers of CFRP applied either fully or partially over the cylinder height. Condition of the cylinders was monitored through half-cell potential measurements, linear polarization resistance, and crack mapping. At the end of the experiment, the cylinders were tested to failure under axial compression. Concrete was analyzed for total chloride content to study the efficiency of the wraps as a barrier for contaminated water. Steel cages were chemically cleaned to calculate the mass lost due to corrosion. It was concluded that applying CFRP wraps significantly decreases corrosion activity when applied over entire specimen. The application of the wraps before corrosion propagation prevented corrosion from taking place, while the application of the wraps after corrosion occurrence dropped the rate of corrosion sharply. Authors suggested that this effect is probably due to the epoxy saturant used to apply the CFRP sheets rather than the sheets itself.

Gadve et al. (2009) investigated the progression of corrosion of steel in concrete after it has been treated with surface bonded FRP. Concrete cylinders with embedded steel bars were immersed in salt water and anodic current is passed through the reinforcement to initiate cracking in concrete. FRP sheets were adhesively bonded on the cylindrical specimens. Anodic current was continued for specified times. Pull out strength, mass loss, half cell potential of the steel and cell voltages were reported as metrics of performance of the samples. It was concluded that FRP wrapped samples showed substantially higher resistance to corrosion. Also wrapping dramatically slows down the rate of corrosion.

Kutarba and Hamilton (2007) experimentally investigated the performance of damaged reinforced concrete beams exposed to accelerated corrosion and repaired with Carbon Fiber-Reinforced Polymer (CFRP). A 5-volt constant potential was applied to accelerate the corrosion process. The beams were firstly subjected to a corrosion process for initial damage and they were then repaired and strengthened and exposed to a second corrosion process. Half-cell potential readings were taken at the beginning and the end of each cycle to determine the corrosion activity. 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. 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.FRP applications decreased corrosion rates during post-repair corrosion by minimizing chloride diffusion.

Mukherjee and Joshi (2005) reported an investigation on the performance of reinforced concrete beam-column joints under cyclic loading. Joints were cast with adequate and deficient bond of reinforcements at the beam-column joint. FRP sheets and strips have been applied on the joints in different configurations. The columns were subjected to an axial force while the beams were subjected to a cyclic load with controlled displacement. The amplitude of displacement is increased monotonically using a dynamic actuator. The hysteretic curves of the specimens were plotted. The energy dissipation capacity of various FRP configurations was compared. In addition, the control specimens were reused after testing as damaged specimens that were candidates for rehabilitation. The rehabilitation was carried out using FRP and their performance was compared with that of the undamaged specimens.

Mukherjee et al. (2004) focused on the mechanical response of concrete columns confined with fiber-reinforced polymer composites. Complicating effects on the mechanical behavior of columns confined with FRP such as deviation from axisymmetric conditions due to noncircular cross section, geometric imperfections, and loading eccentricities were discussed. Experiments were carried out to examine the effects of geometric and loading imperfections on columns of various shapes. A model originally developed for axisymmetric situations was extended to include the complicating effects. An analytical study for the corner radius that avoids concentration of stress was carried out. The theoretical models were verified with the present and published experimental results.

Saidy et al. (2010) experimentally investigated the damaged/repaired reinforced concrete beams exposed to accelerated corrosion. The corrosion rate was varied between 5% (mild) and 15% (severe) which represents loss in cross-sectional area of the steel reinforcement in the tension side. To accelerate the corrosion process for the tension steel reinforcement, salt (NaCl) was added to the mixer before concrete casting so that 3% chloride ions, by weight of cement, were uniformly distributed along the bottom third of each specimen to be corroded. 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. 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.

Spainhour et al. (2008) investigated the corrosion performance of steel reinforcement embedded in concrete encased by carbon fiber reinforced polymer (CFRP) wraps with two different types of epoxies namely-West System 105 (WS), a marine grade epoxy designed specifically for reinforcing fabrics and, Sikagard 62 (SG), a thick, gray epoxy designed for use as a thick, corrosion-resistant, moisture-insensitive protective coating. Nine cylindrical test specimens were cast with different number of CFRP layers with different epoxies. The CFRP wraps were applied to samples in a hand lay-up procedure. An initial coat of epoxy was applied to the bottom and sides of the samples, followed by the application of successive wetted fabric layers then followed by a final clear coat of epoxy. The specimens were immersed, in a 5% Nacl solution at a room temperature and connected to a 12-volt DC power supply, thus impressing a current such that the reinforcing bars are anodic. These experimental results showed that WS epoxy coating has no effect on the onset or rate of corrosion but WS epoxy coating with CFRP wraps delay the onset of corrosion of WS samples takes over twice as long when samples are wrapped. However in the case of SG samples, an epoxy coating was able to delay the onset of corrosion by a factor of 2, and for wrapped SG samples the onset of corrosion takes 4–8 times longer .These results indicate that the SG epoxy with even a single CFRP layer is enough to inhibit the passage of salt water, protect the concrete from deterioration and considerably slow the overall corrosion rate with lower amounts of corrosion mass loss thereby providing a longer period of protection to the underlying concrete and embedded steel bars.

Wootton et al. (2003) also reported that CFRP wraps effectively reduced the corrosion rate in reinforced concrete cylinders.

5.5 CLOSING REMARKS

This chapter presents the literature survey on non destructive and ultrasonic techniques used to monitor corrosion on FRP repaired RC structures. It is observed that the potential difference between the electrode (steel reinforcement) and the adjacent electrolyte (concrete) represents the electrode potential and it is the driving force for an electrochemical reaction to occur. Therefore monitoring the initiation of corrosion and further the propagation of corrosion is necessary. Further FRP wrapping has been thought to serve as a diffusion barrier to inhibit the ingress of chloride ions, oxygen, and moisture into the inside concrete, eventually decreasing the corrosion rate.

CHAPTER 6

EXPERIMENTAL PROGRAM

6.1 GENERAL

In this chapter the experimental setup is presented to evaluate the performance of FRP wrapped specimens. The procedure for monitoring the progression of corrosion of steel in concrete after it has been treated with surface bonded FRP by using NDT techniques namely electrochemical LPR measurement, half cell measurement and ultrasonic guided waves is also explained in detail.

6.2 TEST PROGRAMME

The objective of test programme is to find out the corrosion behavior of CFRP retrofitted slabs by applying active protection using two different levels of current namely 30 mA and 10 mA (equivalent to 126 μA/cm^2 and 40 μA/cm^2 respectively). The test programme involved

1. Determinations of basic properties of constituent materials namely cement, fine aggregates, coarse aggregates and steel bars as per relevant Indian standard specifications.
2. Casting of slabs of size 300 x 300 x 100 mm with concentric 25 mm diameter mild steel bar using M 20 grade concrete.
3. Subjecting the slab specimens to accelerated corrosion by providing initial voltage of 10 mV.
4. Retrofitting corroded slab specimens by wrapping with CFRP sheets and further protecting rebars through active protection by applying anodic current at two different levels of 10 mA and 30 mA. This protection is provided at 3 different stages of corrosion:-
   - Onset of corrosion
   - Onset of crack

➢ Two days after onset of crack

5. In order to study the effect of level of anodic current active protection.

Table 6.1: Test Specimens with Different Level of Current

Description	Dimension (mm.)	Level of current	Wrapping levels	Specimen No.
Group 1	300 x 300 x 100	10 mA	Onset of corrosion	CA-1
			Onset of crack	CA-2
			2 days after crack	CA-3
Group 2	300 x 300 x 100	30 mA	Onset of corrosion	CB-1
			Onset of crack	CB-2
			2 days after crack	CB-3

Test specimens with different level of current are shown in **Table 6.1**. An accelerated corrosion technique is used so that testing could be completed within a reasonable time. Two power supplies are used for this purpose, one for each group. These power supplies allowed application of a constant voltage and constant current. The power supplies had voltage and current capacities of 150 V and 1000 milliamperes (mA) in increments of 1 V and 1 mA, respectively. An LCD screen displayed the instantaneous voltage and current, which allowed continuous monitoring of the fluctuation in the impressed current with time. **Fig. 6.1** shows a general view of the specimens and the power supplies used to accelerate corrosion.

Fig 6.1 Specimens and the Power Supplies Used to Accelerate Corrosion

All specimens are exposed to the same environmental conditions to elucidate the effect of test parameters on corrosion activity and concrete cracking.

6.3 MATERIALS USED

Cement, fine aggregates, coarse aggregates, water and MS bars are used in casting of slabs. The specifications and properties of these materials are as under:

6.3.1 Cement

Ordinary Portland cement of 43 grade is used for the present investigation. The cement is of uniform colour i.e. grey with a light greenish shade and is free from any hard lumps. Summary of the various tests conducted on cement are given in **Table 6.2.** All the tests are carried out in accordance with procedure laid down in IS: 8112-1989.

6.3.2 Fine Aggregates

The fine aggregates used for the experimental work is locally procured and conformed to grading zone III. Sieve Analysis of the fine aggregate is carried out in the laboratory as per IS 383-1870. The sand is first sieved through 4.75mm sieve to remove any particle greater than 4.75 mm sieve and then washed to remove the dust. The physical properties and sieve analysis of fine aggregates are shown in **Table 6.3 and 6.4.**

Table 6.2: Physical Properties of Cement

S.No.	Characteristics	Values obtained	Standard values
1.	Normal Consistency	33%	-
2.	Initial Setting time	48 min	Not be less than 30 minutes
3.	Final Setting time	240 min	Not be greater then 600 minutes
4.	Fineness	4.8 %	<10
5.	Specific gravity	3.09	-
Compressive strength:- Cement : Sand (1:3)			
1.	3 days	24.5 MPa	27 MPa
2	7 days	38 MPa	41 MPa
3.	28 days	45 MPa	43 MPa

Table 6.3: Physical Properties of Fine Aggregates

Sr. No.	Characteristics	Value
1.	Specific gravity	2.46
2.	Bulk density	1.4 g/cc
3.	Fineness modulus	2.56
4.	Water absorption	0.85%
5.	Grading Zone (Based on percentage passing 0.60mm)	Zone III

Table 6.4 Sieve Analysis of Fine Aggregate

Sr. No.	Sieve Size	Mass retained (gm)	Percentage Retained	Cumulative Percentage Retained	Percent Passing
1	4.75mm	4.0	0.4	0.4	99.6
2	2.36 mm	75.0	7.50	7.90	92.1
3	1.18 mm	178.0	17.8	25.70	74.3
4	600µm	220.0	22.0	47.70	52.3
5	300µm	274.0	27.4	75.10	24.9
6	150µm	246.5	24.65	99.75	0.25
7	2.50	0.25	0.25	∑=256.55	

Total weight taken = 1000 gm

Fineness Modulus of fine aggregates = 2.56

6.3.3 Coarse Aggregates

Crushed stone aggregate (locally available) of nominal size 10 mm are used throughout the experimental study. The aggregates are washed to remove dust and dirt and are dried to surface dry condition. The aggregates are tested as per IS: 383-1970. The results of various tests conducted on coarse aggregate are given in **Table 6.5 and Table 6.6** shows the sieve analysis results.

