“MONITORING OF ACTIVELY PROTECTED FRP WRAPPED RC STRUCTURES FROM CORROSION USING GUIDED WAVES”

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CERTIFICATE

This is to certify that the thesis entitled **"Monitoring of Actively Protected FRP wrapped RC structures from Corrosion using Guided Waves"** being submitted by PAYAL SACHDEVA, Roll No. 801322013 in partial fulfillment of award of degree in **MASTERS OF ENGINEERING IN STRUCTURAL ENGINEERING** at Thapar University,Patiala, is an authentic record of her own work under the supervision and guidance of

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ABSTRACT

One of the major causes of catastrophic failures in reinforced concrete structures such as bridges, dams and buildings is the deterioration of reinforcing bars due to corrosion. If the degradation remains unnoticed inside concrete, it further accelerates and causes huge loss of life and property. Removal of concrete to visually inspect the reinforcement is detrimental to the structure. Hence, it is imperative to develop a non-intrusive health monitoring technique for early detection of corrosion related damages in steel embedded in concrete.

The primary object of this work is to evaluate the effectiveness of Active protection provided to RC structures from corrosion using Ultrasonic Guided Waves. Corrosion will be accelerated using impressed current method and CFRP shall be used for Active protection.

Guided ultrasonic waves offer a potentially attractive solution. In the present study, bars embedded in concrete are subjected to corrosion and also protected using Active Protection. Carbon Fiber Reinforced Polymer has been used for Active protection of RC structures from corrosion. These materials have received great attention and their applications to structural repair and retrofit have grown significantly in recent years. CFRP fabric is 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.

These protected specimens are monitored ultrasonically using longitudinal guided waves. A mode with minimal attenuation and mode shape that is suitable for detection of a particular type of damage is chosen from dispersion curves. For this purpose, we conduct the Pulse Transmission Investigations. The reinforcements have been excited at one end only with an ultrasonic pulse using piezoelectric transducer which acts as the transmitter and the receiver itself. Ultrasonic testing is carried out on bars in concrete by simulating corrosion in the form of area loss and delamination. It is observed that corrosion of reinforcing bars in concrete is discernible using ultrasonic guided waves.

This thesis investigates the efficacy of Ultrasonic guided waves in monitoring the actively protected RC structures from corrosion.

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CHAPTER 1

INTRODUCTION

1.1 Corrosion in RC structures

Reinforced concrete (RC) has been developed and applied extensively in the twentieth century and it continues to be used in this century as well. It combines the good compressive strength of concrete with the tensile strength of steel and has proven to be successful in terms of both structural performance and durability. One major flaw, namely its susceptibility to environmental attack can severely reduce the strength and life of these structures. In humid conditions, atmospheric pollutants percolate through the concrete cover and cause corrosion of steel reinforcements. The resulting corrosion products occupy volumes several times that of the steel. The increased volume induces tensile stresses in the concrete that result in cracking, delamination and spalling. As a result, the reinforcements get exposed to direct environmental attack and the corrosion is accelerated. Along with unpleasant appearance (**Fig** 1.1) it weakens the concrete structure to a high degree. Moreover, bond between the steel and the concrete is reduced (Okba et al.2003;Fang et al.2004). Pitting corrosion may also reduce the ductility of the steel bar by introducing notches on the surface of the steel bars that leads to a premature necking (Andrade et al.1993).

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.

In a tropical country like India that has more than 3000 km of coastline where approximately 80% of the annual rainfall takes place in the two monsoon months, corrosion related problems are alarming. In metro cities, the carbon and nitrogen oxide emissions aggravate the situation further by neutralizing the concrete cover. A large proportion of such damage is caused due to insufficient planning and incorrect assessment of the environmental attack such as carbonation and chloride exposure. Corrosion affected structures are highly susceptible to catastrophic collapse. Therefore, in order to restore the strength and life of structure, it is imperative to research for various ways that can effectively reduce the process of corrosion. These include conventional rehabilitation techniques consisting of removing the delaminated areas of concrete, cleaning affected steel and patching with Portland cement mortar. But these techniques are not able to protect the structure from further corrosion. Other methods of impeding corrosion include application of corrosion inhibitors, chloride extraction of chlorides, and cathodic protection. However, corrosion almost invariably affects the capacity of the structure to carry loads. Thus, only corrosion inhibition is not adequate to restore the structure. Increasing its strength is imperative. Also, high quality corrosion detection systems are required to be able to detect this dangerous phenomenon at right time. For this purpose various systems are available like electrochemical techniques, Ultrasonic guided wave monitoring systems, Acoustic Emission monitoring systems etc. With the right damage detection systems and timely planning of appropriate retrofitting maintenance in continual safe performance of the structures and in achieving the potential economic benefits, the dangerous phenomenon of corrosion can be delayed to a great extent.**Fig**.1.1 below shows the corrosion in various elements of the structure.

(a) Corrosion of columns

(b) Corrosion of beams

(C) Corrosion in slabs

Figure 1.1 Corrosion in RC structures (Source: google.com)

1.2 Corrosion monitoring techniques

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 inspect ability 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.

1.3 Corrosion Protection Techniques

All the methods of corrosion protection are divided in four categories: alternative reinforcement method, barrier method, corrosion inhibitors and electrochemical methods.

Alternative reinforcement method: A good alternative reinforcement must be resistant to damage during shipping, storage at the construction site, installation and concrete placement. The reinforcement must also be able to maintain its structural function for the service life of the structure, even in severe service environments. The alternative reinforcement must be economical when compared to conventional reinforcement.

Barrier Method: There are many different corrosion protection methods for reinforcing steel in concrete that can be classified as barriers. Some of these methods work by preventing chloride ions from penetrating the concrete and depassivating the reinforcement. Others work by reducing the movement of air and moisture into the concrete and therefore slowing the corrosion process. Procedures such as using good quality, low water/cement (w/c) ratio concrete and adequate cover have become standard in bridge construction. Sealers are used on bridge decks and substructures in an attempt to keep water and chloride ions from penetrating the concrete. Barrier methods are often used in conjunction with other corrosion protection methods, such as epoxy-coated steel or other alternative reinforcement.

Corrosion inhibitors: Corrosion inhibitors are a class of protective products that are added to the concrete mix to delay and prevent corrosion. As such, they are considered admixtures. Both organic and inorganic inhibitors are commercially available. Calcium nitrite is an inorganic inhibitor and is the most extensively tested corrosion-inhibitive admixture since it was introduced during the 1970's. When applied according to the appropriate specifications and used with high-quality concrete, it performs quite effectively based on experience in the U.S,Japan and the Middle East .

Electrochemical method: Electrochemical method has the ability to stop corrosion in chloride contaminated concrete. It is most often used as a rehabilitation method.

1.4 Gaps in Research Area

FRP has started being used for offering protection against corrosion in addition to improve the load carrying capacity of RC structures. Most of the researches have used FRP for offering passive protection against corrosion. In this work, carbon fiber polymer sheets are used for offering active protection against corrosion. Monitoring the progression as well as protection against corrosion is done using guided waves.

1.5 Objective of work

The primary object of the work is to evaluate the effectiveness of active protection provided by carbon fiber reinforced to RC structures from corrosion using non-destructive technique of ultrasonic guided waves. Corrosion is accelerated using impressed current technique and ultrasonic guided waves are used for monitoring the effect of active protection offered by CFRP against corrosion.

1.6 Format of thesis

The thesis has been divided into seven chapters.

1st chapter gives the brief of corrosion problem and the basic aim of the study.

2nd chapter explains in detail the causes and mechanism of rebar corrosion. Also a brief description on different types of corrosion is been given. Also a thorough review of literature on Fiber Reinforced Plastic (FRP) composite wraps for corrosion protection is also presented.

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 presents a thorough review of literature on nondestructive monitoring techniques as well as the Ultrasonic guided waves for monitoring rebar corrosion in concrete.

5th chapter deals with the experimental programme wherein all tests, procedures and measures to be followed during experiments are explained in detail.

6th chapter deals with results and discussions where findings of the experimental programme are explained in detail.

7th chapter is the concluding chapter.

CHAPTER 2

CORROSION IN RC STRUCTURES

This chapter deals with the corrosion process, how it affects RC structures, how it is monitored and how the reinforcement in concrete is protected from corrosion.

2.1 General

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.

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,

$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$ ……………………………………………………...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 in Concrete

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:

1. Anode

2. Cathode

3. 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.

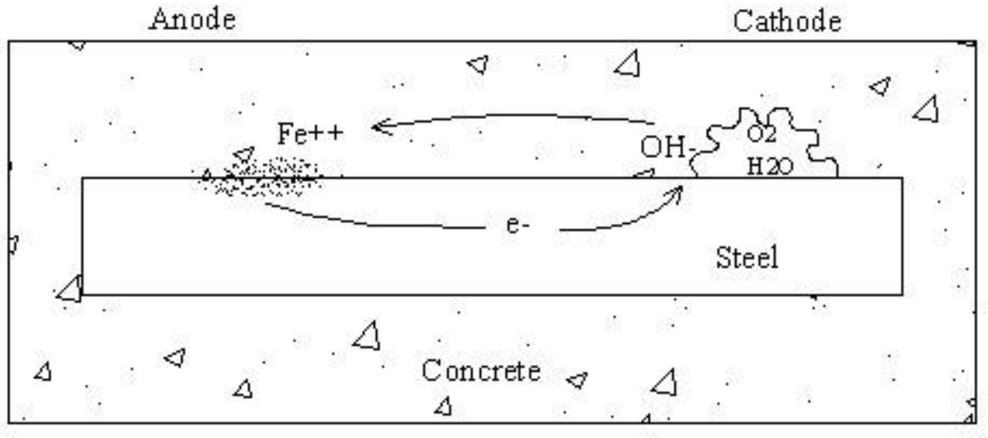

Fig. 2.1 Corrosion Cell in Reinforced Concrete (Gadve et al. 2010)

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

$$Fe \rightarrow Fe^{++} + 2e^{-} \qquad (2.2)$$

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

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

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

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

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

$$4Fe(OH)_2 + O_2 + H_2O \rightarrow 4Fe(OH)_3$$

$$2Fe(OH)_3 \rightarrow Fe_2O_3.2H_2O \qquad (2.5)$$

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.

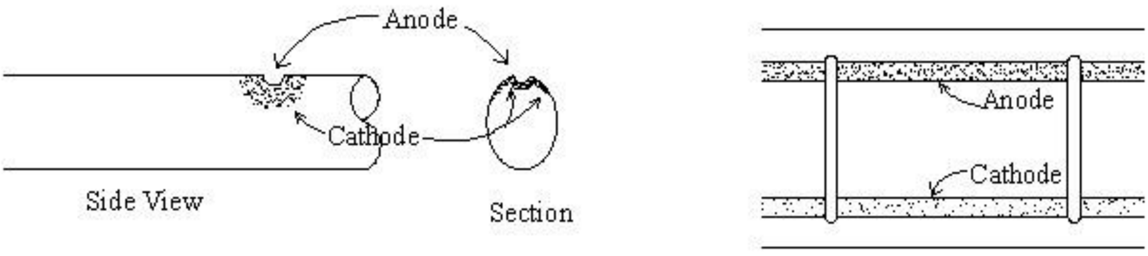

Fig. 2.2 Micro cell and Macro cell (Gadve et al. 2010)

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.**

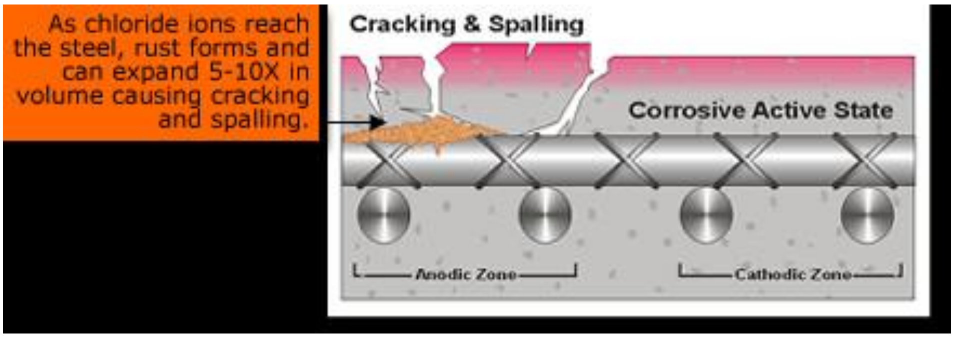

Fig.2.3 Cracking and spalling of concrete due to penetration of chloride ions(Gadve et al. 2010)

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 Corrosion Prevention Methods

All the methods of corrosion prevention are divided in four categories: alternative reinforcement method, barrier method, corrosion inhibitors and electrochemical methods.

Alternative reinforcement method: A good alternative reinforcement must be resistant to damage during shipping, storage at the construction site, installation and concrete placement. The reinforcement must also be able to maintain its structural function for the service life of the structure, even in severe service environments. The alternative reinforcement must be economical when compared to conventional reinforcement.

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Corrosion inhibitors: Corrosion inhibitors are a class of protective products that are added to the concrete mix to delay and prevent corrosion. As such, they are considered admixtures.

Both organic and inorganic inhibitors are commercially available. Calcium nitrite is an inorganic inhibitor and is the most extensively tested corrosion-inhibitive admixture since it was introduced during the 1970‟s.When applied according to the appropriate specifications and used with high -quality concrete, it performs quite effectively based on experience in the U.S.,Japan and the Middle East .

Electrochemical method: Electrochemical method has the ability to stop corrosion in chloride contaminated concrete. It is most often used as a rehabilitation method. This method is explained in detail in the following section.

2.5 Electrochemical Methods Of Prevention

The electrochemical method of corrosion prevention includes anodic protection and cathodic protection.

1. Anodic Protection
2. Cathodic Protection
3. Protection using FRPs

2.5.1 Anodic Protection

Anodic Protection is a technique to control the corrosion of a metal surface by making it anode of electrochemical cell and controlling the electrode potential in a zone where the metal is passive. Anodic Protection is used to protect metals that exhibit passivation in environments whereby the current density in the freely corroding state is significantly higher than the current density in the passive state over a wide range of potentials. Anodic Protection is used for carbon steel storage tanks containing extreme pH environments including concentrated sulphuric acid. Anodic Protection is used to protect metals that exhibit 50% caustic soda where cathodic protection is not suitable due to very high current requirements.

An Anodic protection system includes an external power supply connected to auxiliary cathodes and controlled by a feedback from reference electrode. Careful design and control is required when using Anodic Protection for several reasons, including excessive current when passivation is lost or unstable, leading to possible accelerated corrosion.

2.5.2 Cathodic Protection

The conventional methods of protection such as patch repairs and protective coatings are short term solution to the problem of corrosion in RC structures. It has been reported that Cathodic Protection provides a cost-effective and long-term solution for the repair and rehabilitation of chloride damaged structures. This technique has been applied extensively to a wide variety of structures to provide active and passive protection against corrosion. It has the advantage of eliminating the need of massive removal and replacement of contaminated concrete with minimal maintenance requirement (*Bird, 2002*). Cathodic Protection is based on the principle of connecting an external anode to the metal to be protected (reinforcing steel) and passing an electrical dc current from external anode so that the metal surface become cathodic and do not corrode. By connecting an external anode, the electrical potential between the metal and the electrolyte in contact becomes negative to a value at which anodic reactions at the corroding metal are stifled and only cathodic reactions take place. The external anode used for the cathodic protection can be a galvanic (sacrificial) anode or an impressed current anode.

2.5.3 Protection Using FRP’s

A number of researches have been done to find suitable composite materials that can be used for strengthening the newly constructed as well as old RC Structures. One such composite material that is in common use for the repair and rehabilitation of the structures is Fibre Reinforced Polymer (FRP). FRP delays the onset of corrosion on the reinforcement, thus extending the service life of the structures.

Various FRP materials are available in the market out of which two materials are popular for providing protection against corrosion in India- glass and carbon.

1. Glass Fibre Reinforced Polymer (GFRP)
2. Carbon Fibre Reinforced Polymer (CFRP

2.6 Literature Review For Corrosion Protection

Carbon-Fibre-Reinforced Polymer Repair to extend service life of corroded reinforced concrete beams (2005)

Maaddawy and Soudki (2005) investigated the viability of using externally bonded carbon fibre reinforced polymer (CFRP) laminates to extend the service life of corroded reinforced concrete (RC) beams. The tests were performed on 14 beams, out of which 3 beams were not corroded (1 specimen were kept as a control sample and 2 were strengthened with CFRP laminates), and remaining 11 beams were subjected to different levels of corrosion damage up to a 31% steel mass loss by using an impressed current technique. Out of the 11 beams, 5 beams were not repaired and 6 beams were repaired with CFRP laminates. Two types of CFRP repair schemes were followed. Scheme 1 involved flexural strengthening with a continuous wrapping and Scheme 2 involved flexural strengthening with an intermittent wrapping. It was observed that the corrosion of steel reinforcement reduces the yield and ultimate load of RC beams. The reduction in the yield load of the beams was found to be proportional to the reduction in steel mass loss. Reductions of about 12, 14, 14.5 and 24 % in the yield load were recorded, corresponding to average steel mass loss of about 9.7, 15.4, 22.8 and 30 %. The experimental results indicate that the ultimate strength of CFRP laminated beam at 31% steel mass loss was about 73% higher than that of a similar corroded and unrepaired beam, and 31% higher than the control sample that was neither corroded nor repaired. Though the ultimate strength was increased with CFRP repair, it was observed that the deflection capacity of corroded and repaired beams was on average about 46% lower than the corroded and unrepaired beams. The results also indicate that continuous wrapping provide greater confinement than the intermittent wrapping as the beams repaired with continuous wrapping of FRP showed a higher stiffness and a lower deflection capacity comparatively. It was concluded that CFRP wraps can be effectively used to increase the strength and extend the service life of corroded RC structures.