Table 6.5 Physical Properties of Coarse Aggregates

Sr. No	Characteristics	Value
1	Type	Crushed
2	Specific Gravity	2.66
3	Total Water Absorption	0.56%
4	Fineness Modulus	6.83

Table 6.6 Sieve Analysis of Coarse Aggregates

Sr. No.	Sieve Size	Mass Retained (gm)	Percentage Retained	Cummulative Percentage Retained	Percent Passing
1	20 mm	0	0	0	100
2	10 mm	2516	83.89	83.87	16.13
3	4.75 mm	474	15.8	99.67	0.33
4	PAN	10	0.33	$\sum$= 183.54	

Total weight taken = 3Kg

FM of 10 mm Coarse aggregate = (183.54+500) /100 = 6.83

6.3.4 Water

Fresh and clean tap water is used for casting the specimens in the present study. The water is relatively free from organic matter, silt, oil, sugar, chloride and acidic material as per Indian standard.

6.3.5 Steel Reinforcement

Mild steel bars of 25 mm diameters and 600 mm length are used as longitudinal reinforcement. The central 300 mm length of rebar is embedded in concrete and 150 mm is exposed on both sides in order to make electrical connections. **Table 6.7** shows the properties of reinforcing bars used for casting of RC beams.

Table 6.7 Properties of Reinforcing Bars Used for Casting of RC Beams

Type and size of bar	Ultimate Tensile Stress(MPa)	Yield stress(MPa)	Young's Modulus(GPa)	Percentage Elongation
Mild Steel, 25mm	410	240	200	23

6.3.6 CFRP material

Unidirectional CFRP (electrically conductive) sheets as shown in **Fig. 6.2** having cross section 300 X 0.1176 mm are used for wrapping the corroded samples. The CFRP sheets are obtained from BASF construction chemicals and building systems. **Table 6.8** shows the properties of CFRP Sheets.

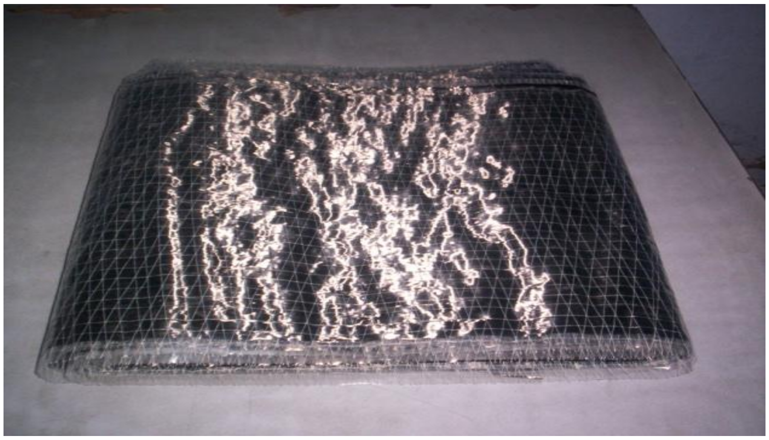


Fig 6.2 CFRP sheet used in the experiment

Table 6.8 Properties of CFRP Sheets

Sr. No.	Physical properties	Value
1	Tensile Strength	3800 MPa
2	Modulus of elasticity	240 GPa
3	Density	1.7

6.3.7 Adhesives

The adhesive used for bonding FRP sheets with concrete is a compatible epoxy system provided by the manufacturer. It is blue pigmented epoxy resin for saturation of MBrace fibre sheet to form in-situ FRP Composite. It is made by mixing base saturant and hardener in ratio 100:40. Mixing of saturant and hardener is done thoroughly for five minutes until components are thoroughly dispersed. Graphite powder is added during mixing in order to make the epoxy conductive. Properties of Epoxy are discussed in **Table 6.9.**

Table 6.9 Properties of Saturant

Sr. No.	Properties	Values
1	Aspect	Translucent Blue Liquid
2	Density	1.13 ± 0.03
3	Mixing ratio, by weight (B:H)	100:40
4	Pot life	25 minutes at 25 degree
5	Tensile Strength	> then 17 MPa
6	Compressive Strength	>40 MPa after 1 day
7	Flexural strength	>35 MPa

6.4 DESIGN OF CONCRETE MIX

Concrete mix is prepared using 43 grade Portland pozzolana cement, fine aggregate (medium-sized natural river sand) and crushed stone coarse aggregate with nominal size of 10 mm. The mix is designed as per Indian Standard Guidelines. The ratio of cement: sand: coarse aggregate is 1:1.49:2.48. The water-cement ratio is 0.5 and compressive strength of concrete after 28 days is 29 MPa.

6.5 TEST PROCEDURE

6.5.1 General

Corrosion initiation takes place when the chloride concentration at the rebar level reaches a critical value. The most established of the electrochemical techniques to assess initiation of corrosion activity is half-cell potential mapping. Steel reinforcement potentials relative to a stable reference half-cell, which can be measured from the surface of the concrete, can be related to the probabilities of corrosion using the guidelines in ASTM C876-91. The method of measurement is based on a simple technique and well established equivalence is available for converting the potential obtained from one reference electrode to another. Thus half-cell potential can serve as a determining parameter for indicating initiation of corrosion. In the present study, the half cell potential measurements are carried out with reference to saturated calomel electrode (SCE). Along with half cell potential, linear polarization resistance test is conducted on all slab specimens by monitoring the specimens daily.

The applicability of ultrasonic waves to identify corrosion mechanism occurring in rebar in concrete is investigated by measuring ultrasonic signals while the bar is subjected to corrosion in chloride environment. An ultrasonic approach is chosen because of the relative feasibility of using an embedded ultrasonic network for monitoring corrosion in real structures. Guided waves are chosen because they have the capability of testing over distances with a sensitivity often greater than conventional non-destructive testing (NDT) techniques, have the ability to test multilayered structures, and are relatively inexpensive due to simplicity and sensor cost.

6.5.2 Preparation and Preconditioning of Steel Bars

Steel bars are cut to the required length of 600mm. Each bar is then wire brushed to remove any surface scale. These are then cleaned by soaking in analytical reagent grade hexane and allowed to air dry. This steel specimen preparation is similar as specified in *ASTM G 109*. Before casting of the test specimens, each reinforcing bar is weighed to 0.1 gm accuracy.

6.5.3 Preparation of Slab Specimen

In the present program, a special moulding system is fabricated for casting the specimens. The slabs are cast in mould of size 300 x 300 x 100 mm with steel bars placed concentrically. First of all the interior of slab mould is oiled, so that the slabs can be easily removed from the mould after 24 hours. While embedding these bars in concrete, they are kept in such a way that 150 mm lengths of these bars is protruded outside of the concrete specimen from both sides. Initial weight of all rebars is measured. When the bars have been placed in position, concrete mix is poured and vibrations are given so that the mix gets compacted. The vibration is done until the mould is completely filled and there is no gap left. The slabs are then removed from the mould after 24 hours. After demoulding the slabs are cured for 28 days using jute bags. The concrete surface of the slabs is then cleaned and all dirt and loose materials are removed before initiation of corrosion/work.

6.6 CORROSION MONITORING TECHNIQUES

Corrosion of steel embedded in concrete is not visually evident until the damage reaches to the external signs of deterioration as rust spots, cracks or spalling. In order to predict the corrosion service life of reinforced concrete structures and to determine the need of repair or rehabilitation, it is necessary to use non-destructive techniques for assessing the corrosion activity and measuring the corrosion rate of the reinforcements. In the present study, the corrosion rate of rebar is monitored by electrochemical methods as well as by means of ultrasonic investigations. The following sections describe both the procedures in detail.

6.6.1 Electrochemical Techniques

The electrochemical measurements are carried out using a versatile instrument (Make ACM, model: serial no.1463 field machine) that is capable of performing various electrochemical tests such as potential measurement, AC impedance technique, potentiostatic cyclic sweep test, LPR measurements etc. **Fig 6.3** shows ACM setup used for electrochemical monitoring**.** The instrument is capable of processing the data and plotting the outputs automatically.

The half cell potential measurement gives only an indication of the corrosion risk of the steel and is linked by empirical comparisons to the probability of corrosion. Therefore along with half cell, linear polarisation (corrosion rate) measurements are taken which provides a valuable insight into the instantaneous corrosion rate of the steel reinforcement, giving more detailed information than a simple potential survey. The LPR data enables a more detailed assessment of the structural condition and is a major tool in deciding upon the optimum remedial strategy to be adopted. Hence the two important electrochemical techniques that are used for the studying the corrosion activity are corrosion potential (E_{corr}) and corrosion current /current density (I_{corr}). These determining parameters indicate the corrosion initiation which account for steel surface condition and the chloride ion concentration in concrete *(Pradhan and Bhattacharjee 2009; Bhavneet 2010).*

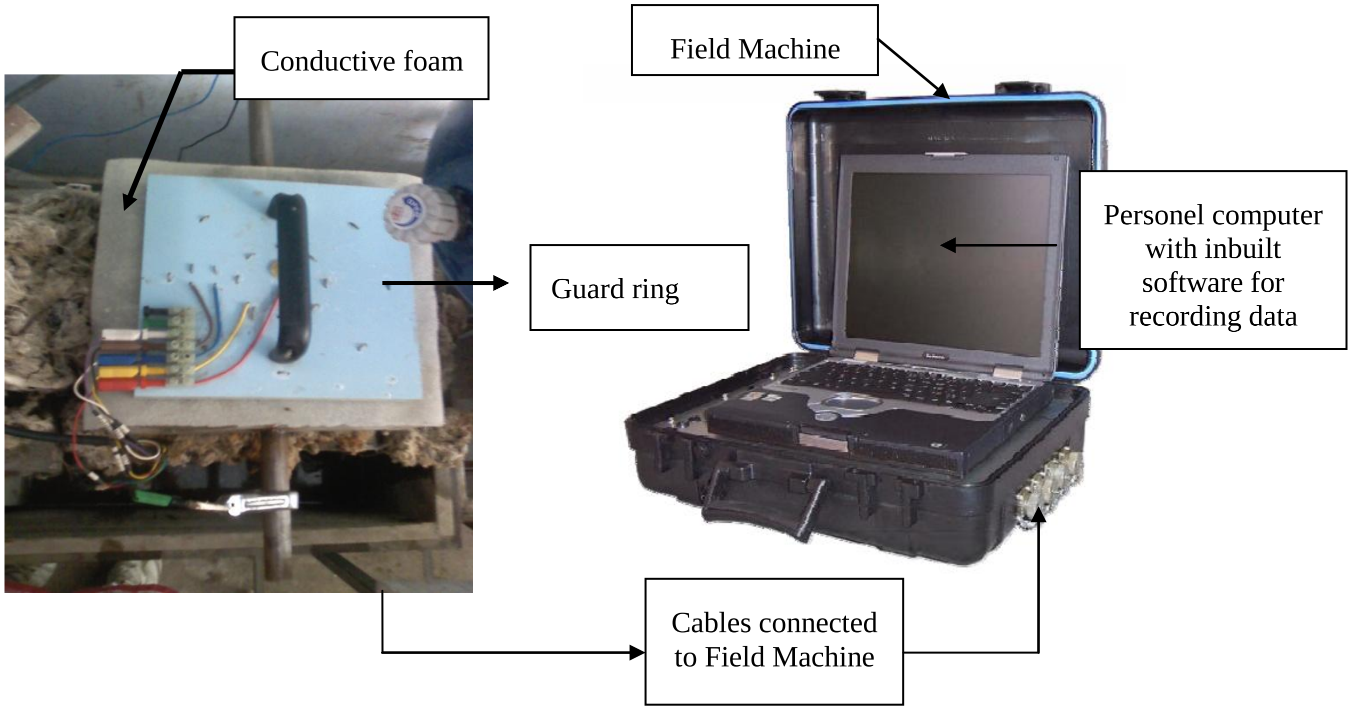


Fig 6.3: ACM Setup Used for Electrochemical Monitoring

6.6.1.1 Half cell potential measurements

In the present study, all the specimens are monitored daily by half-cell potential using a saturated calomel reference electrode by placing the electrode on top surface of the concrete. The procedure followed is ASTM Standard C 876. The power supply is switched off one hour before taking the half cell readings in order to completely depolarize it. To maintain a consistent testing environment over the 30-day experimental test period, the dripping salt water is replaced daily, electrodes are cleaned daily and the wiring and electrical connections checked twice a day. If the corrosion potential reading is more positive than -200mV, probability is that no reinforcing steel corrosion is occurring in the area at the time of measurement and if the potential reading is more negative than -426mV, probability is that the reinforcing steel corrosion is occurring [16]. The ASTM interpretation of half-cell potential (SCE) is summarized inn **Table 6.10**. The experimental arrangement for half cell measurement is shown in **Fig. 6.4**.

Table 6.10 The ASTM Interpretation of Half-Cell Potential Readings

Open circuit potential (OCP) values	Corrosion condition
< -426 Mv	Severe corrosion, corrosion induced cracking may occur
< -276 Mv	High risk, 90% probability of corrosion
-126 to -275 Mv	Intermediate risk, corrosion activity in uncertain
0 to -125 Mv	Low risk, 10% probability of corrosion

Fig 6.4 Half Cell Arrangement

6.6.1.2 Linear polarization resistance (LPR) measurements

Electrochemical LPR technique is especially good at measuring the localized corrosion. LPR measurements on concrete surfaces are performed using guard ring that is supplied with the field machine for precise location of rebar areas. The Guard Ring simply connects to the front panel via the supplied cables. Incorporated into the Guard Ring are a Cu/$CuSO_4$ reference electrode. Before performing the test, conducting sponge is wetted with NaCl solution and placed on the surface of the slab specimen to have proper electrical contact with the guard ring. Guard ring assembly is then placed above the wetted sponge. The electrical connections are made to the steel rebar.

For linear polarization resistance measurement, the working electrode i.e. the steel rebar is polarized to ± 20mV from the equilibrium potential at a scan rate of 0.1mV per second. The experimental arrangement for LPR measurement with guard ring arrangement is shown in **Fig. 6.5**. The polarized surface area of the steel rebar is taken to be that lying under a circle intersecting the midpoint between the two sensor electrodes and only the top half surface area of the steel reinforcement is assumed to be polarized.

Fig. 6.5 Guard Ring Arrangement

For calculation of the corrosion current density I_{corr}, Stern-Geary equation is used; (*Song and Saraswathy 2007*)

$$I_{corr} = \frac{B}{R_p}$$

Where B is the Stern-Geary constant and is given by B = ($\beta_a \times \beta_c$) /2.3($\beta_a + \beta_c$). β_a and β_c are anodic and cathodic Tafel constants respectively. The value of B is taken as 26mV considering steel in active condition. Rp is the polarization resistance.

6.6.2 Ultrasonic pulse velocity measurements

Concrete testing is at present based largely on pulse velocity measurements using through-transmission techniques. This method has become widely accepted around the world, and commercially produced robust lightweight equipment suitable for site as well as laboratory use is readily available.

Fig. 6.6 Karl Deutsch Contact Type Transducers

Fig. 6.7 Transducers attached at the Two Ends of Rebar

All the specimens are monitored by ultrasonic guided wave modes in Pulse Transmission (P/T) mode. The excitation wave mode from the transmitter T travels through the material to its opposite surface where the receiving transducer R is placed. To produce guided waves in the bars of concrete beam two pairs of transducers of 0.1 Mhz and 1 Mhz (Karl Deutsch contact type) as shown in **Fig. 6.6** are used. Transducers having diameter of 25 mm are attached at the two ends of the protruded rebar as shown in **Fig.6.7**. A gel is used as a coupling medium to improve the contact between the samples and the transducers. One transducer acting as a transmitter and the other acting as a receiver are attached parallel to the axis of bars in pulse transmission mode of testing. DPR 300 pulse/receiver is used to generate the ultrasonic pulse, by means of through transmission method, which propagates through the embedded bar in the form of longitudinal waves. It is observed that during the acceleration of corrosion the signal slowly comes down from peak value. **Fig 6.8** shows the set up used for ultrasonic investigations. **Fig 6.9** shows the view of signatures as taken on the computer.