Evaluation of corrosion activity in FRP repaired RC beams (2006)

Masoud and Soudki (2006) monitored the corrosion activity in FRP repaired RC beam specimens using non-destructive techniques such as half cell potential measurements with embedded corrosion probes and Galva Pulse instrument, and destructive techniques such as evaluation of mass loss of reinforcing bars. The experiments were performed on ten beam specimens, which were divided into four groups- control sample that was neither corroded nor repaired; specimens that were corroded to different degrees of corrosion but not repaired; specimens that were corroded, repaired but not exposed to further corrosion and specimens that were corroded, repaired and exposed to further corrosion. Two FRP repair schemes were followed. The first scheme involved wrapping the specimens with GFRP sheets and, the second scheme involved flexural strengthening of specimens with CFRP sheets in addition to GFRP sheets. Galva Pulse measurements were found to be more consistent than the corrosion probe measurements But the corrosion activity was better represented by readings of corrosion probe than Galva Pulse readings since corrosion probes were embedded in the specimens close to the reinforcing bar. It was observed that FRP repaired specimens show a higher rate of decrease in corrosion potential than the unrepaired specimens. The results of the mass loss measurements indicate that mass loss of reinforcing bars reduces by about 16% with FRP repair after 152 days of exposure to corrosion. It was highlighted that the observed reduction in mass loss was mainly due to GFRP wrapping and CFRP sheets provided for the flexural strengthening.

Corrosion Monitoring of RC Structures- A Review (2007)

Song and Saraswathy (2007) presented a review on all the electrochemical and non-destructive techniques used for corrosion assessment. The advantages,limitations and applications of each technique are discussed. It was reported that the NDT techniques are used in combination to obtain maximum information about the corrosion state of rebar. The NDT techniques that were discussed are open circuit potential (OCP), surface potential (SP), concrete resistivity, linear polarization resistance (LPR), Tafel extrapolation, Galvanostatic pulse transient method, Electrochemical Impedence Spectroscopy(EIS), Harmonic analysis, Noise analysis, Embeddable Corrosion monitoring censor, Cover thickness measure,Ultrasonic pulse velocity techniques, X-ray, Gamma Radiography measurement,Infrared thermograph electrochemical measurements, and Visual Inspection.

Corrosion of steel reinforcement embedded in FRP wrapped concrete (2008)

Gadve et al. (2008) investigated the progression of corrosion of reinforced concrete (RC) structures, rehabilitated with FRP composites. Concrete cylinders with embedded steel bars were immersed in salt water and the corrosion of steel was induced by passing anodic current. The current was passed for a specified time in order to accelerate corrosion and initiate cracking in the concrete. The test specimens were then air-dried and wrapped with CFRP and GFRP sheets. Corrosion monitoring was done using non-destructive techniques such as half-cell potential, cell voltages and potentio dynamic scans, and destructive techniques such as pull-out and mass loss tests. The experiments showed that the rate of corrosion slows down dramatically when FRP wraps are used. An increase in pull –out strength, decrease in mass loss and increase in corrosion current was observed. The wrapped samples were found to have 300% higher cell voltage than the control specimens. It was observed that GFRP wrapped specimens exhibited lower corrosion current than the carbon wrapped specimens, due to higher electrical resistance offered by GFRP. The average cell voltage was about 20% more in GFRP than in CFRP, indicating that GFRP is more effective in impeding corrosion when passive protection techniques are used.

Corrosion Process and abatement in reinforced concrete wrapped by fibre reinforced polymer (2008)

Spainhour and Wootten (2008) investigated the effect of number of wrap layers and type of impregnating epoxy on corrosion performance of steel reinforcement embedded in concrete samples wrapped by CFRP sheets. Nine samples of RC cylindrical structures were inspected, that fall into three main groups – control samples that were untreated, those that were only coated with epoxy and, those that were wrapped with one to three CFRP composite layers. Two types of epoxy were considered, namely West System 105 (WS) and Sikaguard 62 (SG). It was observed that the predicted mass loss based on Faraday's law correlated reasonably well with the actual mass loss measured, and CFRP wraps were useful in extending sample

test lives, reducing the rate of corrosion mass loss by delaying the onset of corrosion. It was found that the type of epoxy used for CFRP has a great role to play as it improved the performance of samples. The epoxy SG, was more effective than WS epoxy in delaying the onset of corrosion. However, epoxy alone was not effective in delaying reinforcement corrosion. Results indicated that even the specimens wrapped with FRP sheets using poorer epoxy improved the sample performance when number of FRP layers was increased.

Current Distribution in reinforced concrete cathodic protection system with conductive mortar overlay anode (2009)

Jing and Wu (2009) investigated the current distribution in those reinforced concrete cathodic protection systems that employ carbon fiber reinforced cement (CFRC) as conductive mortar overlay anode. The effect of reinforcement initial corrosion rate, concrete resistivity and magnitude of impressed current density on the current distribution was studied. Experiments were performed on specimens with 9 parallel steel bars (8 mm in dia) placed in 3 layers with rebar spacing of 60 mm. It was observed that when initial corrosion rate is low, current distribution is uniform, but as the corrosion rate crossed the threshold, the uniformity in current distribution worsened severely. **Fig. 2.4** shows that standard deviation of protection current distribution initially increases as corrosion current increases, but is non-uniform after the inflexion point.

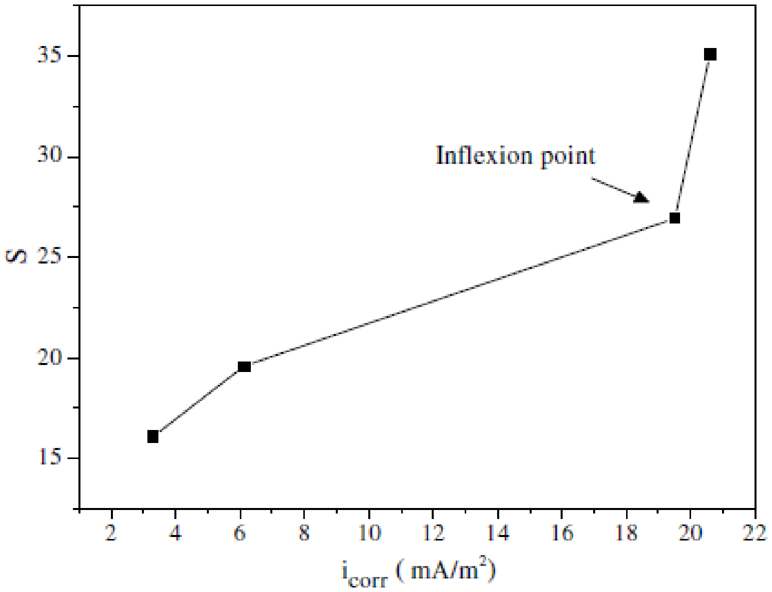


Fig. 2.4: The relationship between corrosion rate and standard deviation of protection current distribution values(Source: Jing and Wu 2010)

It was further observed that the current distribution was affected by concrete resistivity and, the bars farthest from anode received less current as compared to bars near the anode. As seen in the **Fig. 2.5**, the standard deviation of protection current distribution is almost constant when the resistivity is in lower range, but deteriorates rapidly as the value of resistivity increases.

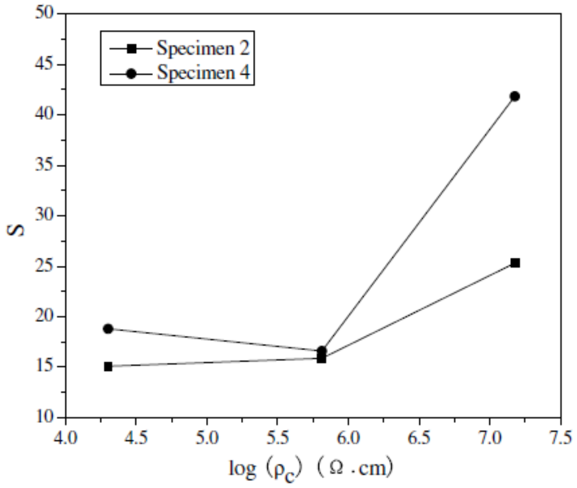


Fig. 2.5: The relationship between concrete resistivity and standard deviation of protection current distribution values

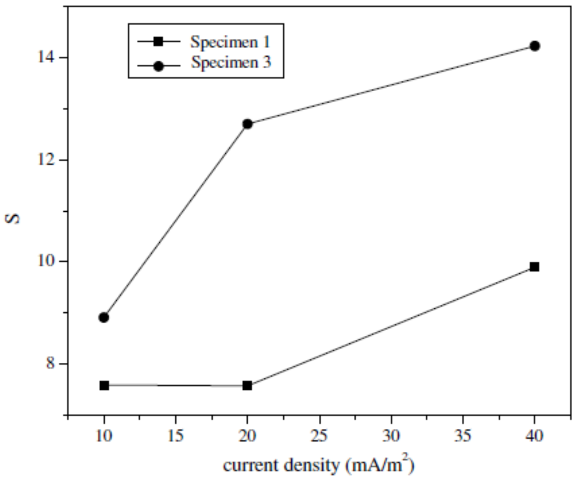


Fig. 2.6: The relationship between impressed current density and standard deviation of protection current

(Source: Jing and Wu 2010)

The observations show that the current distribution is little affected by the magnitude of current density when the corrosion rate is low. But, it worsens as magnitude of current density increases with an increase in corrosion rate at steel.The variation in standard deviation of protection current distribution at high and low corrosion rate is as shown in the **Fig. 2.6**.

Active Protection of Fiber Reinforced Polymer wrapped Reinforced Concrete Structures (2011)

Gadve et al. (2011) investigated active protection of steel embedded in concrete structures wrapped with FRP sheets. The experiments were performed on cylindrical test specimens with an embedded steel bar. The test specimens were divided into four groups- control samples that were not wrapped with FRP sheets, passively protected samples wrapped with GFRP sheets, passively protected samples wrapped with CFRP sheets, and actively protected samples wrapped with CFRP sheets. Carbon FRP was utilized in creating an anode because of its electrical conductivity. It was reported that the use of carbon FRP eliminates the requirement of external anode by the system, thus providing active protection to reinforcing steel. Destructive techniques such as pull -out strength and nondestructive techniques such as potentio dynamic scans and half -cell potential were used as performance metrics of samples. It was observed that the rate of corrosion was reduced to a great extent with the use of FRP wraps as FRP wrapped samples exhibited lower corrosion current and hence lower mass loss. The results indicated that actively protected CFRP wrapped samples show the least loss of mass. It was found that actively protected samples show a poor bond between steel and concrete as indicated by lower pull out strength and requires further research.

2.6 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 corrosion are the ingress of chloride ions and carbon dioxide to the steel surface. Protecting RC structures against corrosion is a must and various corrosion protection methods are discussed. Review of literature corresponding to corrosion and its protection are presented. 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.

CHAPTER 3

NDT TECHNIQUES FOR MONITORING OF RC STRUCTURES

3.1 General

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 Basic Methods for NDT of RC Structure

1. **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.
2. **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.
3. **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.

4. **Schmidt/rebound hammer test,** used to evaluate the surface hardness of concrete. The hammer measures the rebound of a spring-loaded mass impacting against the surface of the sample. The test hammer will hit the concrete at a defined energy. Its rebound is dependent on the hardness of the concrete and is measured by the test equipment. By reference to the conversion chart, the rebound value can be used to determine the compressive strength . When conducting the test the hammer should be held at right angles to the surface which in turn should be flat and smooth.

5. **Carbonation depth measurement test**, used to determine whether moisture has reached the depth of the reinforcing bars and hence corrosion may be occurring.

6. **Permeability test**, used to measure the flow of water through the concrete.

7. **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.

8. **Cover meter 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.

9. **Ultrasonic pulse velocity testing**, 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.

10. **Ground penetrating radar or impulse radar testing,** used to detect the position of reinforcing bars or stressing ducts.

3.2 Ultrasonic Guided Waves

Although a number of different non-destructive testing methods have been developed, but the common method with some typical application that have been adopted for non-destructive testing of RC structures is explained in the following section. This section provides an understanding of ultrasonic guided waves.

3.3 Ultrasonic Waves

Elastic waves in all frequency ranges -ultrasonic, sonic and subsonic- can be classified into two groups: Body Waves or Bulk waves and, Surface Waves or Guided Waves

(**Fig. 3.1**). Body waves travel through the bulk material while surface waves propagate along the surface. Sound waves travel as a bulk wave in any elastic material where the sound does not interact with the edges of material therefore acting as infinite extent of material. The velocity of sound in materials varies with its elastic properties which can be calculated by measuring the time of flight between the two points.

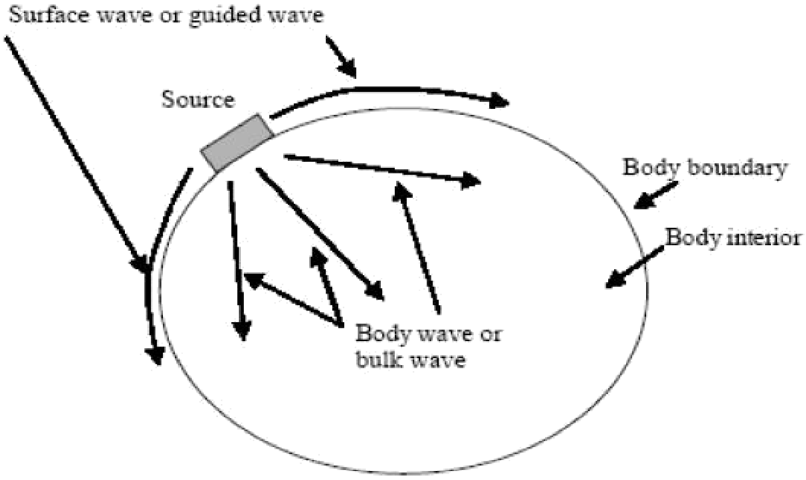


Fig. 3.1: Body waves and Surface waves generated by an ultrasonic source (Kundu, 2004)

Velocity can be related to a variety of different material properties and conditions and is often used as a test of concrete uniformity, where velocity is usually displayed on a contour map. Large cracks and voids can be detected by an increase in travel time. However, when ultrasonic wave is constrained within the boundaries and is guided by the geometry of the structure, it becomes a guided wave, that has the ability to travel long distances with minimum loss of energy. The structure that guides the wave is termed as “waveguide". Surface waves are often called guided waves because of the geometry of the boundary which guides them. The basic requirement for an ultrasonic wave to be a guided wave is that the thickness of the waveguide must be comparable to the operating wavelength (**Fig. 3.2**). However, if the thickness of the material is much greater than the operating wavelength, then bulk waves and surface waves exist (**Fig. 3.3**).

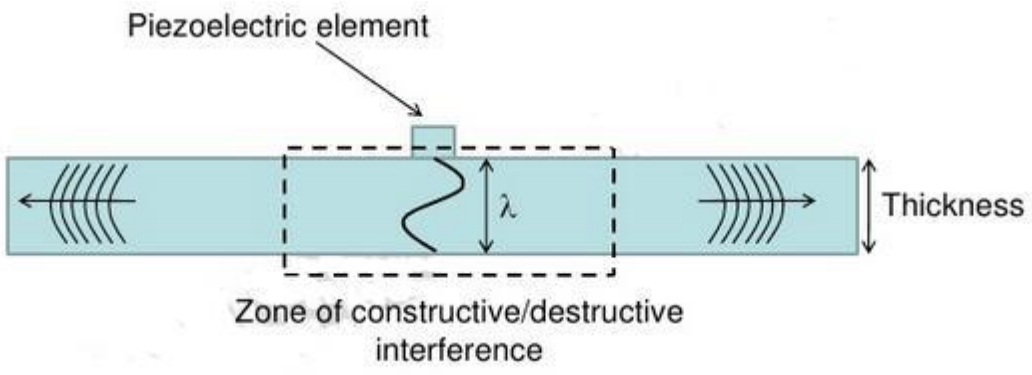


Fig. 3.2: Propagation of guided waves through a structure (www.wins-ndt.com)

Major advantages of guided waves include quickness, low cost and often improved sensitivity to a variety of defects. For a well -conditioned rebar, guided wave can propagate at least 300 feet and have the whole rebar tested in seconds based on the received time-domain signals.