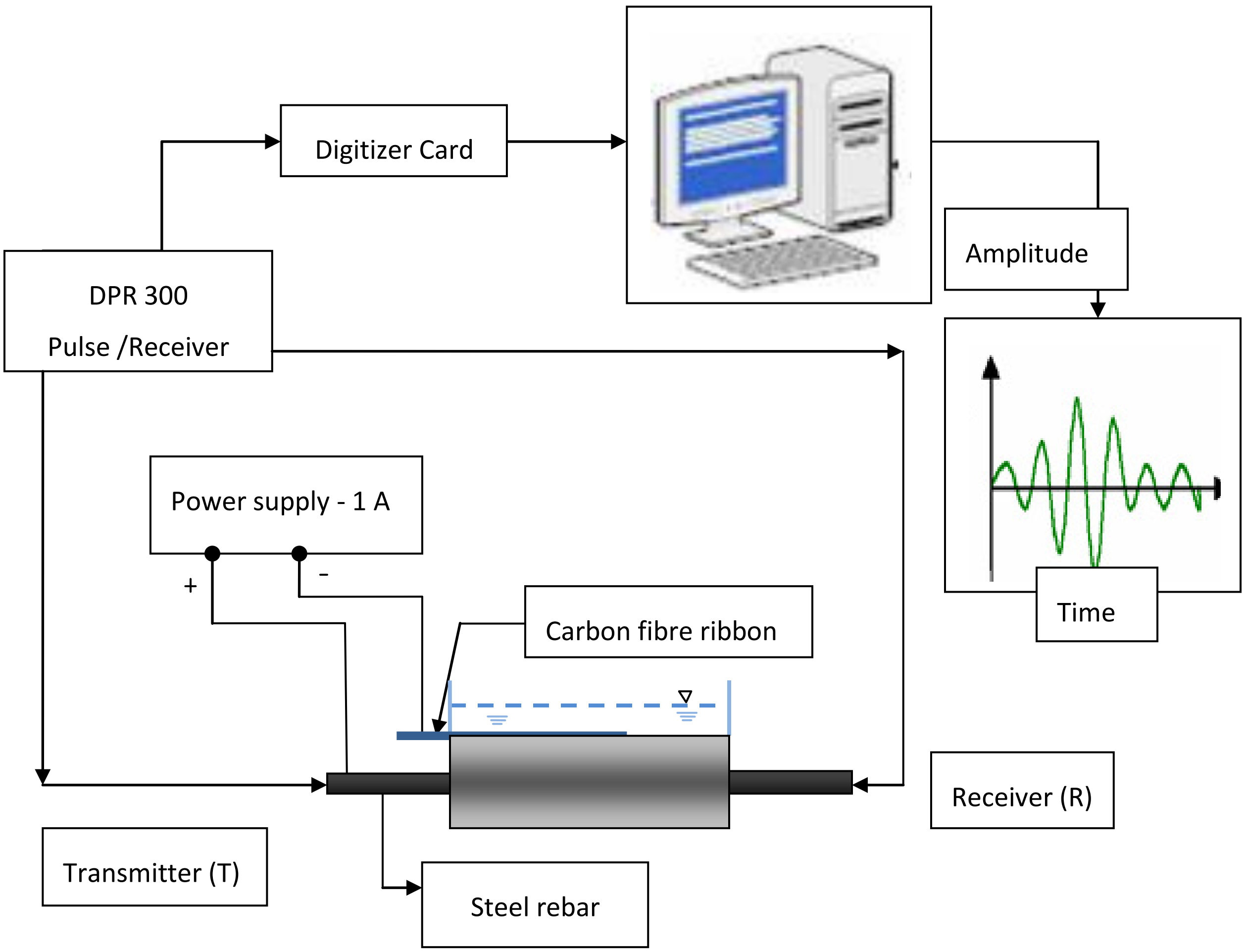


Fig. 6.8 Set Up Used For Ultrasonic Investigations

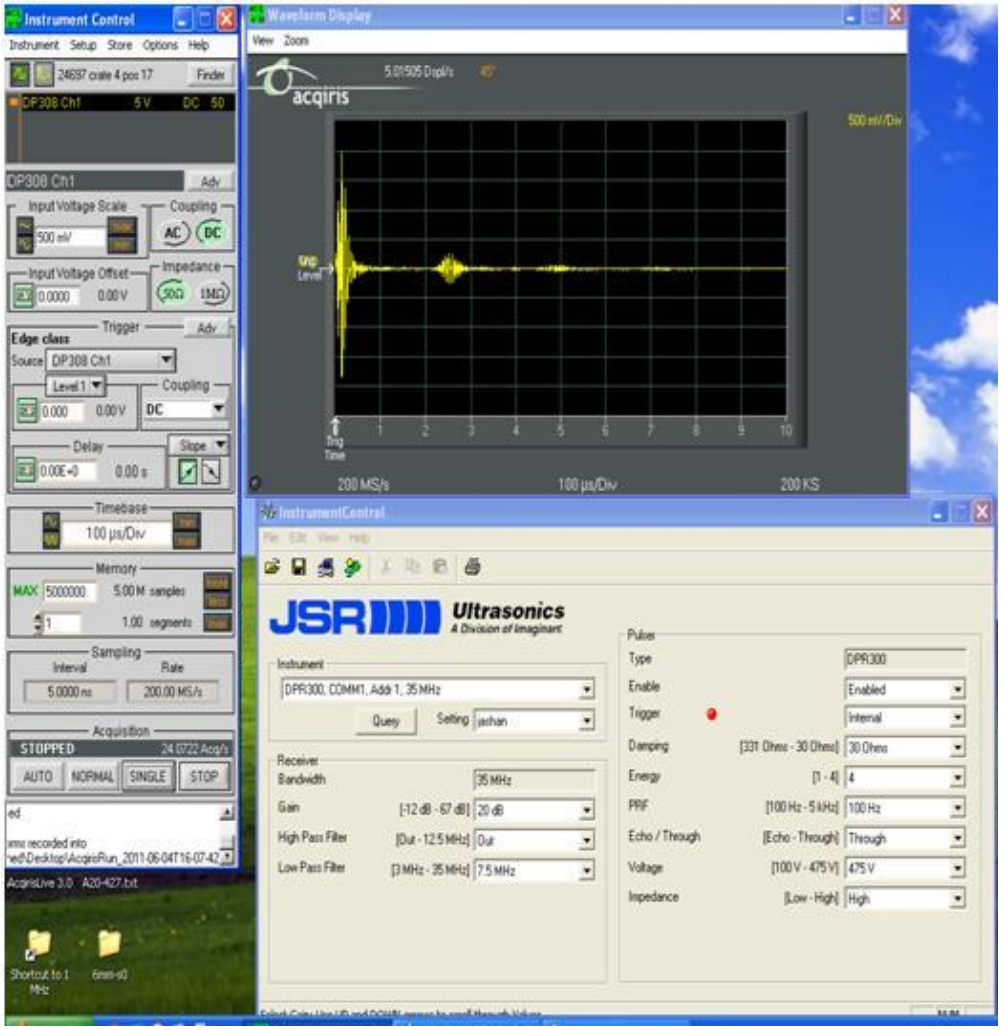


Fig 6.9 View of Signatures As Taken On the Computer Screen

6.7 INDUCING CORROSION IN STEEL REBAR

The objective of inducing corrosion to the reinforcing bar is to simulate the corrosion damaged concrete. The commonly used methods of inducing corrosion in RC specimens can be recalled as salt spray *(Debaiky et al. 2002; Gadve et al. 2009)* Chloride diffusion *(Masoud and Soudki 2006)*, alternate drying and wetting in salt water *(Debaiky et al. 2002 and Soudki 2006)* and impressing anodic current *(Wootton et al. 2003).* Previous studies have shown that test specimens kept in a salt spray chamber for more than 100 days did not show any visible signs of corrosion. This method was not found suitable considering the time constraint. Method of adding chlorides artificially to the concrete during casting is an effective method of initiating corrosion in steel rebar. This method was not considered because it did not simulate the present condition of interest. Alternate immersion into NaCl (Sodium Chloride) solution and drying of the specimens also induces corrosion. However, the quickest method of inducing corrosion is by impressing anodic current. In this method, NaCl solution is supplied to the specimens and a direct current is passed making the reinforcement bar as an anode and another metal nobler than steel in electro-chemical series as cathode. Incidentally, this method has been used by a number of previous investigators *(Bonacci & Maleej 2000; Masoud et al. 2001; Bhavneet et al. 2010; Gadve et al. 2009).*

Fig. 6.10 View of Stainless Steel Mesh **Fig 6.11 Dripping With 5% Nacl Solution**

Present method of inducing accelerated corrosion

In this investigation, the specimens are kept fully saturated by continuously dripping with 5% NaCl solution as shown in **Fig 6.10**. Mats are placed over the tops to provide even distribution of NaCl solution. The rebar is used as anode. A stainless steel (SS) mesh is rolled around 300 mm length of specimen and tied together with metal ties in order to assure electrical continuity and is used as cathode **(Fig. 6.11).** The reinforcement extended 150 mm on both sides past the concrete to allow easy access for making electrical connections to the steel. The constant voltage of 10 mV is impressed in order to accelerate corrosion. The DC regulated power supplier (DCRPS) used in the present study could supply 1000mA DC at 30V. The rebar is connected to the positive terminal of the external DC source and negative terminal is connected to the SS mesh. It is more common to maintain a constant voltage between the cathode and the anode *(Soudki 2006; Gadve et al. 2009).* Half-Cell potential, linear polarization measurements and ultrasonic signals are obtained daily for all the specimens throughout the duration of experiment.

6.8 WRAPPING THE PRE-CORRODED SPECIMENS

Two fiber materials are popular in the rehabilitation of structures in India- glass and carbon. Carbon scores higher than glass in terms of strength, stiffness, durability corrosion and fatigue resistance in structural rehabilitations. Electrically conductive carbon fiber sheets offer a possibility of cathodic protection of the structure. Therefore, carbon fiber sheets have been used in the present investigation.

Method of applying wraps

The samples are air dried prior to the application of FRP wraps. Manufacturer's specifications are followed in the application of the wraps. A grinder is used for rounding off the sharp corners and removing local unevenness from the surfaces as shown in **Fig 6.12**. A mixture of two components of epoxy resin and hardener is mixed in the ratio 100:40 for wrapping the carbon fiber sheets onto concrete. Since the epoxy adhesive used is not electrically conductive, therefore it is made conductive by adding 20-25% of conductive graphite powder. **Figure 6.13** shows the epoxy on concrete surface.

Fig. 6.12 View of Grinder

Figure 6.13 Applying Epoxy on Concrete

Fig 6.14 Placing Carbon Fiber Sheets **Fig 6.15 Rod Used For Smoothening**

Unidirectional CFRP sheet is used for wrapping. One layer of CFRP sheet is wrapped throughout 300 mm length of the test specimens and an overlap of 50 mm is provided at the ends of the sheets. This CFRP wrapped test specimen is additionally provided with adhesively bonded 25-30 mm wide carbon ribbon so that uniform distribution of direct current throughout the specimen is possible for effective application of active protection. Sufficient pull is applied to the fibre sheet to ensure uniform direction of fiber and absence of wrinkles as shown in **Fig 6.14**. Care is taken to avoid air gaps between the concrete surface and the confining carbon fibers. For this plain rod is rubbed for smoothening on top surface of CFRP sheet as shown in **Fig 6.15** so that the sheet makes uniform bond with epoxy. All the wrapped specimens required one day to cure.

6.9 ACTIVE PROTECTION

Active protection is a technique which aims at stopping rebar corrosion in chloride contaminated concrete. The alkalinity of the concrete around the rebars is restored, and an environment favorable to the passivation of steel is re-created. The technique is based on the application of a DC current in which the rebar acts as cathode and CFRP sheets wrapped on the external surface of the concrete, are used as anode. It is an electrochemical process, exactly opposite to that of corrosion process, which also involves anode, cathode and electrolyte.

6.10 CORRODING THE WRAPPED SPECIMENS

One of the objectives of study is to investigate the effect of impressed current for active protection. To simulate corrosion damaged structures, prior to the application of wrap an initial exposure is applied. In practice, the FRP wraps are applied on structures that are corroded to varying degrees. Therefore, different exposure durations are chosen prior to the application of the wrap. Three exposure durations - onset of corrosion, onset of visible crack, and 2 days after onset of visible crack are applied. The total duration of exposure is 40 days for all specimens. That is why different levels of current is selected after wrapping the corroded specimens at different levels as explained earlier. For this all specimens are subjected to constant anodic current. 10 mA and 30 mA current is applied and for group-1 and group-2 respectively. The setup of the specimens is shown in **Fig 6.16**. Ponding with 5 % NaCl is done. The positive terminal is connected to the carbon fibre ribbon and the negative terminal is connected to the rebar as shown in **Fig.6.17.** Corrosion monitoring is done as explained earlier using half cell, LPR and ultrasonic guided waves.