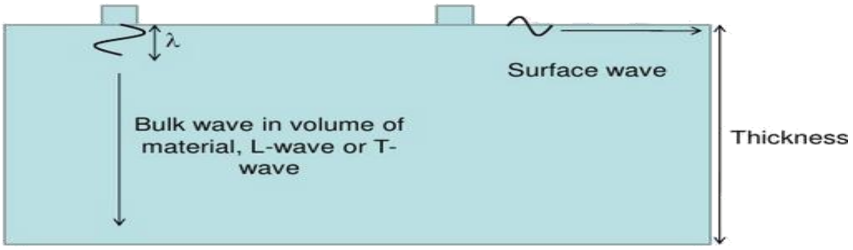


Fig. 3.3: Wave Propagation when thickness of material >> wavelength (www.wins-ndt.com)

Another advantage of the guided wave is that it only needs access to a small area of the specimen for source loading, such as rebar end or some small area of the structure. Moreover, guided waves can propagate in the structure as a whole, and therefore, have the potential to inspect the entire structure from a single point. Thus, a guided wave excited at the exposed end of a rebar would be reflected from any defect in the bar, allowing defects to be accurately located. Guided Wave testing (GWT) is one of the latest methods in the field of non-destructive ultrasonic monitoring for flaw detection. There are numerous advantages of Ultrasonic Guided Wave testing such as:

1. High sensitivity, enabling the detection of small flaws
2. High penetrating power, enabling the detection of flaws that are deep inside the structure
3. Testing is possible through the accessibility of only one surface
4. Capability of testing over long distances
5. Some capability of estimating the size, orientation, shape and nature of defects
6. Greater accuracy than other NDT techniques

7. Easily portable
8. Non-hazardous to the surrounding materials

Moreover, with this technique, frequency and mode tuning can be done to evaluate different types of deterioration or damage in structures.

3.3.2 Types of Guided Waves

There are different types of guided waves based on the geometry of the structure (waveguide) through which guided wave travels (**Fig. 3.4**)

(a) Plate wave or Lamb wave
(b) Bar wave
(c) Rod wave or bar wave
(d) Cylindrical guided wave
(e) Rayleigh wave
(f) Generalized Rayleigh-Lamb wave

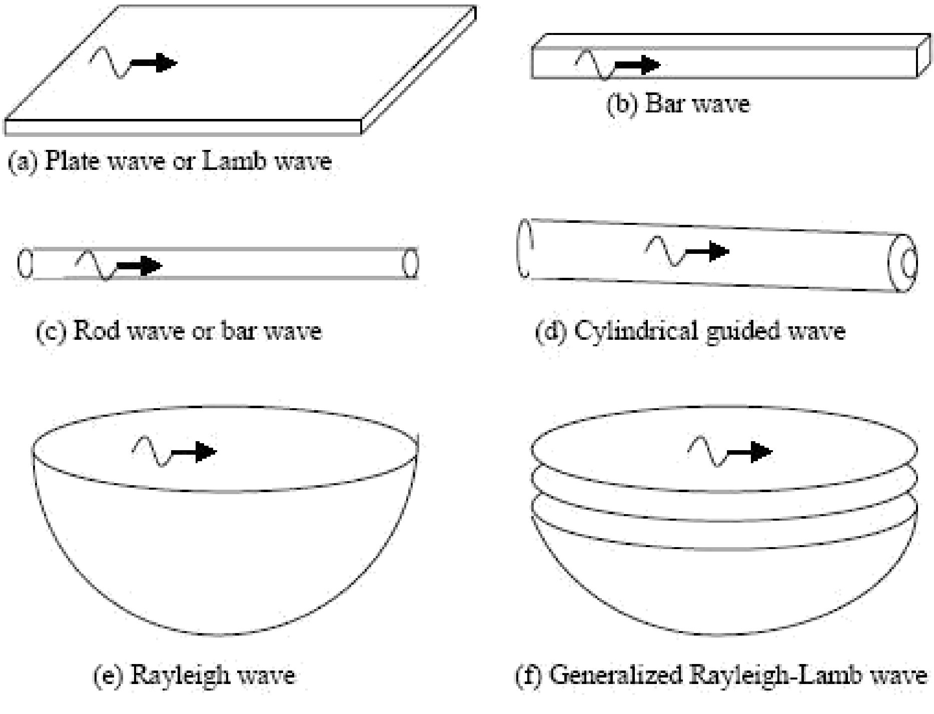


Fig. 3.4: Different types of guided waves (Kundu, 2004)

If the structure of the waveguide is a homogenous half space, then the guided wave propagating along the surface of the half space is called Rayleigh wave, named after its inventor. Waves propagating through a plate like structure with two parallel stress free boundaries are known as Lamb waves. Elastic waves propagating through a hollow cylindrical or pipe structure are called cylindrical guided waves. When the guided waves propagate through a solid rod or bar, they are known as bar waves.

3.3.3 Modes of propagation of Ultrasonic Guided Waves

Ultrasonic waves propagate in the reinforced steel bars in the form of guided waves. The waves are directed in the bar by the geometry of the structure, as discussed in the previous section. The current research uses guided waves as the test specimens are slab RC structures. There are three types of propagating waves, or modes in a slab waveguide:

(a) Longitudinal mode (L)
(b) Torsional mode (T)
(c) Flexural mode (F)

Longitudinal modes have radial and axial displacements, torsional modes have angular displacements and flexural modes have axial, radial and angular displacements. These modes are represented by the notation L (m,n), T(m,n) andF(m,n) respectively. In this notation, “m” represents the circumferential displacement and is a function of cos (m,θ) , and “n” represents the sequential order of mode. For longitudinal modes, the variable “m” is zero as they are axially symmetric. For flexural modes, the variable “m” varies as cos(mθ) around the circumference of the steel bar. For e.g., L(0,1) is the notation for first longitudinal mode.

3.3.4 Limitations of Guided Waves

There are few limitations of guided waves such as:

1. Complicated properties as compared to bulk waves
2. Highly dispersive i.e., wave velocity can vary considerably with frequency
3. Multiple modes, with different velocities can exist at any given frequency, thus complicating the signal interpretation (Beard et al, 2003)

3.4 Ultrasonic Testing

3.4.1 Basic Principle

Ultrasonic technique is based on the principle of physics that govern the propagation of sound waves in any medium. According to this principle, sound waves travel at a specific velocity through a given medium in a predictable direction, and when they encounter a boundary with a different medium, they get reflected. Since 1940's, the laws of physics for the propagation of sound waves through solid materials has been used to detect internal discontinuities in metals such as hidden cracks, voids, porosity, etc. Sound waves above the audible frequency of 20 kHz are designated as ultrasonic. The wavelength of ultrasonic waves is of the same order of magnitude as visible light, and therefore these waves exhibit many properties similar to light, such as focusing, reflection and refraction. Ultrasonic waves are transmitted through solid materials such as steel by high frequency particle vibrations. The transmission of these waves is similar to pointing a flash light in a room with various objects that reflect the light. The directed ultrasonic wave is reflected by internal defects of the material such as cracks or voids.

Ultrasonic testing is a safe and well-established NDT technique that involves the propagation of high frequency sound waves to predict material strength, and detect the presence of internal flaws such as cracking, voids, honeycomb, decay and other damage. The generation and detection of gel between the transducers and the structure. These transducers introduce a sound wave perpendicular to the surface that is guided by the geometry of the structure. These transducers are typically used for detecting voids, porosity, cracks, or delaminations, and for measuring the thickness of the material.The set up for ultrasonic flaw detection includes a function generator that generates an electric signal, an electro-acoustic transducer that converts the electric signal to sound wave, and a PC to display the initial and reflected pulses. Pulses of longitudinal, elastic stress waves are generated by an electro-acoustical transducer that is held in direct contact with the surface of the concrete under test.

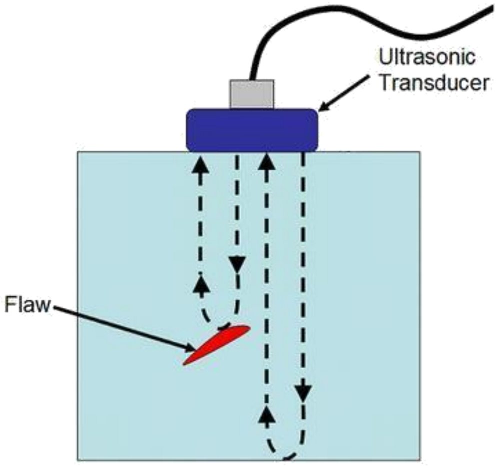


Fig. 3.5: Principle of Ultrasonic wave generation and detection (www.ni.com)

After traversing through the concrete, the pulses are received and converted into electrical energy by a second transducer or by the same transducer and is displayed on the screen (Song and Saraswathy, 2007). Two basic quantities are measured in ultrasonic testing; time of flight the i.e., amount of time for the sound to travel through the sample, and amplitude of received signal. Based on velocity of travel through the material and round trip time of flight through the material, thickness can be calculated as follows:

$$T = V\,t / 2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3.1)$$

where,
T = Material Thickness
V = Material Sound Velocity
t = Time of Flight

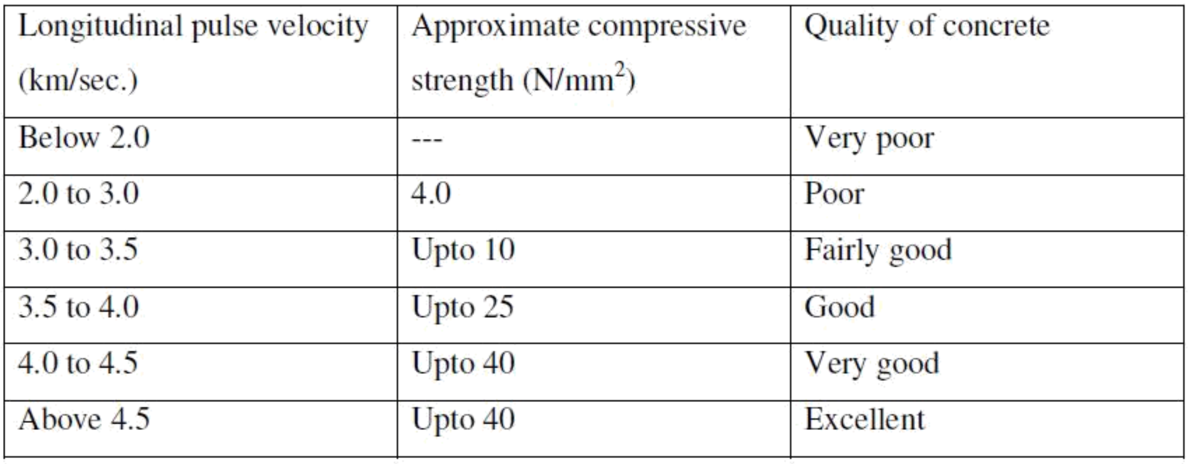
Measurement of the relative change in signal amplitude can be used in sizing flaws or measuring the attenuation of a material. The relative change in signal amplitude is commonly measured in decibels. Decibel values are the logarithmic value of the ratio of two signal amplitudes. This can be calculated using the following equation:-

$$A_{dB} = 20 \log_{10}\frac{A_1}{A_2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.2)$$

dB = Decibels
A1 = Amplitude of Input Signal
A2 = Amplitude of Transmitted/ Received Signal

Song and Saraswathy (2007) demonstrated ultrasonic pulse velocity (UPV) technique for corrosion monitoring. This technique measures the speed of sound for flaw detection. The interpretation of data is very difficult in UPV technique as a large number of factors affect the pulse velocity. The relationship between ultrasonic pulse velocity and the quality of concrete is given as follows in

Table 3.1: Longitudinal Pulse velocity v/s concrete



Longitudinal pulse velocity (km/sec.)	Approximate compressive strength (N/mm^2)	Quality of concrete
Below 2.0	---	Very poor
2.0 to 3.0	4.0	Poor
3.0 to 3.5	Upto 10	Fairly good
3.5 to 4.0	Upto 25	Good
4.0 to 4.5	Upto 40	Very good
Above 4.5	Upto 40	Excellent

He (2006) investigated the use of ultrasonic guided waves to determine the length of the reinforcement i.e., steel bar embedded in concrete and the amount of delamination between the steel bar and concrete. The deviation from the expected length may indicate a fracture in the reinforcing bar, and the delamination between steel and concrete imply a weak bonding condition.

3.4.2 Methods for Ultrasonic Testing

Most commonly used methods for ultrasonic testing are:

(a) Pulse Transmission method

(b) Pulse Echo method

(a) Pulse Transmission method

In the pulse-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. Scanning of the material using this method will result in the location of defects, flaws, and inclusions in the X -Y plane (**Fig. 3.6**).By measuring the relative change of the amplitudes of the input and the received signals, the relative severity of the flaw is assessed.

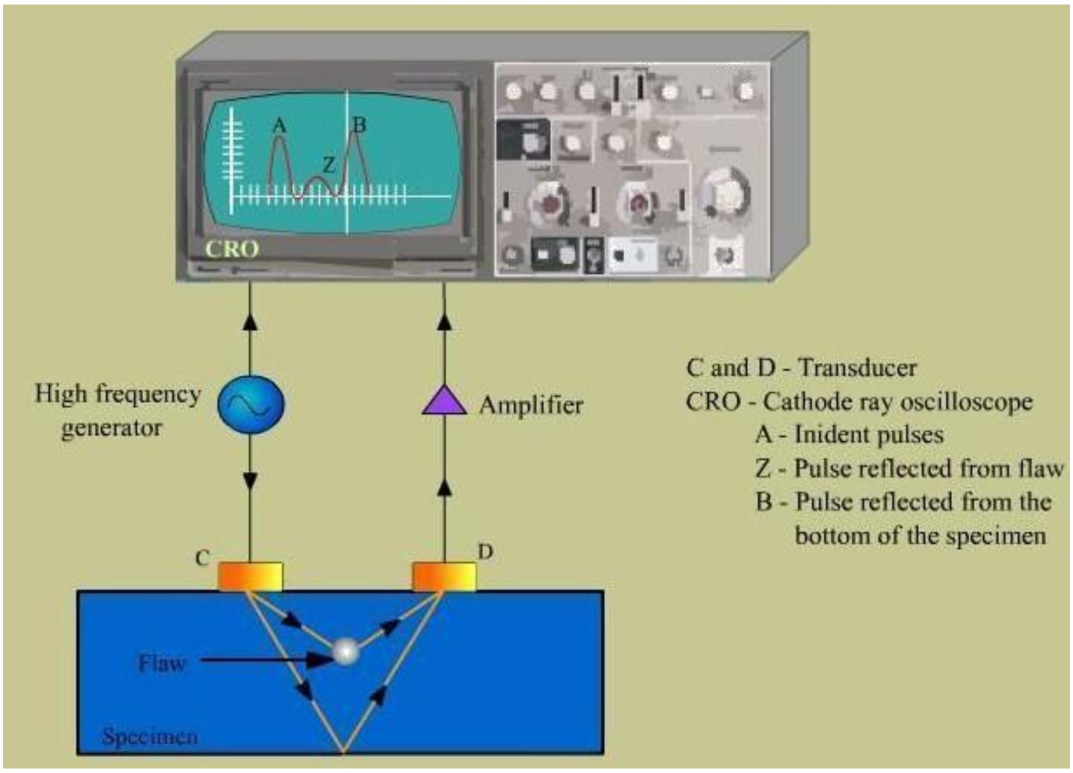


Fig. 3.6: Pulse Transmission method of testing (www.msheiksirajuddeen.blogspot.in)

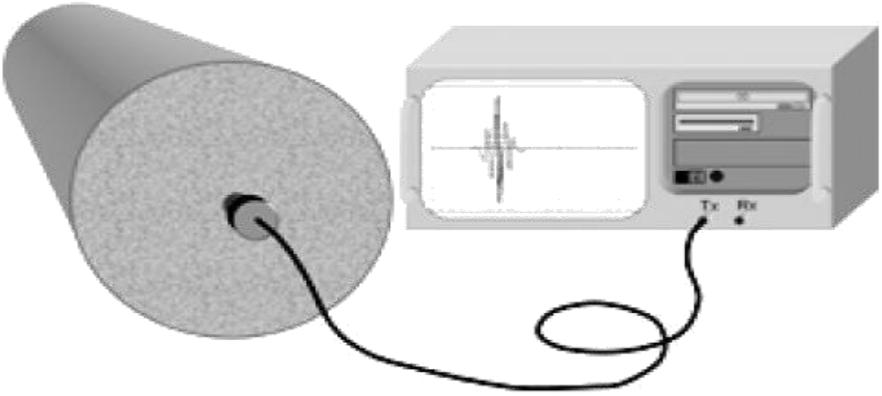
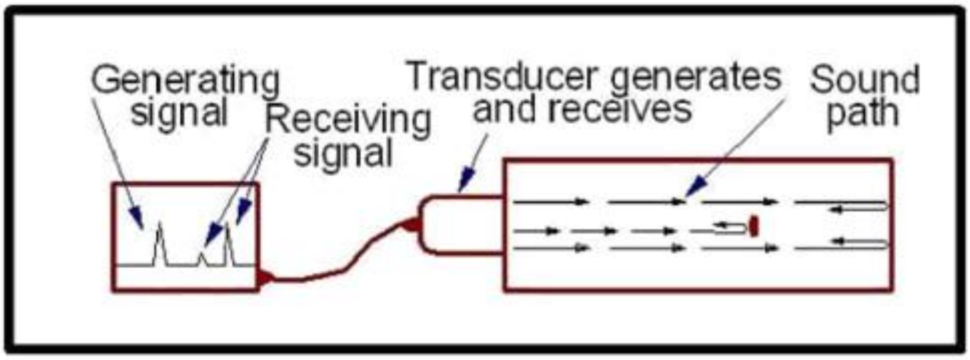


Fig. 3.7(a): Set-up for pulse echo method (He, 2006)

(b) 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 (**Fig 3.7**).