Fig 6.16 Setup of Beam Specimens

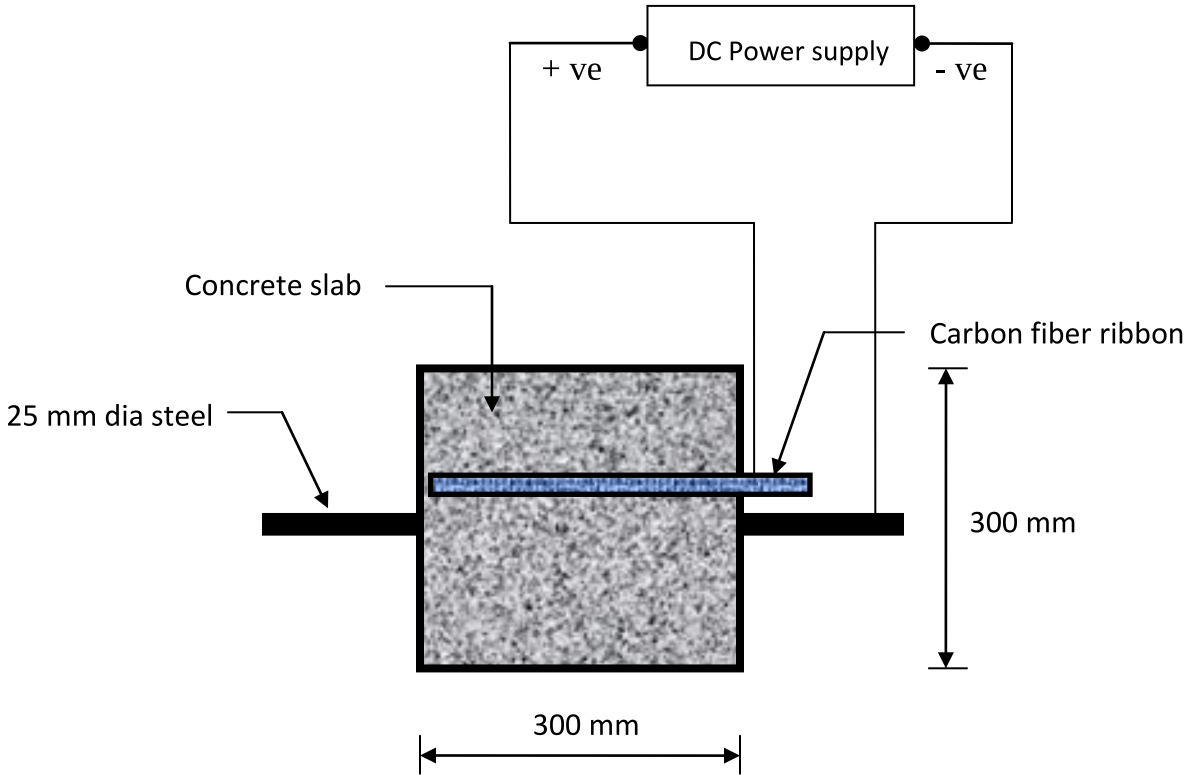


Fig. 6.17 Top View of Beam Showing Terminals for Active Protection

6.11 CLOSING REMARKS

In this chapter the procedure for monitoring corrosion of reinforcing bars by various methods is discussed in detail. Corrosion monitoring, can give a more complete picture of the changing condition of a structure in time as well as in the three physical dimensions of the structure. Therefore properly monitoring the structures for corrosion performance and taking suitable measures at the appropriate time could affect enormous saving. Proper care should be taken during wrapping of CFRP sheet which is also discussed in detail.

CHAPTER 7

RESULTS AND DISCUSSIONS

In this chapter, the findings of an experimental investigation are presented, wherein various corrosion tests have been conducted to evaluate the performance of FRP wrapped specimens actively protected against corrosion.

7.1 GENERAL

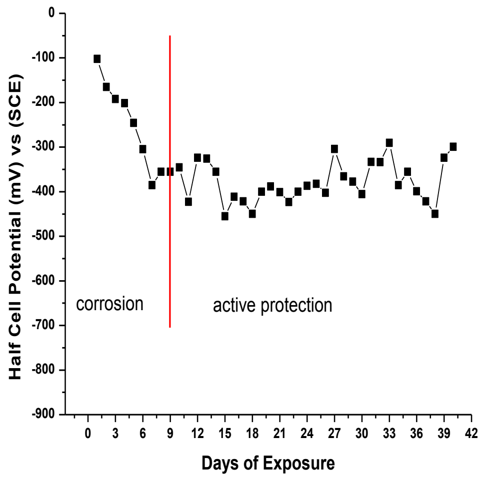
There are a number of techniques that can be used to carry out assessment of a structure suffering from corrosion of the reinforcement *(Broomfield, 2002).* However, in order to determine the rate of deterioration of the structure, it is useful to monitor the condition change with time. The objective of our present study is to investigate the efficacy of active protection with CFRP composites used for the repair of corroded reinforced concrete slabs. First, the slabs are subjected to acceleration corrosion process to initiate corrosion. They are then repaired and actively protected so that corrosion of steel can be avoided. Monitoring is done using three test methods namely half cell, LPR and ultrasonic measurements.

7.2 ELECTROCHEMICAL MEASUREMENTS

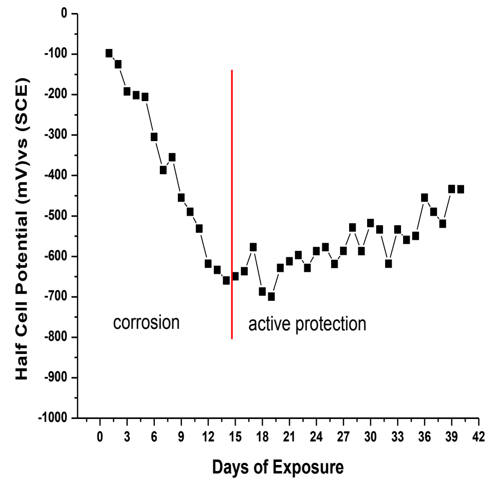
7.2.1. Half cell measurements

Half-cell potential (E_{corr}) of reinforcing steel bars in all the specimens is recorded everyday throughout the duration of experiment. Saturated calomel electrode is used as a reference electrode. In order to measure the electrochemical signals correctly, the specimens should be depolarized. To achieve this purpose, prior to the measurement of the half-cell potential, the current is interrupted for one hour. The major objective of our study is to investigate the effect of applied current during active corrosion protection on behavior of slabs. Two levels of applied current ie. 10 mA (40 $\mu A/cm^2$) and 30 mA (126 $\mu A/cm^2$) are chosen for this purpose. Further for each group three different levels of corrosion are considered. It consists of (i) onset of corrosion, (ii) onset of visible crack and (iii) two days after onset of visible crack. **Fig.7.1 and 7.2** shows the variation of half cell potential during the test period for group 1 and group 2 for all three stages of corrosion respectively.

Protection provided at onset of corrosion slab CA-1



Protection provided at onset of visible crack slab CA-2



Protection provided at two days after visible crack - slab CA-3

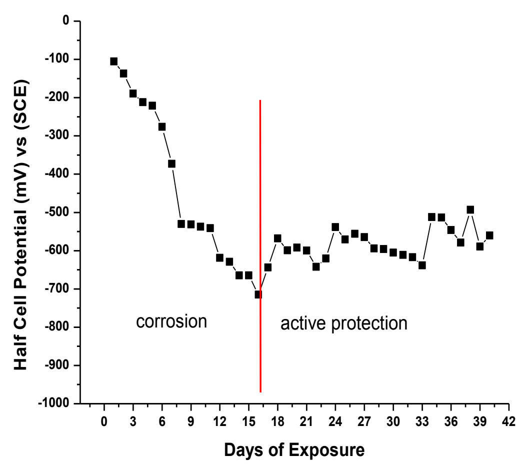
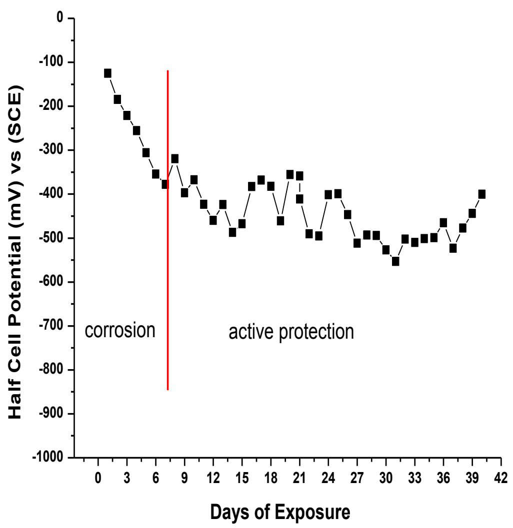
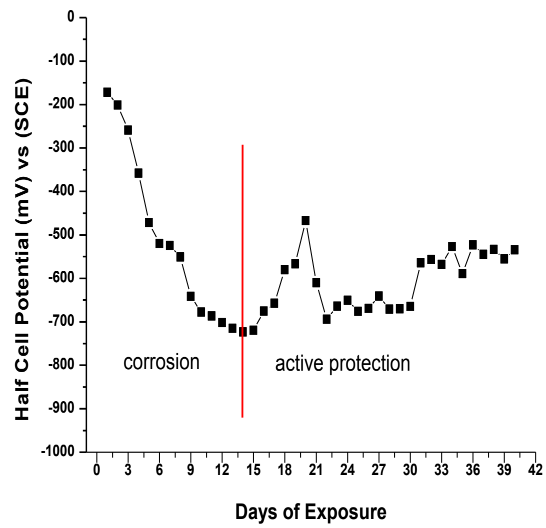


Fig. 7.1 Variation of half-cell potential with time (Current applied-10 mA)

Protection provided at onset of corrosion slab CB-1	Protection provided at onset of visible crack slab CB-2
	

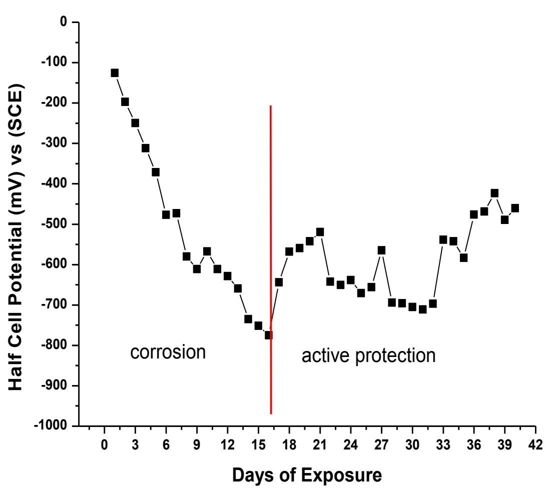
Protection provided at two days after visible crack - slab CB-3


Fig. 7.2 Variation of half-cell potential with time (Current applied-30 mA)

Observations

Establishing structures potential map, according to ASTM C876-91, is the most commonly applied electrochemical technique for diagnosing the corrosion risk of reinforced concrete structures *(Pradhan and Bhattacharjee (2009); Saidy et al.(2010))*. ASTM C876-91 suggests that the corrosion possibility of rebar embedded in concrete is higher than 90% when the open circuit potential is lower than -426 mV (SCE). From the experimental results, it is observed that the half cell measurements keep on varying with time but within a certain defined range. In the initial stages of corrosion acceleration, the half cell potential values are less than the corrosion threshold values ie -426 mV, which indicates that corrosion, has not started yet. Then the values kept on decreasing towards the more negative side indicating depassivation of rebar, until it reached a stage of severe corrosion. This rate of drop is nearly uniform for all specimens. With the passage of time longitudinal cracks appeared along the length of the rebar as shown in **Fig.7.3**. The reason behind this is due to the formation of corrosion products around the rebar that occupies volume larger than the original volume of the rebar, causing bursting stresses in the concrete. This indicates that corrosion has caused enough steel cross section loss and the structural capacity of the element is significantly impaired. The occurrence of longitudinal cracking if not repaired may often be precursors to more critical and dangerous situation. That is why retrofitting of slabs is required at this stage.