(b)

Fig. 3.7(b) Guided wave propagation and signal received (www.cnde.iastate.edu)

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. 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, and (with proper scanning hardware and software) where the flaws are located in the X -Y plane.

When there is an interface such as a crack, void or flaw in the wave path, part of the energy is reflected back from the interface and received by the same transmitting transducer. The reflected energy is converted into an electrical signal which is processed in a computer and digitized for display. The most commonly used method to analyze the reflected ultrasonic wave is time-of-flight (TOF) display, or A-scan. The discontinuities closer to the ultrasonic transducer are detected sooner than those farther away from the transducer. **Fig. 3.8** depicts TOF display.

In TOF display, x-axis is not typically units of time but is converted to distance. The time of flight between the excitation and reflected pulse is measured from the display. Knowing the velocity of the wave, the location of the defect can be calculated as follows:

$$D = V\,t \qquad \text{……………………………………..(3.3)}$$

where,

D = Distance of defect from transducer end,

V = Velocity of wave and,

t = Time of Flight

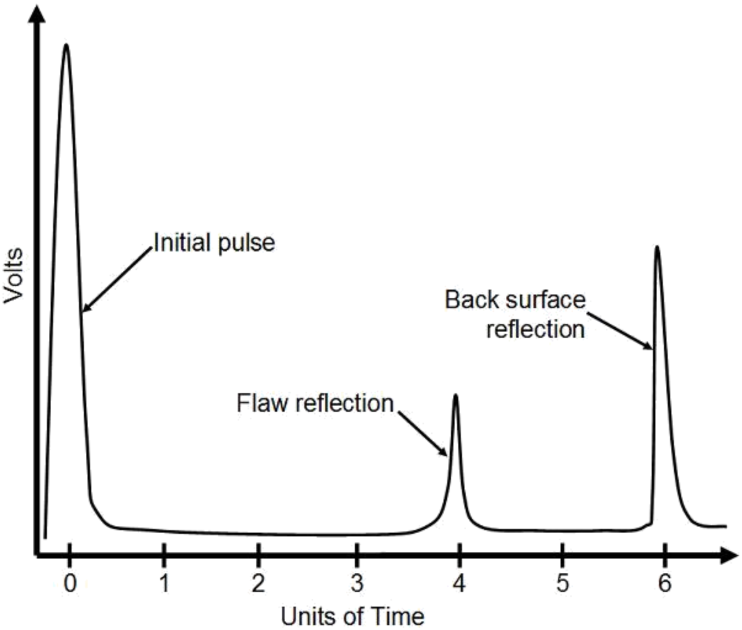


Fig 3.8: Pulse Echo method of testing (www.ni.com)

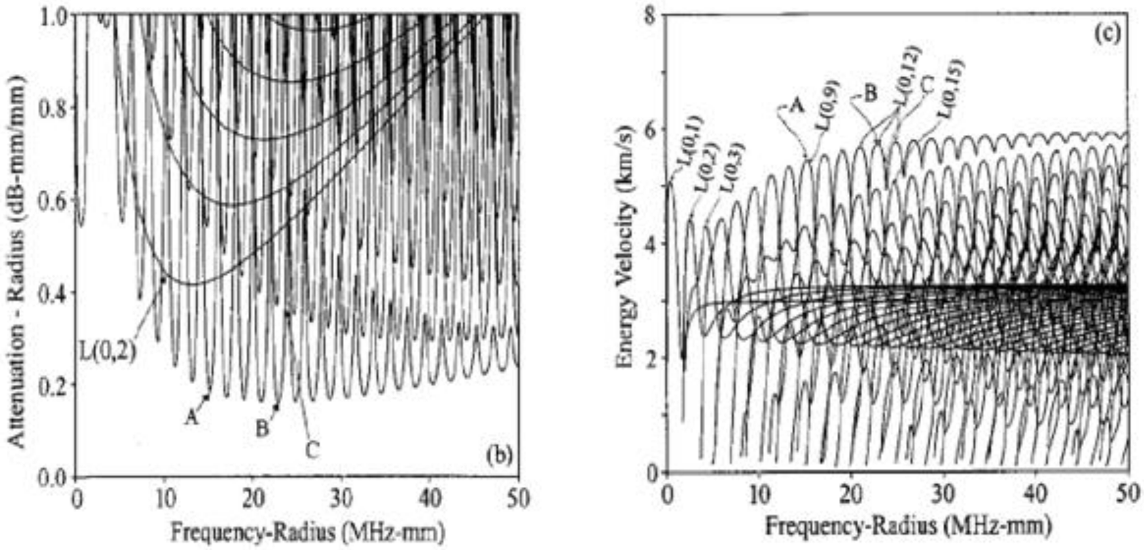
Thus, pulse-echo technique of ultrasonic testing can be efficiently used for detecting the extent of damage caused by corrosion in RC Structures. The current research uses pulse-echo technique for ultrasonic monitoring.

3.5 Review Of Literature Related to use of Ultrasonic Guided Waves in RC Structures

High Frequency Low-Loss Ultrasonic Modes in Imbedded Bars (2001)

Pavlakovic et al. (2001) investigated the behaviour of ultrasonic guided modes that show minimum attenuation while propagating along the waveguide formed by the steel bar embedded in lower impedence grout, in order to maximise the inspection range of tendons. Two test specimens were constructed, comprising of a mild steel bar at the center of a plastic pipe filled with grout. For the first specimen, bar was undamaged, and for the second specimen, notches were cut approximately 500 mm from each end of the bar. Both pulse - through and pulse-echo tests were carried out. It was found that the dispersion curves of circular steel bar imbedded in lower impedence medium show a series of modes having attenuation minima at higher frequencies. These attenuation minima occurred at the same frequencies where the energy velocity maxima occurred (**Fig. 3.9**).

The attenuation minima and energy velocity maxima correspond to points where leakage of energy into the imbedding medium is minimized. It can be seen from the figure that the value of attenuation minima decreases with an increase in frequency, up to a frequency- radius of 23 MHz-mm. Beyond this point, the material attenuation in the bar becomes a significant factor and attenuation at the minima increases. The experimental investigations also illustrate that the non-leaky mode that exists in a flat plate imbedded in cement grout does not exist in a circular bar imbedded in grout.



(a) **(b)**

Fig. 3.9: Dispersion curves of axi symmetric L(0,n) modes of steel bar imbedded ingrout (a) attenuation; (b) energy velocity(www.ni.com)

Ultrasonic Guided Waves for Steel bar Concrete Interface Testing (2002)

Na et al. (2002) investigated the feasibility of detecting and quantifying delamination at the steel-concrete interface using ultrasonic guided waves. The experiments were performed on three sets of specimens. Specimen sets 1 and 2 comprised of four cylindrical structures each with different amounts of separation (0, 25, 50, 75 % of concrete steel interface). Specimen set 3 comprised of three concrete beam structures- specimen with different amounts of separation without stirrups, specimen with different amount of separation with stirrups and, specimen with same amount of separation at different positions with stirrups. Ultrasonic testing was conducted in through transmission mode. Two experimental set ups were devised for both relatively high and low frequency transducers and four Transmitter/Receiver arrangements (TRA1, TRA2, TRA3, TRA4) were designed to generate, propagate and receive guided waves through steel bars and concrete (**Fig. 3.10**).

Two annular solid couplers of different dimensions were used to launch flexural cylindrical guided wave modes along the steel bar, and an angular solid coupler holder was used to launch lamb waves in concrete beams when steel bar was not accessible. Petroleum jelly was used as a couplant. Experiments were conducted 4 -8 times with every arrangement to investigate the consistency of results. Based on the experiments, V(f) curves were obtained,

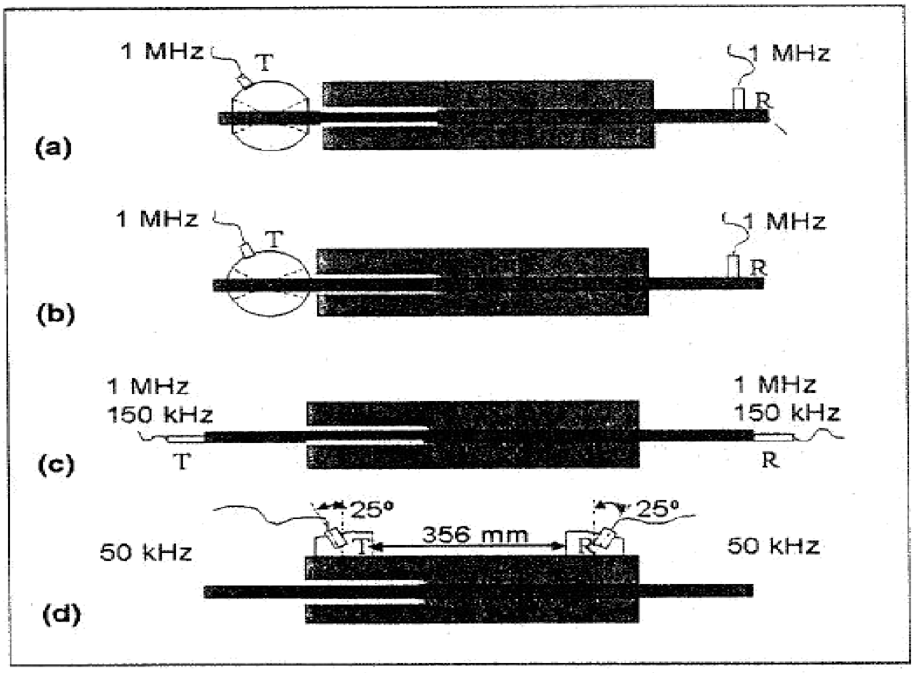
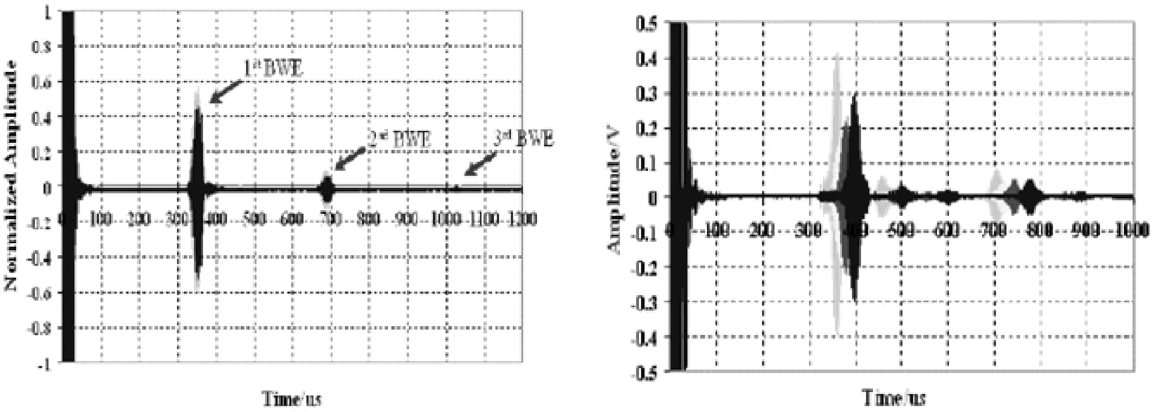


Fig. 3.10: Different transmitter/receiver arrangements for experimental investigation: (a and b) spherical solid coupler transducer holders; (c) transmitter and receiver in direct contact at the ends; (d) solid coupler transducer holder on concrete with 25 degree incident and reception angles(www.ni.com)

For specimen sets 1 and 2, it was observed that TRA1 is most efficient in predicting or quantifying the degree of separation. The sensitivity was affected by the selection of transducer frequency in TRA3. In case of TRA4, the detection sensitivity was affected by the distance between concrete surface and separation region. For specimen set 3, it was observed that in addition to the above conclusions, the amplitude of V(f) curves of specimens without stirrups were stronger than the specimen with stirrups. The results obtained with TRA1 and TRA2 were considerable if proper transmitter angles were used. The experimental investigation showed that the efficiency of annular shaped holders used for exciting flexural cylindrical guided wave modes was comparatively more than other holders. It was observed that though signals generated by relatively larger angles of incidence were more sensitive to discontinuities, however the propagating signal strength for a large incident angle was not always higher than the signals generated by smaller incident angles. It was concluded that the guided wave technique can be applied to predict or quantify the degree of separation or delamination using pulse through transmission mode. However,other techniques such as pulse-echo method are required to predict the exact location of separation.

Health Monitoring of Rock Bolts Using Ultrasonic Guided Waves (2006)

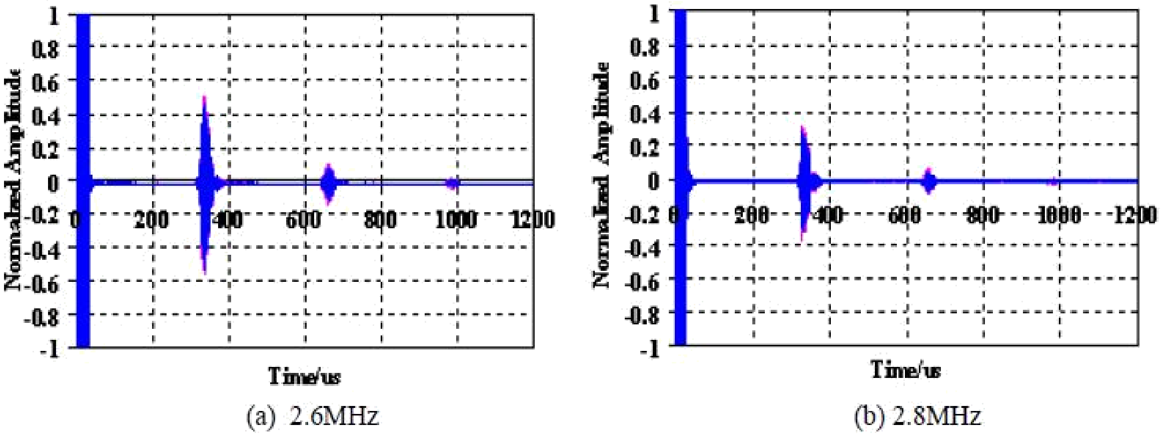
He et al. (2006) investigated the use of ultrasonic guided waves in a two –layered structure (composed of solid steel and semi-infinite layer of concrete) to measure the length of steel rod embedded in concrete and to estimate the amount of delamination between a steel rock bolt and concrete. A Semi -Analytical Finite Element Method (SAFEM) model was used to calculate the high frequency theoretical wave structures for a rod embedded in concrete. The ultrasonic testing was conducted on six specimens with different amounts of delamination (0, 25, 33, 50, 75 and 100% of the entire rod length) using pulse-echo technique. The experimental results illustrate that, in order to determine the length of an embedded rod, one must use guided wave modes at higher frequencies. A transducer with a center frequency of 1 MHz or higher was found to be suitable for length determination. For most frequencies above 1 MHz, there was a little amplitude difference between a completely bonded interface and a 33% delaminated specimen, as seen in **Fig 3.11**



(a) 2MHz transducer (b) 1MHz transducer

Fig. 3.11: Several experimental results obtained using pulse-echo measurements at different frequencies. (a) Waveform at 1.8MHz, grey for no delamination, black for 1/3 delamination (b) Echoes at 1.58, 1.38, 1.18 and 0.98MHz from left to right (He et al. (2006))

The lower frequency guided wave modes showed better results while estimating delamination at the steel-concrete interface. It was concluded that any transducer with a center frequency larger than 2 MHz is not suitable for delamination estimation. **Fig. 3.12** shows that higher frequency modes at excitation frequency of 2.6 MHz and 2.8 MHz are insensitive to the presence of delaminaion, as there is a little change in signal amplitude.



(a) 2.6MHz (b) 2.8MHz

Fig. 3.12: Waveforms typical of those obtained above 2MHz. There is almost no contrast between the delaminated specimen and the completely bonded specimen. Grey for no delamination and black for 1/3 delamination (He et al. (2006))

It was concluded that ultrasonic guided wave pulse-echo technique can be applied to inspect large lengths of embedded rods.

Practical Guided wave inspection and applications to structural health monitoring (2007)

Cawley (2007) studied the application of ultrasonic guided waves for the long range inspection of large structures such as airframes. The problem of overlapping of reflections from different features in complex structures was highlighted. An increase in feature density made it impossible to analyze an individual reflection or, an extra reflection from a defect. This problem was resolved by subtracting the current response from a baseline measurement taken when the state of structure was known and this made it possible to monitor the changes in the response of the structure. However, this method required a high degree of signal stability with time in the absence of damage, or a scheme that could correct benign changes such as temperature variations. One such scheme,temperature compensation was implemented and considerable results were obtained. It was emphasized that some other benign changes such as moisture uptake in adhesives are also a matter of concern and a great deal of research is required to realize a reliable health monitoring system for complex structures.

Longitudinal Guided waves for monitoring corrosion in reinforced mortar(2008)

Ervin et al. (2008) investigated guided wave modes in both low and high frequency ranges capable of monitoring corrosion in reinforced concrete. The fundamental longitudinal modes L(0,1) and L(0,9) were chosen for experimental testing at low and high frequency respectively. L(0,1) mode was chosen because it shows negligible signal loss due to material absorption. It was used to access interfacial damage between steel and mortar. L(0,9) mode was selected because it is the fastest and lowest attenuating mode in the system. Experiments were conducted to examine the effect of reinforcing ribs, water and mortar on low and high frequency guided waves. Ultrasonic testing was carried out in a through transmission mode on rebar in air, rebar immersed in water, rebar embedded in mortar, corroded rebar in air and reinforced mortar specimens undergoing accelerated corrosion(**Fig.3.13)**

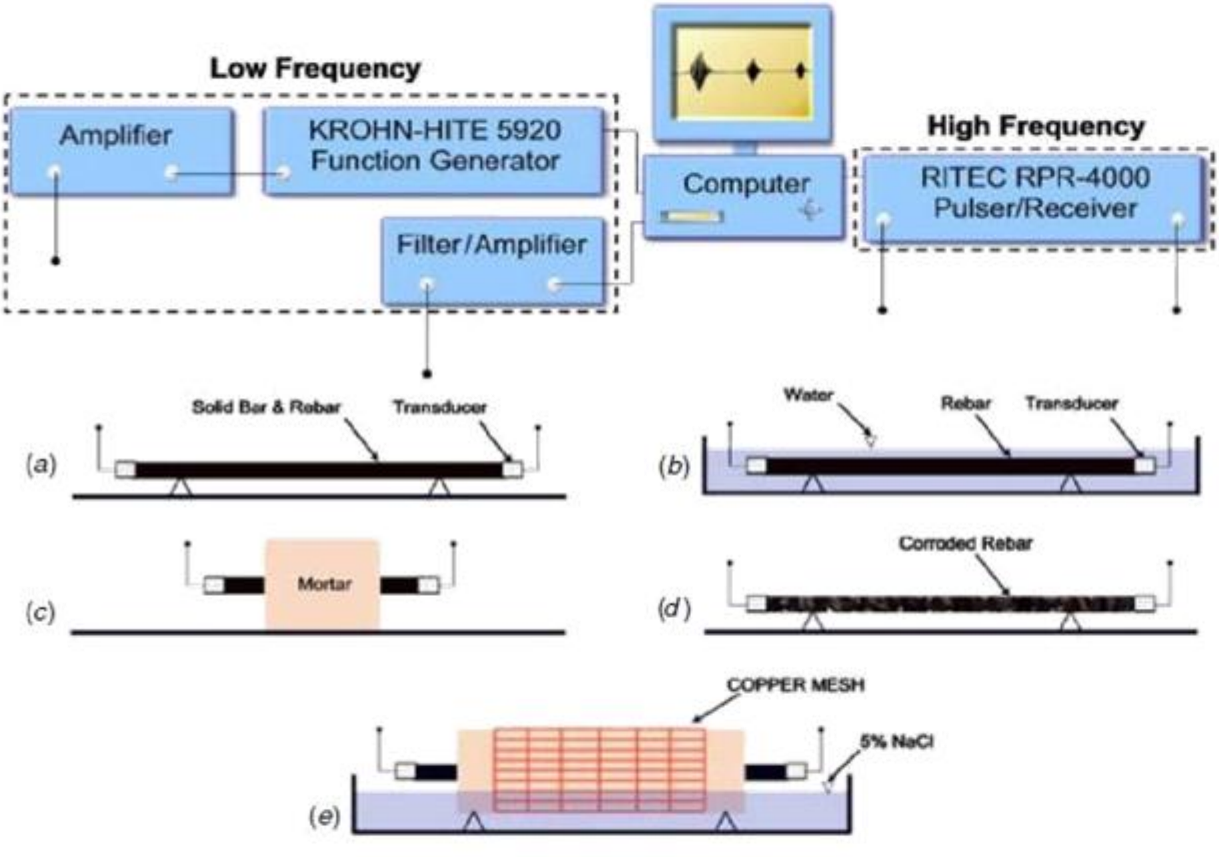


Fig. 3.13: Through-transmission testing for low - and high-frequency longitudinal wave testing on (a) a solid bar and rebar in air, (b) rebar immersed in water, (c) rebar embedded in mortar, (d) corroded rebar in air and (e) reinforced mortar specimens undergoing accelerated uniform corrosion. (Ervin et al. (2008))

Testing showed that reinforcing ribs has an attenuative effect on guided wave propagation only in certain frequency ranges. Guided wave was less affected at higher frequencies where the wave displacement structure is predominately concentrated at the centre of the bar, and negligibly affected when the wavelength is much longer than the characteristic dimension of the rib. Testing confirmed that L(0,1) mode has some sensitivity to water over the frequency range tested, with attenuation increasing with frequency. It was observed that the lowest frequencies of L(0,9) mode show sensitivity to water while the higher frequencies show diminished sensitivity. For the bars embedded in mortar, testing showed that the low frequency mode was highly attenuated, resulting in monitoring of relatively short distances (e.g. 1 m). The attenuation shown by L(0,9) mode was much smaller than L(0,1) mode. For rebar specimens extracted from accelerated corrosion tests, testing showed that L(0,1) was not substantially affected in the lowest range. However, interesting results were seen for L(0,9) mode. It was observed that there was no frequency content between frequency domain peaks when the corrosion damage frequency was low. As the corrosion level increased, the frequency content between frequency domain peaks, referred to as "web" frequencies started to increase. The attenuation curves for rebar in air, water and mortar are shown in F**ig. 3.14**.

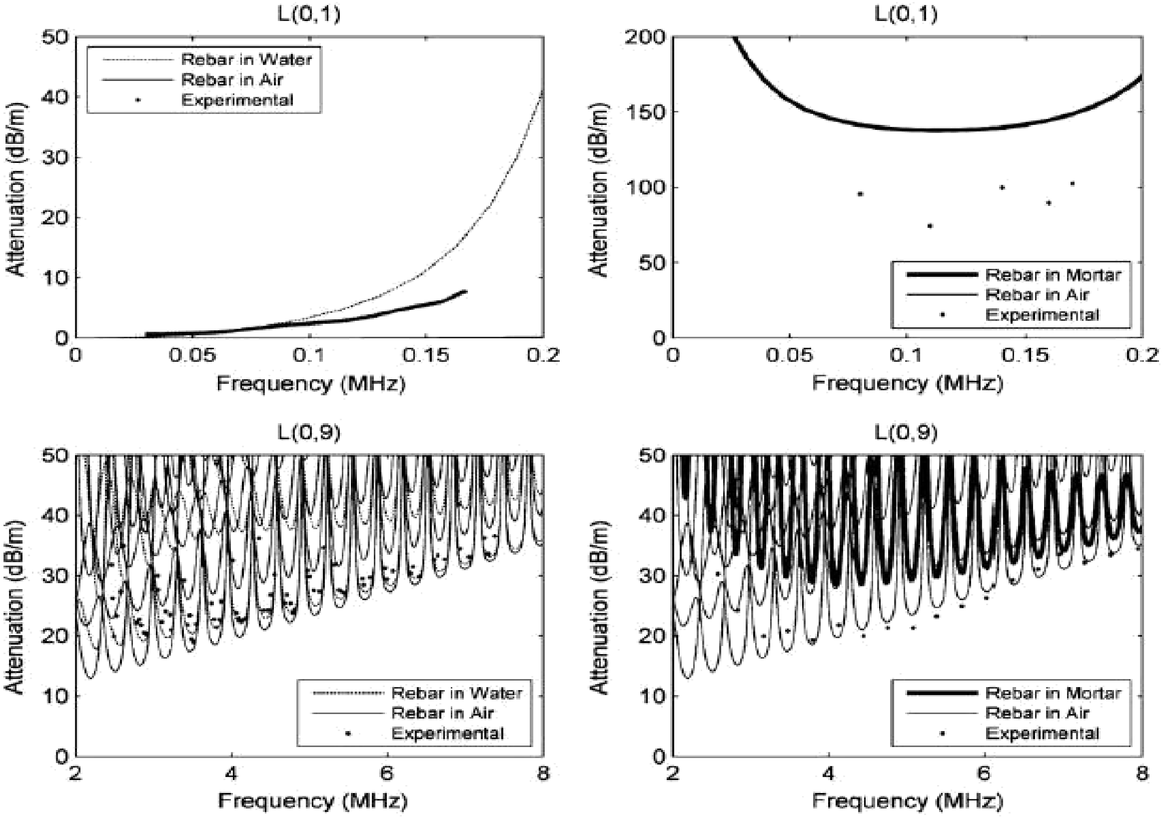


Fig. 3.14: Theoretical attenuation curves with experimental attenuation measurements for rebar in air, immersion in water and embedment in mortar at low and high frequencies (Ervin et al. (2008))

For rebar specimens undergoing accelerated corrosion, testing showed that L(0,1) was highly attenuated such that it was not detected until after corrosion had initiated and corrosion product accumulation caused mortar cracking. Once detected, L(0,1) mode was sensitive to the combined effect of bond deterioration and mortar stiffness reduction. The results indicate that the signal strength of L(0,1) mode was increasing as the mass loss was advancing(**Fig.3.15**)

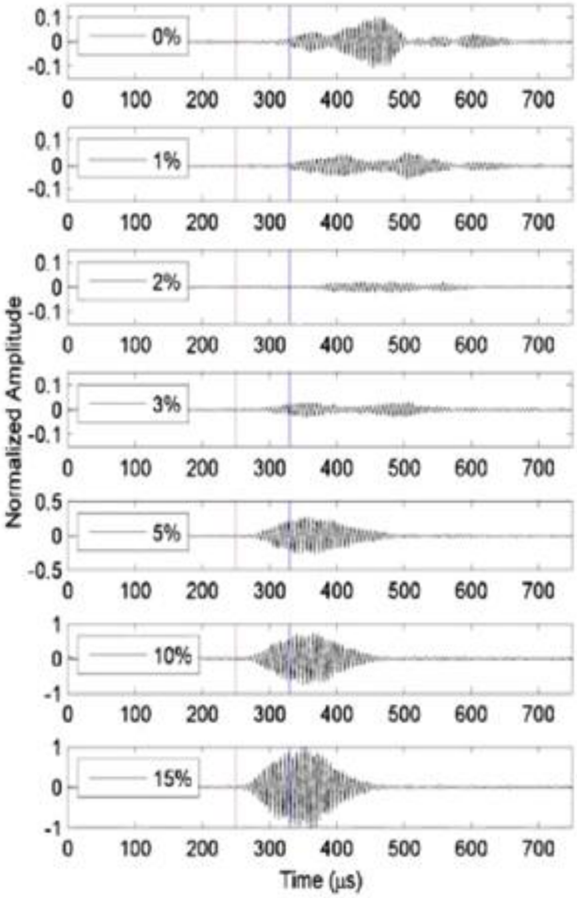


Fig. 3.15: Time domains at different levels of mass loss for low -frequency monitoring of accelerated corrosion. Left and right vertical lines are the arrival times for the L(0, 1) and F(1, 1) modes, respectively . The input signal was a 164 kHz 15-cycle pulse, with a band pass of 159 kHz and 169 kHz. (Ervin et al. (2008))

L(0,9) mode was relatively insensitive to the surrounding interface conditions at high frequencies. This allowed the monitoring of steel cross sectional area and bar topography, from the onset of corrosion to severe pitting (**Fig. 3.16**)

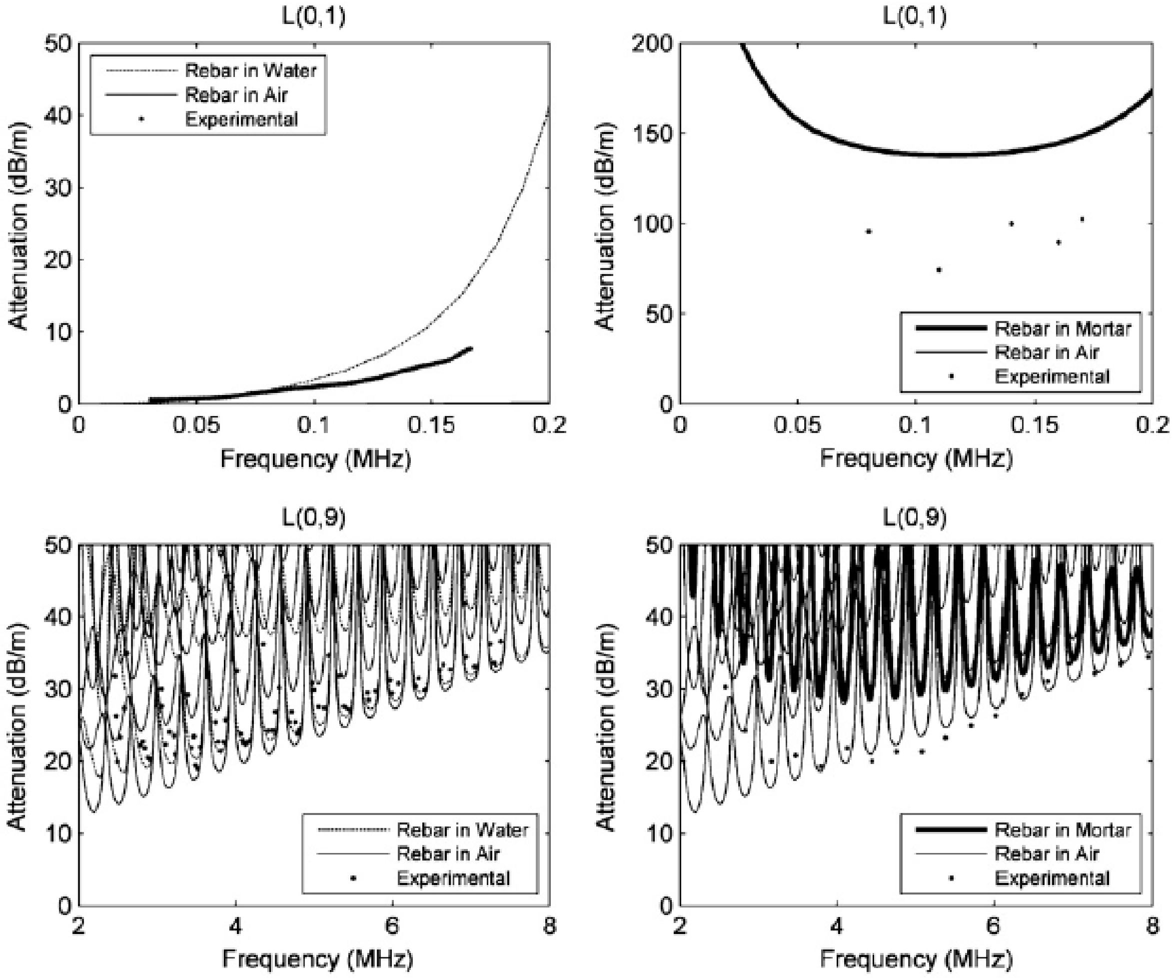


Fig. 3.16: Time domain response at different levels of mass loss for high - frequency monitoring of accelerated corrosion. The input signal was a 5.08 MHz single cycle pulse, with a band pass of 2 MHz and 10 MHz. (Ervin et al. (2008))

Non-destructive Ultrasonic evaluation of CFRP-concrete specimens subjected to accelerated ageing conditions (2010)