Fig. 7.3 Longitudinal crack along the length of rebar

From the results, it is observed that, there is sudden drop in half-cell potential of the rebar specimens after a certain interval of time. This indicated that a certain amount of chloride has reached the steel bar as expected and is responsible for the corrosion initiation as it has become anodic.

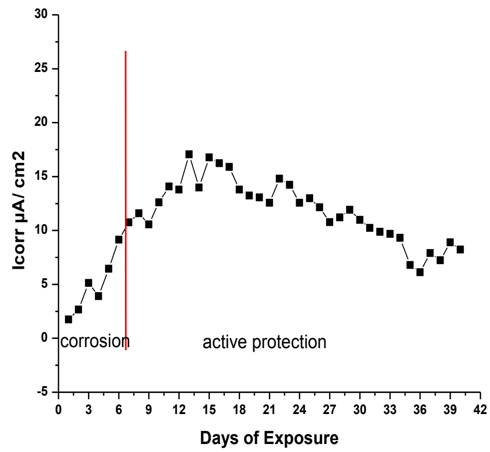
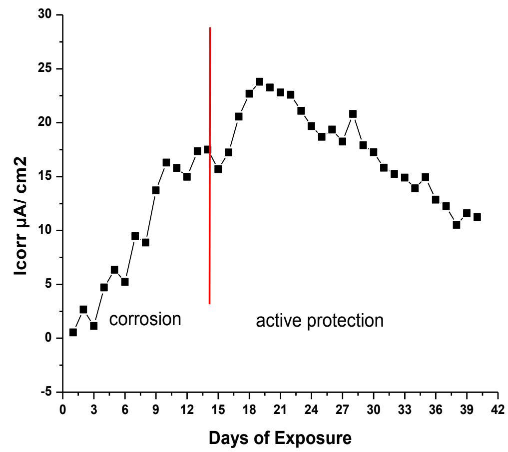
However, after active protection ie. after wrapping and providing impressed current of 10 mA and 30 mA, the half cell value rises slowly, in all the specimens irrespective of time of wrapping and applied current. It indicates that FRP did serve as an effective barrier for chlorides and prevented corrosion activity from taking place to some extent. Similar observations were made by *Gadve et al. (2010)* for FRP wrapped samples. However, the E_{corr} value of specimens is still in the state of active corrosion and will require some more time to reach passive stage. Therefore, in order to fully evaluate the effectiveness of FRP composite wrap in corrosion prevention, long-term testing is required on specimens that have been adequately repaired.

7.2.2 Corrosion Rate by LPR Technique

Half cell potential (E_{corr}) is effective only in monitoring the corrosion initiation. *Feliu et al. (2009)* found that E_{corr} depends on the degree of wetness of the concrete to a great extent. *Xu and Yao (2009)* concluded that the corrosion state of steel in chloride containing and chloride-free structures tends to be confused if the decision is based exclusively upon the E_{corr} values. Therefore LPR measurements are necessary as the values obtained from corrosion current density (Icorr) indicate the progression of corrosion in the propagation phase.

Observations

From the determined corrosion current density values by LPR method it is observed that the corrosion current density (I_{corr}) increased with days of exposure to applied voltage due to increase in chloride concentration around the rebar in all the specimens. As the corrosion progresses in the slabs the value of corrosion current (I_{corr}) rises. This is because of the depassivation of layer formed around the rebar due to the concentration of chlorides. From the graphs, it is concluded that during the acceleration process, the I_{corr} values are between 7 – 10 $\mu A/cm^2$ which indicates low corrosion. As we are increasing the exposure value the I_{corr} rises upto 25 $\mu A/cm^2$ which indicates moderate corrosion. Further as the exposure value increases, I_{corr} reaches 35 $\mu A/cm^2$ which indicates severe corrosion and crack is observed. Similar observations were made by *Martínez and Andrade (2009)*. Current readings, expressed in terms of the corrosion current density I_{corr}, are shown in **Figs. 7.4** and **7.5** for the 40-day test period.

Protection provided at onset of corrosion slab CA-1	**Protection provided at onset of visible crack slab CA-2**
	

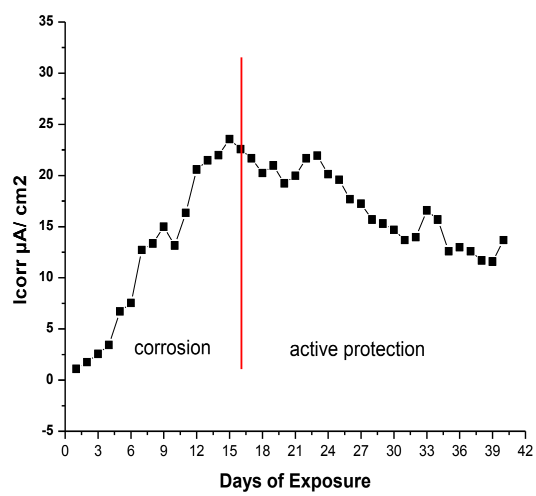
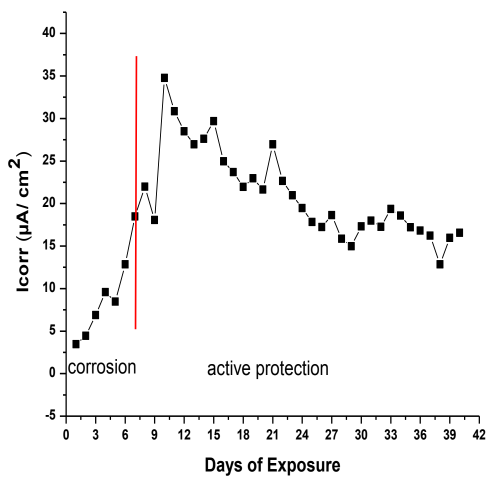
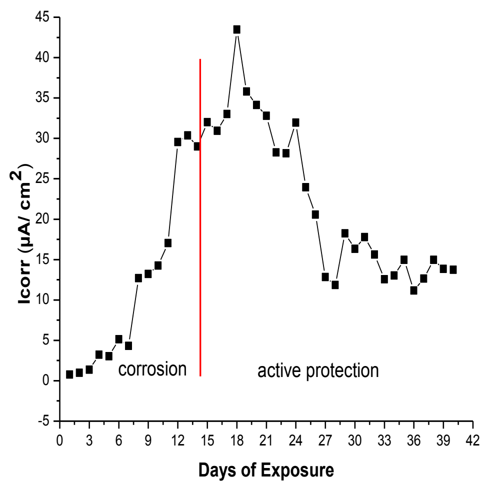
Protection provided at two days after visible crack slab CA-3


Fig. 7.4 Variation of LPR with time (Current applied-10 mA)

Protection provided at Onset of corrosion slab CB-1	Protection provided at Onset of visible crack slab CB-2





Protection provided at two days after visible crack slab CB-3

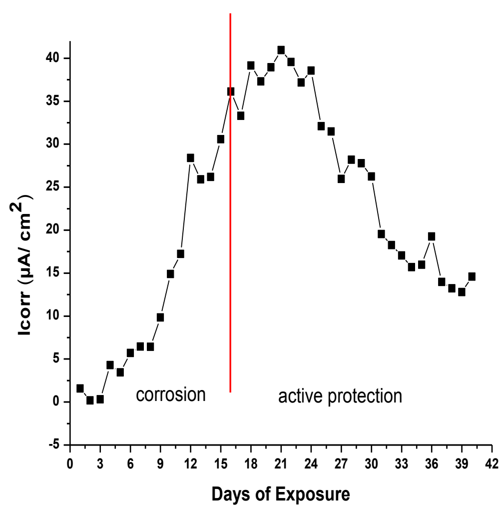


Fig. 7.5 Variation of LPR with time (Current applied-30 mA)

However, after active protection i.e. wrapping with CFRP sheet at three different stages of corrosion as mentioned earlier, the value of I_{corr} starts decreasing and corrosion risk is coming down from high to moderate. This trend is common irrespective of level of retrofitting and of applied current. *Koleva et al. (2006)* applied active protection by passing direct current to steel reinforcement and observed that corrosion current density decreases as the period of exposure increases. Lower I_{corr} for the wrapped samples establishes that wrapping significantly reduces the rate of corrosion. Similar observations were made by *Gadve et al. (2010)* in which the FRP wrapped samples had lower I_{corr} than the control sample.

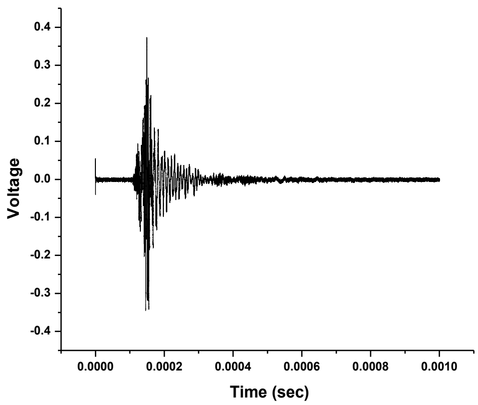
On comparing the effect of level of applied current on corrosion current, it is observed that the values of corrosion current are in the range of 10-20 $\mu A/cm^2$ irrespective of level of applied current. Moreover, there is lot of fluctuation in the values of I_{corr} when the applied current is 30 mA. It clearly indicates that higher applied current does not help in providing greater and faster protection.

7.2.3 Ultrasonic Measurements

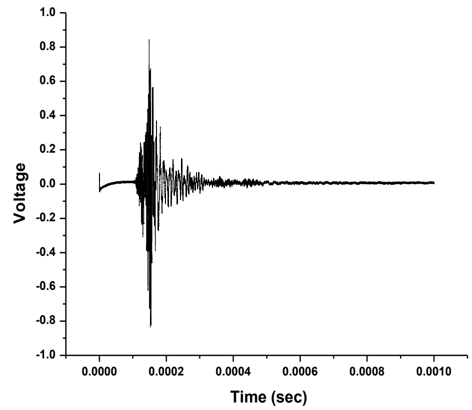
Ultrasonic techniques have been used for assessing FRP– concrete structures because of their safety, low-cost, and flexibility, in addition to the high sensitivity. *Mahmoud et al (2010)* utilized ultrasonic pulse velocity to assess damages within FRP-encased concrete. The embedded reinforcements in concrete can be excited at one end. The bar acts as a waveguide that assists its propagation. The waves leak into concrete and thus attenuate before reaching the receiver at the other end of reinforcement. (*Goueygou et al. (2008); Jung et al. (2002); Raisutis et al. (2007); Sharma et al. (2010)).* The excitation signal consisted of a compressive spike pulse.