Mahmoud et al. (2010) investigated the use of ultrasonic waves for non -destructive structural health monitoring of CFRP bonded concrete specimens subjected to water immersion ageing at controlled temperatures of 25 -60 degree Celcius. The feasibility of using non -destructive ultrasonic technique as an alternative to destructive technique was analyzed. Narrow -band transducers with center frequency of 110 kHz were used to generate and receive surface waves at the external face of CFRP. The signals received by the transducer were amplified, digitized and processed to extract the parameters: average power ( ), maximum amplitude ( ) and maximum power- frequency ratio ( ) in both time and frequency domains. The variations in these parameters due to water –immersion ageing at different temperatures were monitored over 12 weeks. Results indicated a decrease in the measured ultrasonic parameters due to ageing over time. A simultaneous destructive study was carried out on mode -11 fracture loading of CFRP concrete samples subjected to some ageing conditions and temperature and a parameter ,fracture energy was obtained. A correlation analysis was performed at each ageing temperature, between the non -destructive parameters and destructive parameter (as shown in **Fig. 3.17**)

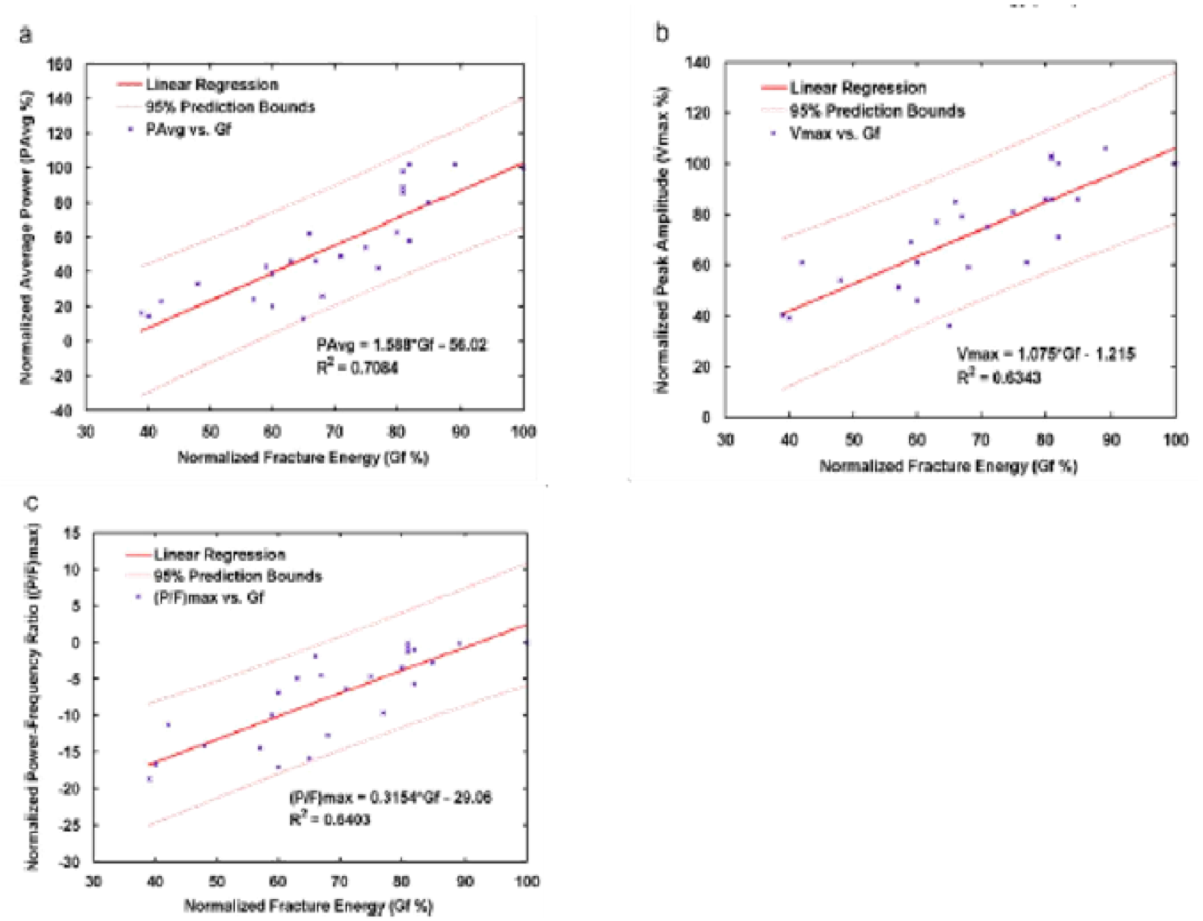


Fig 3.17: Linear regression of non -destructive ultrasonic parameters vs. fracture energy results of CFRP–concrete samples subjected to accelerated aging temperatures: (a) average power( ) vs. Fracture energy( ), (b) peak amplitude(Vmax) vs. Fracture energy( ), and (c) maximum power–frequency ratio of PSD ((P/F)max) vs. fracture energy( ). Linear equations and 95% prediction bounds are shown. (Mahmoud et al. (2010))

The results indicate a good correlation between the ultrasonic parameters and fracture energy at all temperatures. It was concluded that non -destructive ultrasonic technique can be used for the structural health monitoring of CFRP protected concrete structures.

Application of Ultrasonic Guided Waves for non -destructive testing of defective CFRP rods with multiple delaminations (2010)

Raisutis et al. **(2010)** analyzed the possibility of using non -destructive ultrasonic guided waves for inspection of small diameter CFRP rods used in gliders. The models such as 3D numerical solutions, finite difference and finite element were used to investigate the propagation of ultrasonic guided waves in defective CFRP rods with multiple delaminations. The experiments conducted demonstrate that ultrasonic guided waves can be applied for testing of defective CFRP rods. The immersion technique based on the excitation of longitudinal guided wave mode L(0,1) to monitor the amplitude of leaky waves over the rod, was proposed. The delamination type defects were indicated by a reduction in amplitude or complete disappearance of leaky waves over a defected zone. It was shown that the propagation of L(0,1) guided waves was not hampered by the delamination type defects. L(0,1) mode was just converted into other modes that did not generate leaky waves. Thus, a possibility of detecting a series of defects in CFRP rods was seen. The future scope for non -contact generation of longitudinal L(0,1) guided wave mode by a more advanced ultrasonic technique was emphasized for online testing of CFRP rods.

Longitudinal Guided Waves for Monitoring Chloride Corrosion in Reinforcing Bars in Concrete (2010)

Sharma and Mukherjee (2010) discussed the use of longitudinal guided ultrasonic waves to monitor notch and debond defects in steel bars in concrete simulating pitting and delamination phenomenon caused by corrosion. The low and high frequency ultrasonic pulse echo and pulse transmission technique was used for early detection of damages in steel in RC beams. The exact location and magnitude of damage was indicated by efficient combination of the two ultrasonic monitoring techniques. Ultrasonic guided wave monitoring utilizing specific core and surface seeking modes was applied to identify corrosion mechanism in a bar embedded in concrete. In general, huge pitting and non -uniform area loss highlighted by severe signal attenuation marks chloride corrosion, which was well unravelled by core seeking mode. It began with delamination shown by signal rise with surface seeking mode. It was concluded that through judicious selection of ultrasonic modes, the complete corrosion mechanism in RC structures can be successfully identified.

Monitoring Corrosion in Oxide and Chloride Environments Using Ultrasonic Guided Waves (2011)

Sharma and Mukherjee (2011) investigated the type of corrosion mechanism in chloride and oxide environments in RC beams. Ultrasonic guided waves with specific core and surface seeking modes were used for monitoring rebar corrosion in beams. It was observed that in case of Chloride corrosion in beams, when core - seeking mode was propagated, the signal was highly attenuated, thus indicating pitting and non-uniform area loss. When surface seeking mode was propagated, there was an initial rise in the signal strength and then a fall, thus indicating delamination followed by local loss of material. In case of Oxide corrosion in beams, it was observed that when core -seeking mode was propagated, there was a slow fall in signal strength, indicating the absence of pitting. When the surface - seeking mode was propagated, there was an initial drop in the signal due to the pressure build up by the formation of corrosion products, indicating a slow corrosion rate and localized corrosion and eventually, a gradual rise in signal strength was observed, indicating slow bond deterioration. The ultrasonic voltage trends of the received signal in both chloride and oxide corrosion specimens using surface-seeking and core-seeking mode are shown in **figures 3.18 (a) and (b)** respectively.

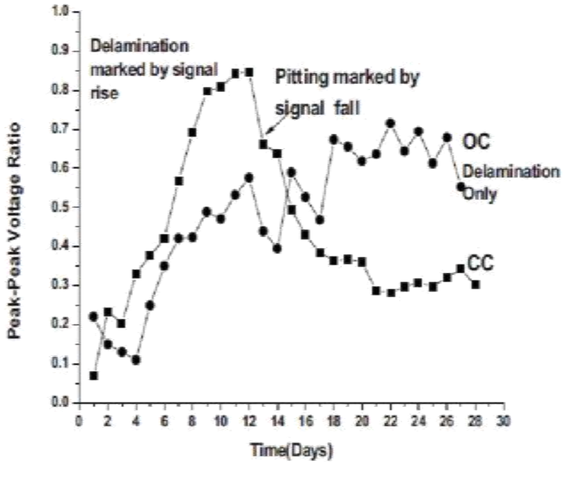


Fig. 3.18(a) : Peak-peak voltage ratio with surface-seeking mode

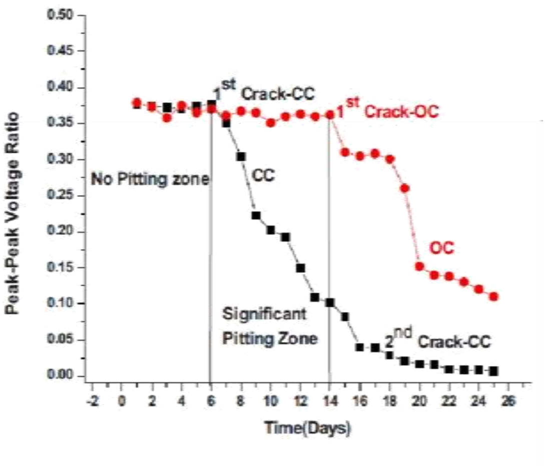


Fig. 3.18(b) : Peak-peak voltage ratio with core-seeking mode

(Sharma and Mukherjee (2011))

Thus, the mechanism and rate of rebar corrosion was successfully monitored in chloride and oxide environments through appropriate selection of modes. Simultaneous destructive tests were also carried out on RC beams, and it was found, that non-destructive Ultrasonic technique correlate well with the destructive technique.

Non-destructive Evaluation of Corrosion in Varying Environments using Guided Waves (2013)

Sharma and Mukherjee (2013) reported non-destructive evaluation of reinforcing bars that are corroding in the presence and absence of chlorides utilizing ultrasonic guided waves. Ultrasonic guided wave monitoring utilizing specific core and surface seeking modes to identify the type, rate, and mechanism of corrosion in a reinforcing bar in concrete subjected to different exposure conditions was discussed. The experimental investigation involved monitoring of RC beams undergoing accelerated impressed current corrosion. In general, huge pitting and non-uniform area loss highlighted by severe signal attenuation marks chloride corrosion, which was well picked up by core seeking mode. It began with delamination shown by signal rise with surface seeking mode. In oxide corrosion, the rate of corrosion was slow, localized, and marked by slow bond deterioration as depicted by signal strength rise in surface seeking mode. Pitting was insignificant in core seeking mode in OC. Thus, it was observed that through a judicious selection of ultrasonic modes, different types of corrosion in RC structures can be successfully identified. Bars at different stages of corrosion were ultrasonically monitored in both oxide and chloride environments to explore the ability of ultrasonics to predict the level of deterioration of the bars. It was done successfully by correlating ultrasonic voltage ratio with destructive parameters of mass loss, tensile strength and bond strength in the two common corrosion environments. It was concluded that, although the use of guided waves is effective in identifying the presence of corrosion in rebars in widely varying environments, the method needs access to the ends of rebars. At site, bars that are most susceptible to corrosion need to be exposed at the ends to perform the test. Also the signal -to-noise ratio should be above the ground noise level .

3.6 Closing Remarks

This chapter presents the literature survey on the use of ultrasonic guided waves to monitor corrosion in 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 4

EXPERIMENTAL PROGRAM & METHODOLOGY

4.1 General

The objective of the research is to investigate the efficacy of ultrasonic guided waves to monitor the behaviour of RC slab specimens during various stages of corrosion i.e., after the initiation of corrosion, and after the protection of slab specimens with the help of CFRP's (Carbon Fiber Reinforced Polymer). Also, the destructive tests of pull-out and mass loss are conducted in order to evaluate the damage done by the corrosion and the effectiveness of FRPs in protecting RC specimens from corrosion.

4.2 Test Program

The objective of test program is to monitor the actively protected RC slabs from corrosion using Ultrasonic Guided Waves. The test program involved:

1. Determination of basic properties of constituent materials namely cement, fine aggregates, coarse aggregates and steel bars.
2. Casting of slabs of size 300 x 300 x 100 mm with concentric 25 mm diameter mild steel bar using M20 grade concrete.
3. Subjecting the slab specimens to accelerated impressed current corrosion at a constant voltage at 20 V to varying exposure duration.
4. Using Active protection for corrosion impediment with the help of Carbon Fiber Reinforced Polymer (CFRP).
5. Monitoring corrosion using Ultrasonic Guided waves during the entire period of exposure to corrosion and after protection using CFRP.
6. Destructive tests of pull-out strength and mass loss of the reinforcing bar subjected to corrosion protection are measured after the corresponding days of exposure to corrosion.

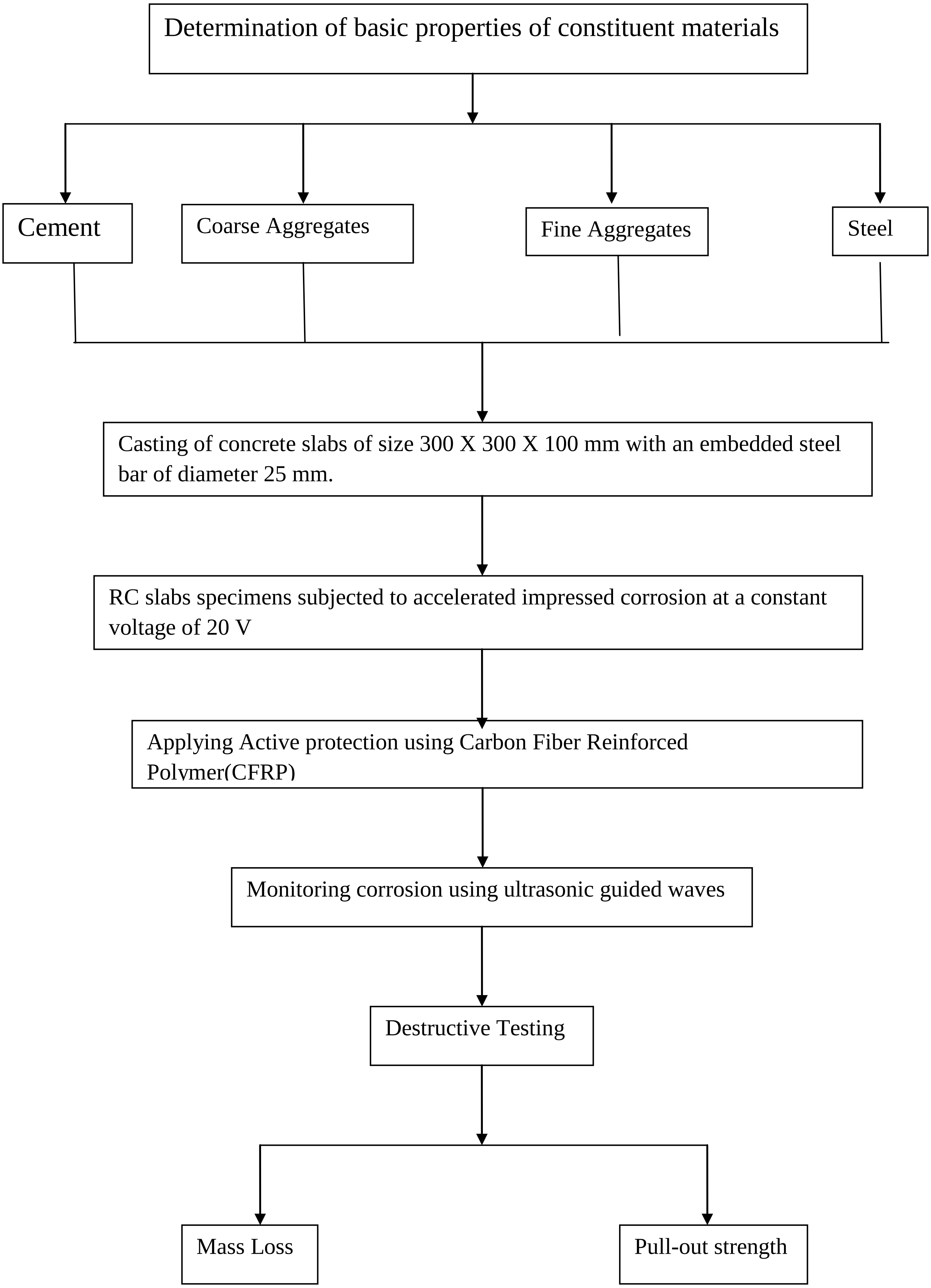


Fig. 4.1 shows the Flow chart of experimental way

4.3 Materials Used

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

1. ***Cement:*** Ordinary Portland cement of 43 grades 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 various tests conducted on cement are given in **Table 4.1**. All these tests are carried out in accordance with procedure laid down in IS: 8112 -1989.