For monitoring two different phenomena of pitting and delamination occurring as a result of corrosion, two different frequencies and modes have been identified *(Sharma and Mukherjee 2010).* The selection of frequencies for testing is done using the software Disperse. The modes that are easily distinguishable and have lowest signal attenuation are selected. The beams are monitored till the ultrasonic signature completely vanishes for all the specimens. Ultrasonic testing results are reported as Voltage-Time (V-t) values. *Bhavneet et al. (2010)* selected 25 mm diameter rebar and concluded that one mode at a frequency of 0.1 MHz (surface seeking mode) is sensitive to delamination effect of corrosion rebar and mode at a frequency of 1 MHz (core seeking mode) is sensitive to loss of material changes. Therefore these two frequencies are taken for complete analysis of corrosion process**. Fig. 7.6 and 7.7** shows typical trend of the signal variations at different stages.

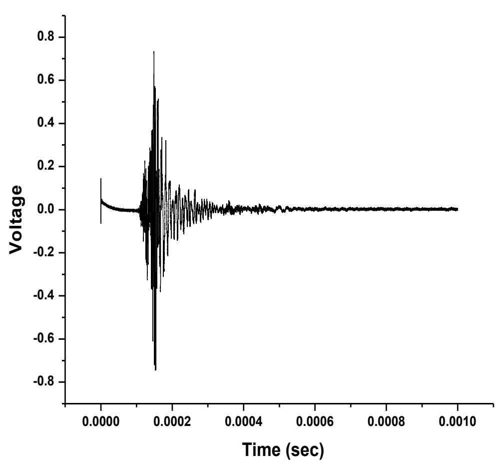
Signature peak



Corrosion acceleration



After wrapping



15 days after wrapping

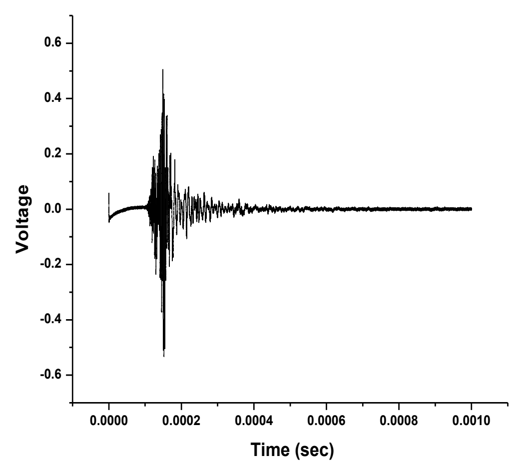
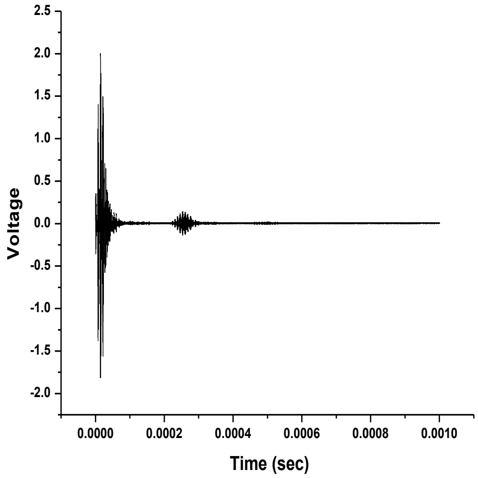
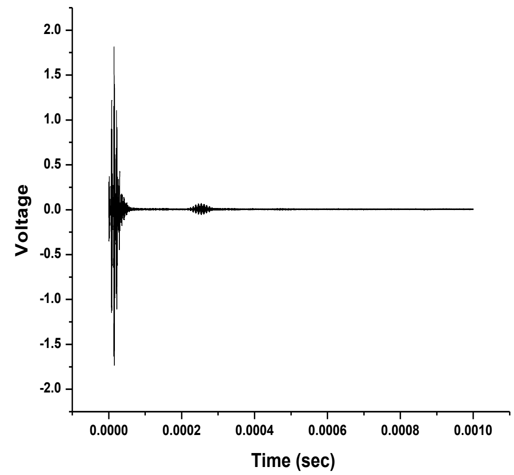


Fig. 7.6 Typical Signal peaks at Different Stages of corrosion subsequent protection (0.1 MHz)

Signature peak	Corrosion acceleration
	

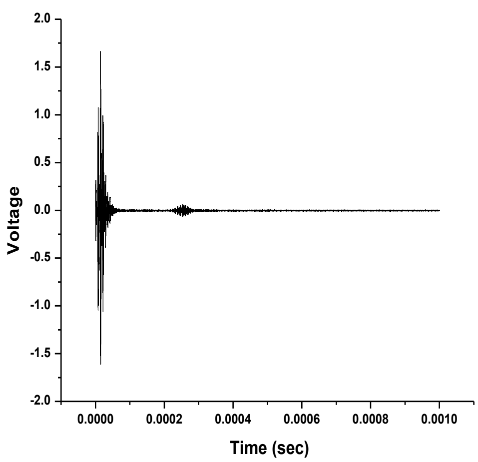
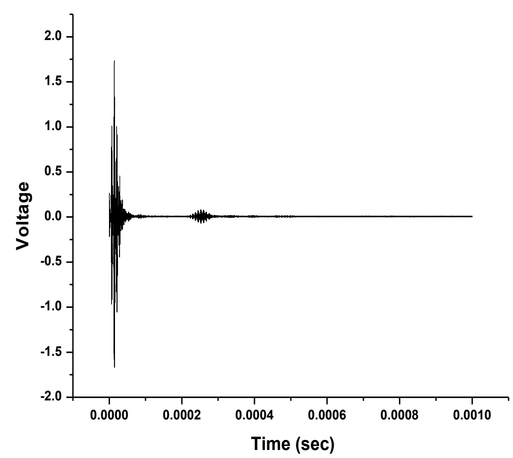
After wrapping	15 days after wrapping
	

Fig. 7.7 Shows Typical Signal Peaks at Different Stages of corrosion subsequent protection (1 MHz)

Observations

The specimens are first evaluated ultrasonically in the undamaged condition so as to establish a baseline in order to measure the change in fundamental amplitude of the waveform (or attenuation). All the specimens are monitored by ultrasonic guided wave modes in Pulse Transmission (P/T) mode. It is observed that the ultrasonic signature peaks showed significant changes before and after wrapping. For 0.1 MHz frequency, the peak of signal keeps on increasing during accelerated corrosion and after wrapping the peak slowly decreases with the increase in exposure duration irrespective of the current applied in all the specimens. On the other hand, when the transducers of frequency 1 MHz are used, the peak of signal decreases with increase in corrosion while after wrapping the signal increases. It is observed that there is large variation in signature peaks when 0.1 MHz frequency transducers are used whereas for 1 MHz frequency small variation is seen.

From the ultrasonic plots, the mechanism of corrosion of reinforcing bar begins with the formation of flaky rust product having large volume causing the delamination of the bar from the surrounding concrete resulting in increased signal amplitudes. The delamination zone marks the onset of corrosion phenomenon in a bar undergoing accelerated corrosion and is well picked up by the surface seeking mode. As corrosion progresses, it is marked by local loss of area in the form of pitting and crevices as well as debonding of bar which can be detected by core seeking mode.

Mahmoud et al. (2010) observed similar signal variations by using surface acoustic waves (SAWs) monitoring of concrete specimens externally bonded with carbon fiber-reinforced polymer (CFRP) composites. **Fig. 7.8 and 7.9** shows peak voltage trends of transmitted pulse for different current levels.

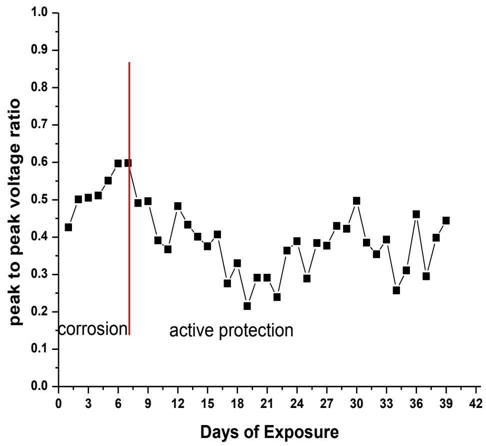
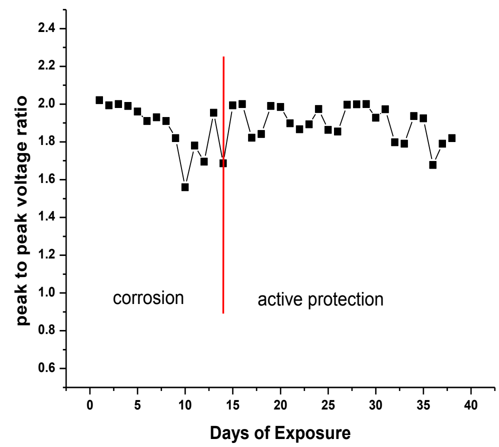
Protection provided at onset of corrosion slab CA-1	Protection provided at onset of corrosion slab CA-1
 (0.1 MHz)	 (1 MHz)

Fig 7.8 (a): Peak to Peak Voltage ratio of transmitted pulse (Current applied-10 mA)