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 4.75 mm 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 4.2** and **4.3**.

Table 4.1: Physical properties of cement

S. No.	Characteristics	Values obtained	Standard Values
1	Normal Consistency	33%	_
2	Initial setting Time	48 min	Not less than 30 min
3	Final setting Time	240 min	Not more than 600 min
4	Fineness	4.8 %	_
5	Specific gravity	3.05	_
6	Compressive strength		

S. No.	Days	Average Strength
1	3	24.8 MPa
2	7	37.5 MPa
3	28	47.6 MPa

Table 4.2: Physical properties of fine aggregates

S. No	Characteristics	Value
1	Specific gravity	2.59
2	Bulk density	1.33 g/cc
3	Fineness modulus	2.63
4	Water absorption	0.89
5	Grading zone (based on percentage passing 0.60 mm) Zone III	–

Table 4.3: Sieve analysis of fine aggregates

Sr.No.	IS-Sieve (mm)	Wt. Retained (gm)	%age Retained	%age Passing	Cumulative % Retained
1	4.75	14.5	1.45	98.55	1.45
2	2.36	37	3.70	94.85	5.15
3	1.18	246.5	24.65	70.20	29.80
4	600 µ	205.5	20.55	49.65	50.35
5	300 µ	287.5	28.75	20.90	79.10
6	150 µ	177	17.70	3.20	96.80
7	Pan	32	3.20		
	Total	**1000.00**		**SUM**	**262.65**
				FM =	*2.62*

Total weight taken: 1000gm

Fineness modulus of fine aggregates = 2.68

3. ***Coarse aggregates:*** Crushed stone aggregates (locally available) of nominal size 10 mm are used throughout the experimental study. The aggregates are washed to remove the dust and dirt and are dried to surface dry conditions. The aggregates are tested as per IS: 383-1970.The results of various tests conducted on coarse aggregates are given in **Table 4.4** and **Table 4.5** shows the sieve analysis results.

Table 4.4: Physical properties of coarse aggregates

S. No.	Characteristics	Value
1	Type	Crushed
2	Specific gravity	2.69
3	Water absorption	0.5557 %
4	Fineness Modulus	6.91

Table 4.5: Sieve Analysis of Coarse aggregates

S. No.	Sieve size	Weight retained(gm)	Percentage Retained	Percent Passing	Cumulative Percentage Retained
1	80	0.00	0.00	100.00	0.00
2	40	0.00	0.00	100.00	0.00
3	20	68.5	2.28	97.72	2.28
4	10	2776.5	92.55	5.17	94.83
5	4.75	113.5	3.78	1.38	98.62
6	Pan	0.00	0.00	0.00	
	Total	**3000.00**		**SUM**	**195.73 + 500 =**
				FM =	*6.95*

FM of 10 mm coarse aggregates= 6.95

4. ***Water:*** Fresh and clean tap water is used for casting slabs in the present study. The

water is relatively free organic matter, silt, oil, sugar, chloride and acidic material as per Indian standard.

5. ***Steel reinforcement:*** Mild steel bars of 25 mm diameter and 600 mm length are used as reinforcement. Half of the steel rod (300 mm) is embedded in the concrete and half remains exposed to environment, in order to make electrical connections and conduct pull-out test later on. **Table 4.6** shows the properties of reinforcing bars used for casting of RC slab structures.

Table 4.6: Properties of reinforcing bars used for casting specimens

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

6. ***Fiber Reinforced Polymer:*** The FRP material used is CFRP (Carbon Fiber Reinforced Polymer) as shown in F**ig. 4.2** below.

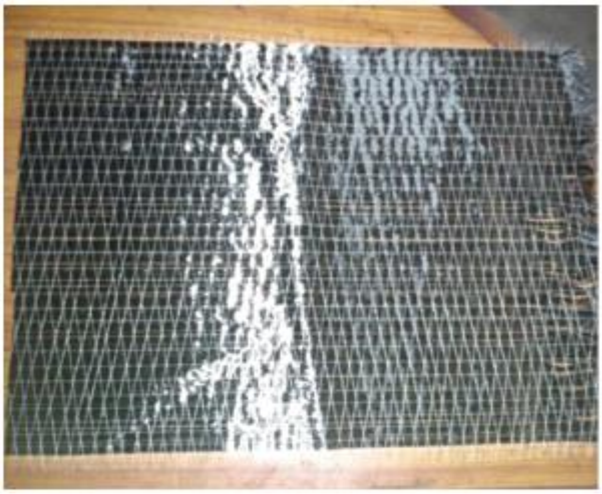


Fig. 4.2: CFRP laminate sheet

The various properties of CFRP laminates are given in **Table 4.7**

Table 4.7: Properties of CFRP as supplied by manufacturer

Material	Thickness (mm)	Tensile Strength(MPa)	Tensile Modulus(GPa)	Ultimate Strain	Electrical conductivity
CFRP	0.1176mm	3800	240	0.015	551

7. ***Adhesives:*** The adhesive used for bonding FRP sheets with concrete is compatible epoxy system (MBrace). It is blue pigmented resin for saturation of Mbrace fibre sheet to form in -situ FRP composite. It is made by mixing base saturant and hardener in the 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 the epoxy are discussed in **Table 4.8**.

Table 4.8: Properties of epoxy

S. No.	Properties	Values
1	Aspect	Translucent blue liquid
2	Density	1.13 ± 0.03
3	Mixing ratio, by weight	100:40
4	Pot life	25 minutes at 25 degree
5	Tensile strength	> 17MPa
6	Compressive strength	> 40 MPa after 1 day
7	Flexural strength	> 35 MPa

4.4 Design of Concrete Mix

Concrete mix is prepared using 43 grade Portland Pozzolana cement, fine aggregate (medium-sized river sand) and crushed stone coarse aggregate with a nominal size of 20 mm. The mix is designed as per Indian standard guidelines. Mix design properties were calculated as 1:1.49:2.48. The water-cement ratio was kept as 0.5 and average compressive strength obtained after 28 days of curing is 29 MPa.

4.5 Test Procedure

4.5.1 General

Corrosion initiation takes place when the chloride concentration at the rebar level reaches a critical value which is an established fact. 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 of corrosion in real structures. Guided waves are chosen because they have the capability of testing over distances with sensitivity often greater than conventional non - destructive (NDT) techniques, have the ability to test multilayered structures, and are relatively inexpensive due to simplicity and sensor cost.

4.5.2 Preparation and Preconditioning of Steel bars

Steel bars are cut to the required length of 600 mm. 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 dry in air. Before casting of the test specimens, each reinforcing bar is 0.1 gm accuracy.

4.5.3 Preparation of Specimens

In the present program, the slabs of size (300x300x100) mm are cast with an embedded steel bar of 25 mm dia & 600 mm length such that 150 mm length of the bar is exposed to the surrounding environment from both the ends. First of all, interior of the slab mould is oiled, so that slabs could easily be removed from the mould after 24 hours. Initial weight of the bars is measured. When the bars have been placed in position, concrete mix is poured and vibrated for better compaction. The slabs are then removed from the mould after 24 hours and are cured for 28 days in an open tank. The concrete surface of the slabs is then cleaned up and all dirt and loose materials are removed.

4.5.4 Inducing Corrosion in Concrete

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 (Gadve et al., 2008), Chloride diffusion (Masoud and Soudki, 2006) and impressed current method. Previous studies have shown that the 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. This method was not considered because it did not simulate the present condition of interest.

Alternate immersion into NaCl 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 it in electrochemical series as cathode.The rebar was made anode. A stainless steel (SS) mesh is rolled around the circumference of the concrete slab and tied together with metal ties in order to assure electrical continuity and is used as cathode . The constant voltage of 20 V is impressed in order to accelerate corrosion. The DC power supply (Aplab make) was used as a voltage source . This power supply has the voltage and current capacities of 64V and 10A. The rebar is connected to the positive terminal of the external DC source and negative terminal is connected to SS mesh. It is more common to maintain a constant voltage between the cathode and anode (Masoud and Soudki, 2006; Gadve et al., 2008). A screen on the box of power supply displayed the instantaneous voltage and current .This gave us the facility of monitoring the fluctuations in the current with time. **Fig.4.3(a) & 4.3(b)** shows the setup of slab specimens wrapped with SS mesh.

Fig. 4.3: (a) Slab Specimen

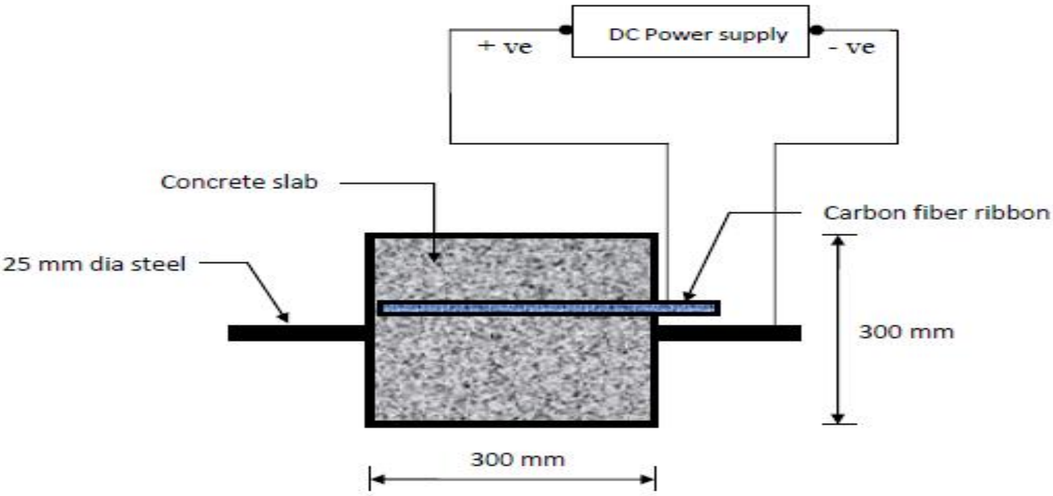


Fig. 4.3(b) Top View of slab Showing Terminals for Active Protection

Fig. 4.4: Slab specimen wrapped with CFRP

4.5.5 Active Protection

Since carbon is electrically conductive, an attempt was made to use this property in applying active protection to the reinforced concrete system without using any external anode. In this case the carbon fiber sheets that were wrapped around the slab reinforced concrete specimen themselves were used as anodes and the reinforcing bar as cathode. To achieve this, the wrapping system had to be modified in two ways. 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. **Fig 4.4** shows the epoxy on concrete surface. A ribbon of carbon fibers was stitched through the CFRP sheet in the perpendicular direction of the fibers. The ribbon was extended beyond the sheet by about 25 mm. It was used as the anode terminal for supplying electricity to the CFRP sheet. The ribbon pressed against the fibers of the sheet and ensured proper contact and uniform conductivity. The only non-conductive part in the system was the epoxy adhesive used to bond the carbon sheets into concrete. In the present study, the epoxy was made conductive by mixing conductive particulates into the epoxy. The conductive particulates that were used are commercially available graphite powder of particle size in the range from 0.1µ to 10µ.

An external DC power supply system was used to impress current for active protection. The positive terminal of DC power supplier was connected to protruding ribbon of the carbon sheet and the negative terminal was connected to the reinforcing bar, to be protected from corrosion. A constant voltage of 20V was impressed between the carbon fiber (cathode) and reinforced steel (anode). To simulate the practical conditions of applying active protection to the reinforced concrete structures in corrosive environment, the specimens were exposed to corrosion, with all necessary electrical connections for active protection.**Table 4.9** shows the Test Matrix for specimens.

Table 4.9: Test Matrix for Specimens

Wrap Material	Total Exposure in days	Total exposure in days (before protection)	Total exposure in days (after protection)	Protection	Nomenclature
Unwrapped	28	28	--	No	Control (C)
Wrapped with carbon fiber	28	3	25	Active	APC-3
	28	6	22	Active	APC-6
	28	9	19	Active	APC-9

Total 12 slab specimens were casted. The specimens which were control slab,were subjected to 28 days of impressed current corrosion. Further 3 slab specimens were subjected to 3 days accelerated corrosion and during the remaining 25 days,it was actively protected against corrosion (APC-3). Rest 3 specimens were APC-6 and APC-9 with the details of corrosion acceleration and protection as mentioned in **Table 4.9**.

4.5.6 Destructive Tests

(a)Pull-out strength test: Pull out strength test was conducted on all the specimens. When the specimens have been completely exposed to corrosion for about 28 days, the pull out test is carried out on them. This is done by securing the slab in a universal testing machine and attaching the grip on to the protruding portion of the reinforcing bar.

(b)Mass-loss: After the pull out test has been conducted, the steel bars are taken up to calculate the mass loss. For this purpose, the steel bars are cleaned up and then immersed in the acidic solution to remove the corrosion products .The acidic solution used is 50% solution of hydrochloric acid to which hexamethylene tertramine will be added with a concentration of 3.5 g per litre. Steel bars will be immersed in this solution for about 10 -15 min, depending on how much they have been corroded, and then taken out to measure their weight. The process is repeated 4-5 times so that the weight of the steel bars is stabilized to ensure that all the corrosion products were removed. The final weight of the steel bars were compared to the original weights to determine the mass loss.

4.6 Ultrasonic Guided Wave Investigation

4.6.1 Method of Testing

For ultrasonic guided wave investigation, pulse-transmission (PT) testing method is adopted. 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 Make Contact Type) as shown in **Fig. 4.7** are used. Transducers having diameter of 25 mm are attached at the two ends of the protruded rebars shown in **Fig.4.6**. 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.Setup of ultrasonic investigation is shown in **Fig.4.5.**

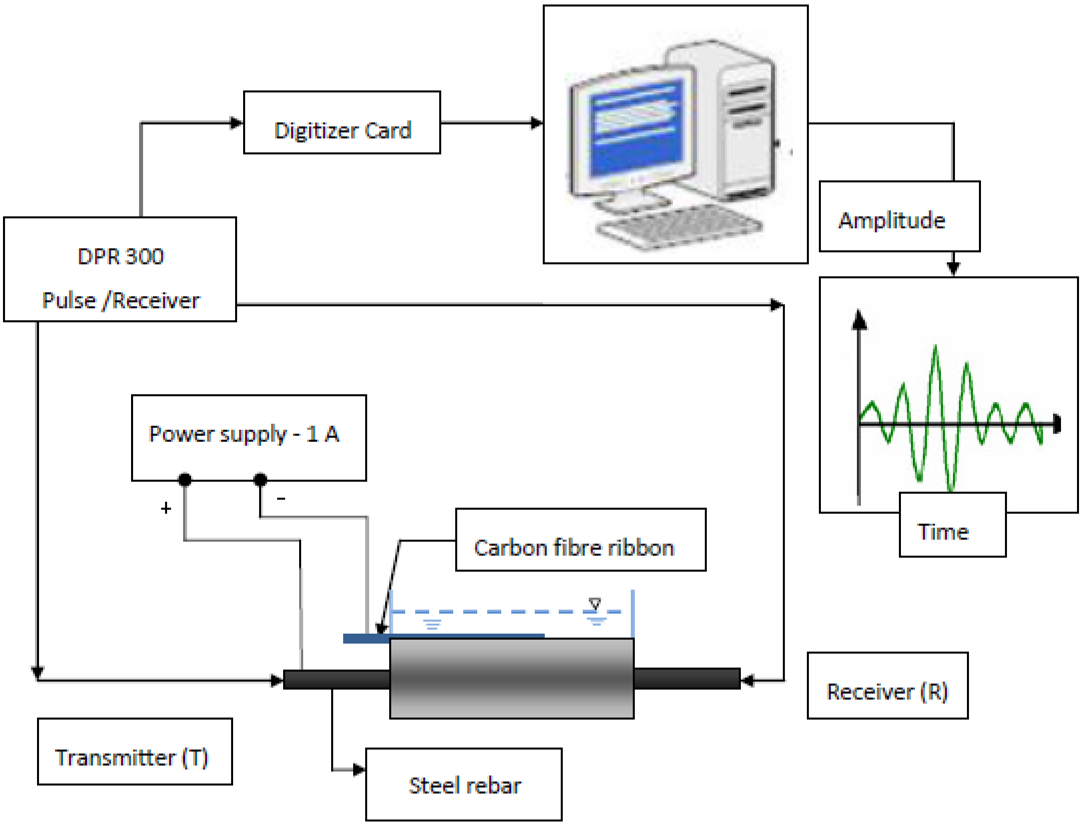


Fig. 4.5: Set up for Ultrasonic investigations

Fig. 4.6: Pulser Receiver system (DPR 300) (Karl Deutsch Make)

Fig. 4.7: Contact type transducers (Karl Deutsch Make)

4.6.2 Selection of Excitation mode and Frequency

The selection of a suitable test mode and frequency is done after analyzing the dispersion curves using the software Disperse. According to Sharma and Mukherjee (2010), modes that have lowest signal attenuation and at the same time are easily distinguishable are selected. Generally, modes at low attenuation are used to maximize the inspection range and at the same time to minimize the effects of dispersion and also minimize the interference of other modes in the received signal. These modes at L(0,1) at 0.1 MHz which is a low frequency and low attenuation mode. Another mode L(0,7) at 1 MHz is a high frequency low leakage mode which has very low attenuation and hence found suitable for monitoring rebar corrosion in RC structures.(Sharma and Mukherjee (2011),(2013))

Another important feature for the selection of modes was mode shape that determines the radial distribution of displacement and energy density. The authors have utilized specific surface seeking and core seeking modes of L(0,1) and L(0,7) respectively to monitor the complete corrosion mechanism in the presence of chlorides in a reinforcing bar in concrete . L (0,1) was named as a *surface seeking* mode which was sensitive to surface changes in the reinforcing bars due to corrosion . It picked up the initial delamination of the reinforcing bar from surrounding concrete due to chloride induced corrosion. Another major effect of chloride corrosion was the pitting in the bar and manifested itself in a mode that progressed mainly through the core of the bar and had negligible surface component. L (0, 7) was such a mode and it was referred to as the *core seeking* mode **.** These two modes were also successfully used to distinguish between corrosion mechanisms in two environments of oxides and chloride.