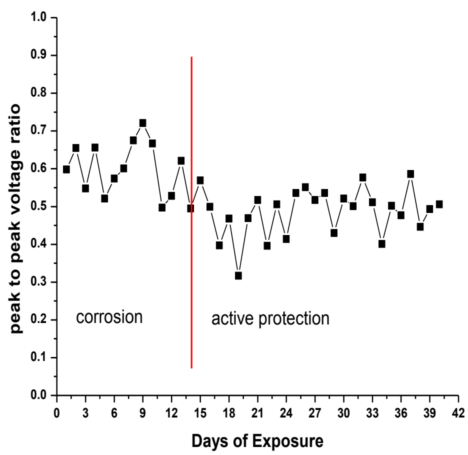
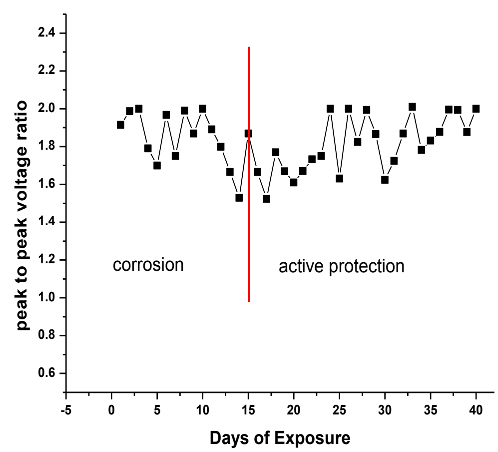
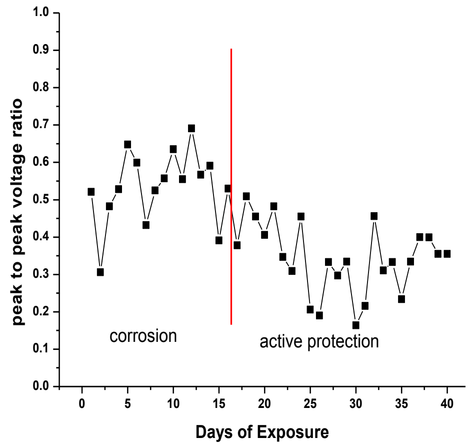
Protection provided at onset of visible crack slab CA-2	Protection provided at onset of visible crack slab CA-2
 (0.1 MHz)	 (1 MHz)

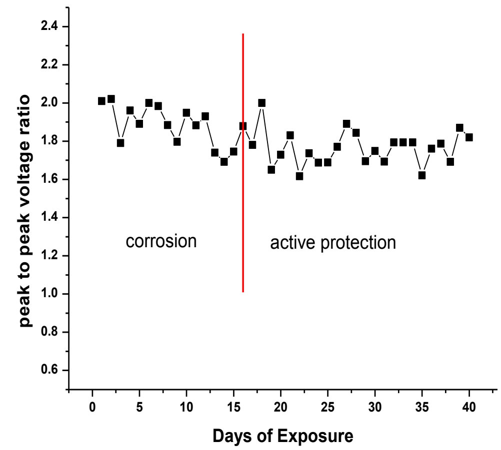
Fig 7.8 (b): Peak to Peak Voltage ratio of transmitted pulse (Current applied-10 mA)

Protection provided at two days after visible crack - slab CA-3



(0.1 MHz)

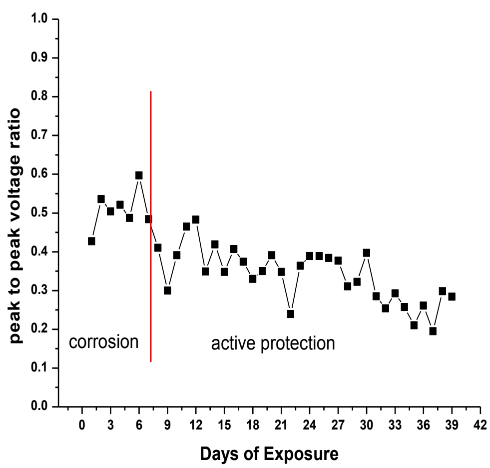
Protection provided at two days after visible crack - slab CA-3



(1 MHz)

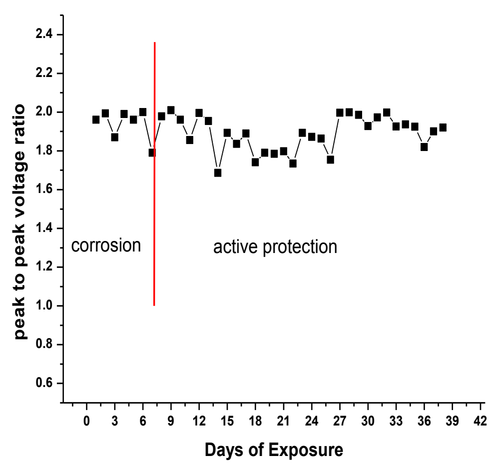
Fig 7.8 (c): Peak to Peak Voltage ratio of transmitted pulse (Current applied-10 mA)

Protection provided at onset of corrosion slab CB-1



(0.1 MHz)

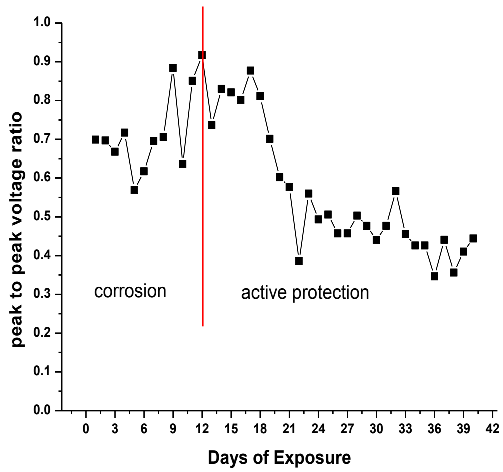
Protection provided at onset of corrosion slab CB-1



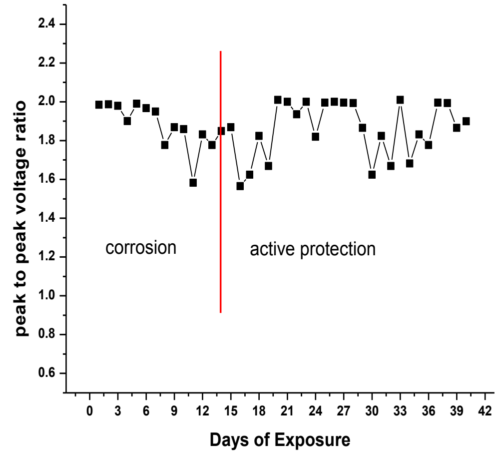
(1 MHz)

Fig 7.9 (a): Peak to Peak Voltage ratio of transmitted pulse (Current applied-30 mA)

Protection provided at onset of visible crack slab CB-2	Protection provided at onset of visible crack slab CB-2



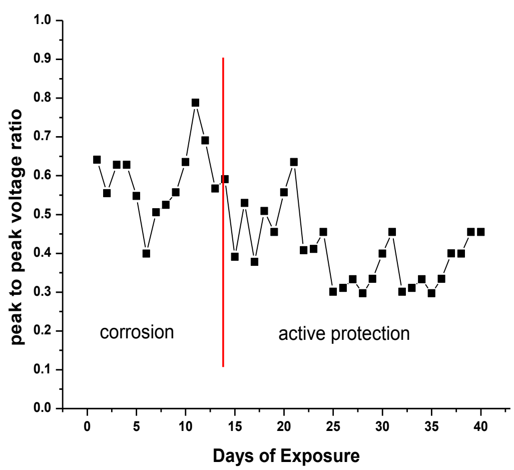
(0.1 MHz)



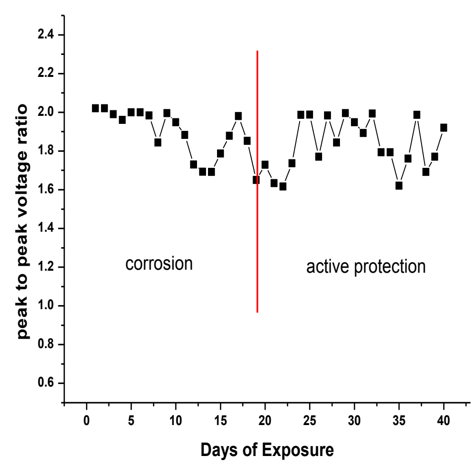
(1 MHz)

Fig 7.9 (b): Peak to Peak Voltage ratio of transmitted pulse (Current applied-30 mA)

Protection provided at two days after visible crack - slab CB-3	Protection provided at two days after visible crack - slab CB-3



(0.1 MHz)



(1 MHz)

Fig 7.9 (c): Peak to Peak Voltage Ratio of transmitted pulse (Current applied-30 mA)

7.3 CLOSING REMARKS

For corrosion progression monitoring, LPR and the ultrasonic pulse transmission has been a satisfactory investigation. The test results showed that although CFRP sheet wrapping decreased the corrosion rate, the corrosion could continue to occur, therefore long term monitoring is required in order to completely eliminate the corrosion activity.

CHAPTER 8

CONCLUSIONS

The conclusions drawn through the results obtained from various tests carried out in the present research work for evaluating the corrosion performance of corroded specimens wrapped with FRP and subsequently protected by providing impressed current are presented in this chapter. From the results it is concluded that:-

CFRP can be used effectively in providing active protection to reinforced concrete structural components by using carbon wrap itself as anode and modifying the adhesive epoxy to conduct electric current. The protection current could modify the material structure to a favorable trend in terms of corrosion protection and prevention. It is observed that active protection reduces the rate of corrosion in concrete specimens exposed to an aggressive chloride environment.

CFRP is effective at any stage of corrosion, irrespective of time of wrapping and applied current. When impressed current of 10 mA and 30 mA is provided in all the specimens, there is considerable change in half cell and LPR values, which indicates that FRP did serve as an effective barrier for chlorides and prevented corrosion activity from taking place to some extent.

In fact, under natural conditions the process of reinforcement corrosion is very slow; usually the first crack observed on the outer concrete surface appears after many years. So laboratory studies need an acceleration of corrosion process to achieve a short test period. This is accomplished by applying an electric current of constant magnitude to the rebar. The results obtained show that in accelerated corrosion process, rust formed on steel expands, makes its concrete cover crack, and induces a loss of bonding between reinforcement and concrete.

The half-cell potential is the most stable and reliable determining parameter for indication of rebar corrosion initiation in chloride contaminated concrete and the value of this indicating half-cell potential is around -426mV(SCE) as per ASTM C 876 – 91.

Although half cell potential is a good indicator of initiation of corrosion it is not effective in monitoring its progression. LPR data provides a valuable insight into the instantaneous corrosion rate of the steel reinforcement and is a reliable method than half cell potential method.

In order to monitor the corrosion progression, ultrasonic measurements have proved to be a reliable method.

Both electrochemical techniques and ultrasonic measurements are efficient in monitoring corrosion behavior of steel rebar. However, no single technique is capable of providing all information about corrosion behavior and hence these should be used simultaneously in order to get reliable results.

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