In this study, these two characteristic modes would be further used for corrosion monitoring of reinforcing bars embedded in slabs to investigate the effectiveness of active protection offered by FRP wraps from corrosion in accelerated conditions.

4.7 Closing Remarks

In this chapter, monitoring of corrosion in RC slab specimens by ultrasonic guided waves technique is discussed in detail. Corrosion monitoring gives a bright picture of the various changes in the structural behaviour of the building. Thus, we can say proper monitoring of structures for corrosion performance and taking suitable measures at appropriate time can be a lot of benefit. Proper care should be taken while wrapping FRP which is also discussed in detail.

CHAPTER 5

RESULTS AND DISCUSSIONS

5.1 General

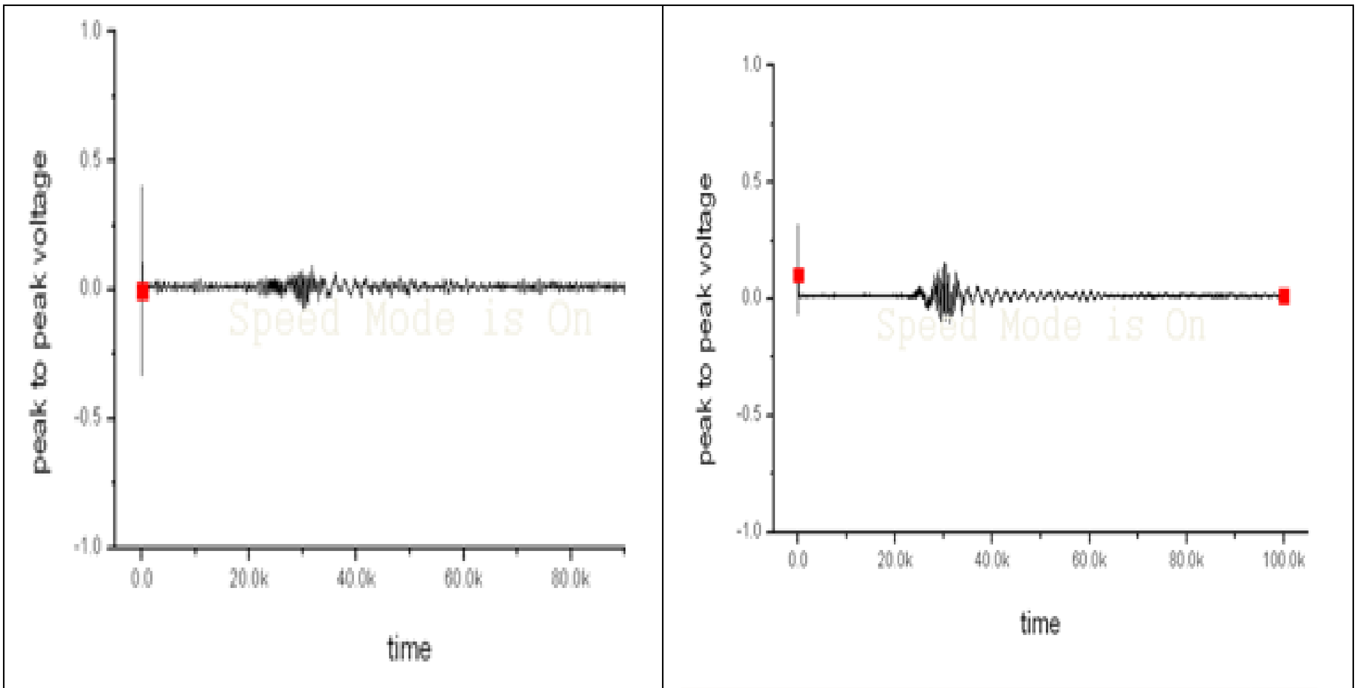
There are a number of techniques that can be used to carry out the assessment of a structure suffering from corrosion of the reinforcement (Broomfield, 2002). However, in order to determine the rate of deterioration of the structure; it is useful to monitor the condition change with time. It was carried out using the ultrasonic guided waves. Ultrasonic guided waves are used to monitor corrosion taking place in RC slabs before and after protection. Efficacy of guided waves to monitor effectiveness of anodically protected RC structures is investigated in the study. Destructive tests of mass loss and pull out tests were also carried out.

5.2 Ultrasonic Monitoring Measurements

Ultrasonic techniques have been used for actively protected RC concrete structures against corrosion because of their safety, low-cost, and flexibility, in addition to high sensitivity. Specific ultrasonic guided waves have been used to monitor corrosion progression in structures which are protected against corrosion by active protection. 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 the concrete and thus attenuate before coming back where it will be received by the transducer (Raisutis et al., 2007; Goueygou et al., 2008; Sharma and Mukherjee, 2010).The exciting signal consisted of a compressive spike pulse.
RC slab specimens are tested in pulse transmission mode using L (0, 1) and L (0, 7) mode at a frequency of 0.1 MHz and 1 MHz respectively. Ultrasonic pulse transmission signals were recorded after every 24 hours of the continuous exposure of RC slab specimens to corrosive conditions.

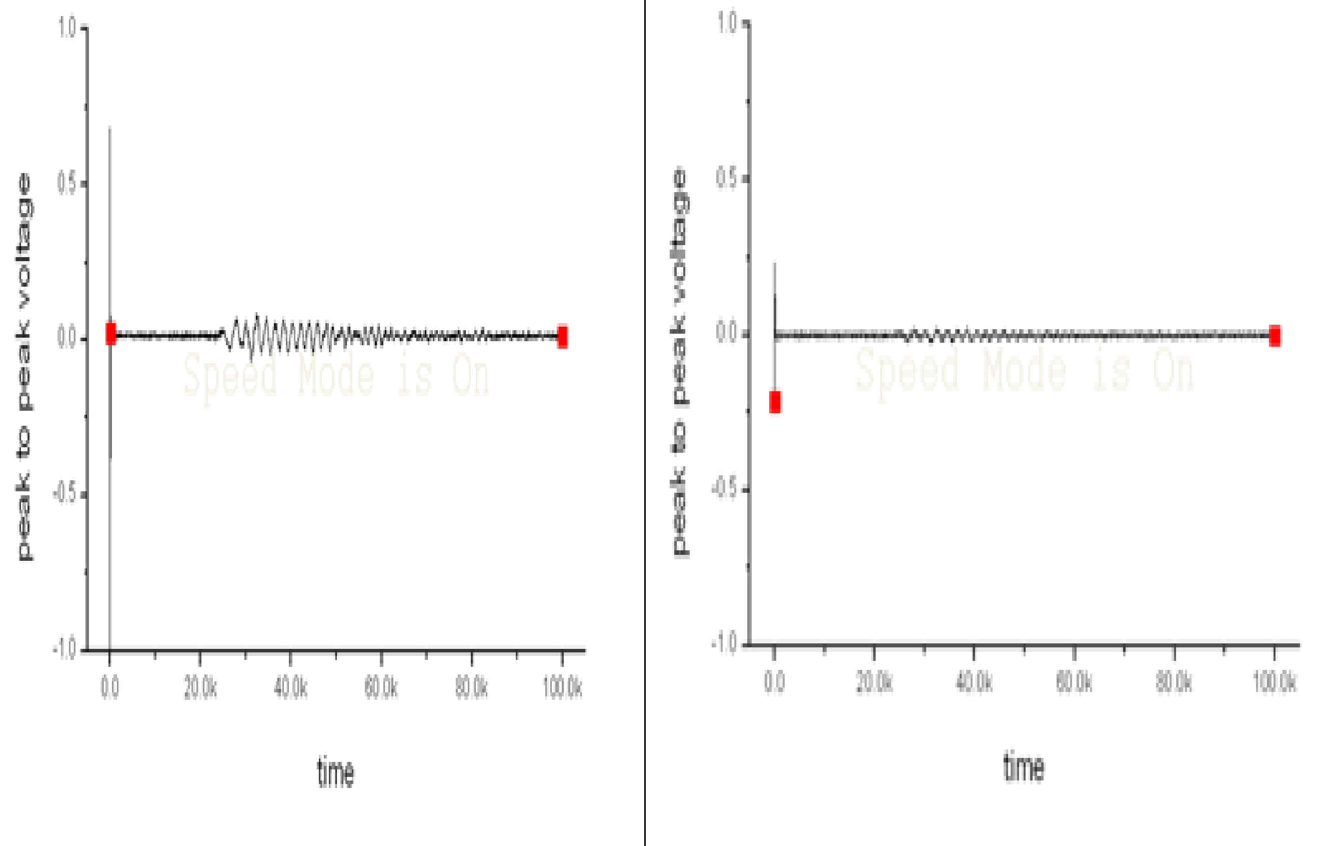
5.2.1 Ultrasonic Monitoring in control samples

Fig.5.1 The damage in RC slab due to corrosion can be studied by studying the relative change in the amplitude of the received signal obtained at different instants. Relative signal attenuation of the transmitted signal which was healthy signal can be related to the extent of damage in the reinforcing bar due to corrosion and **Fig 5.2** shows the transmitted signals obtained with L(0,7) mode at 1 MHz through the embedded bar at different durations of exposure in control RC slab samples.



(a) Healthy signal

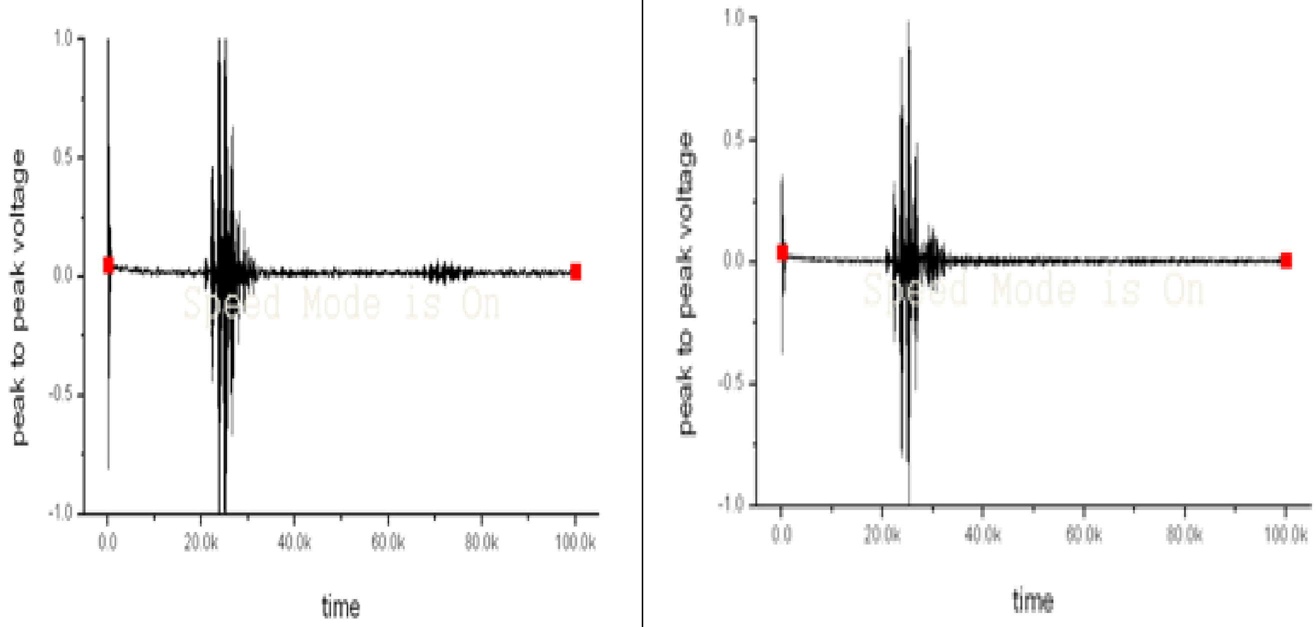
(b) After 5 days



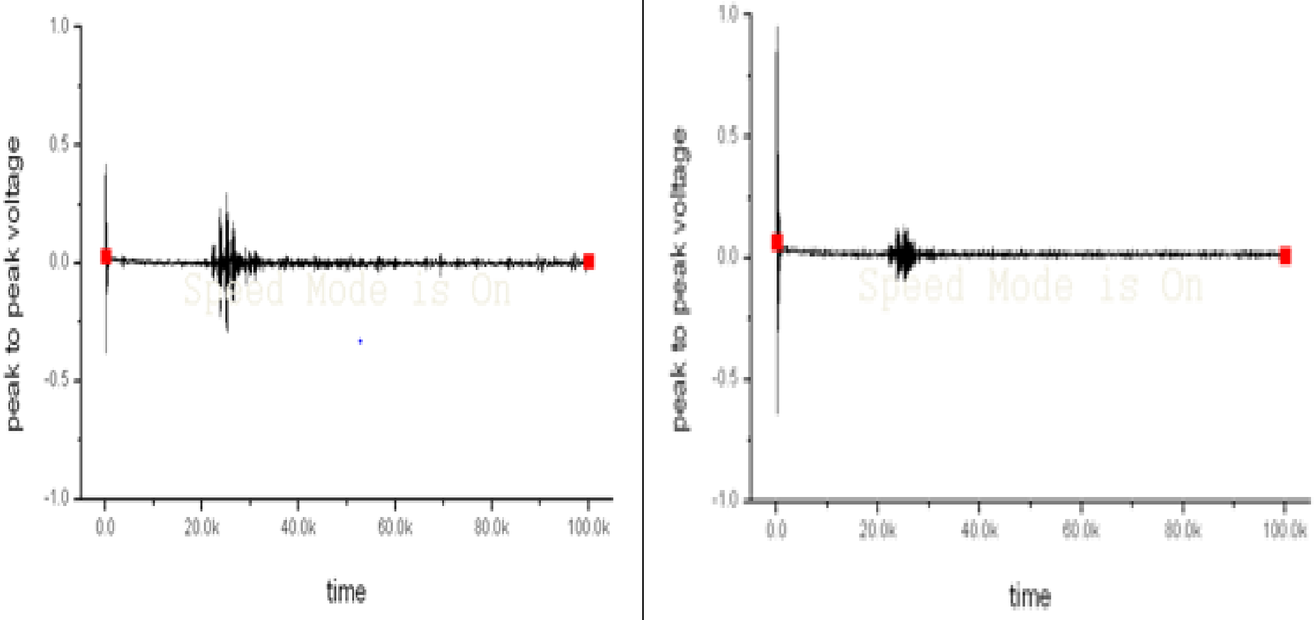
(c) After 15 days

(d) After 25 days

Fig. 5.1 Typical Signals in control sample using L(0,1) mode at different exposure durations to corrosion



(a) Healthy signal **(b) After 15 days**



(c) After 20 days **(d) After 28 days**

Fig. 5.2 Typical Signals in control sample using L(0,7) mode at different exposure durations to corrosion

The trends of normalized transmitted pulse with healthy signal of control sample at different periods of exposure are plotted using L(0,1) and L(0,7) modes respectively.

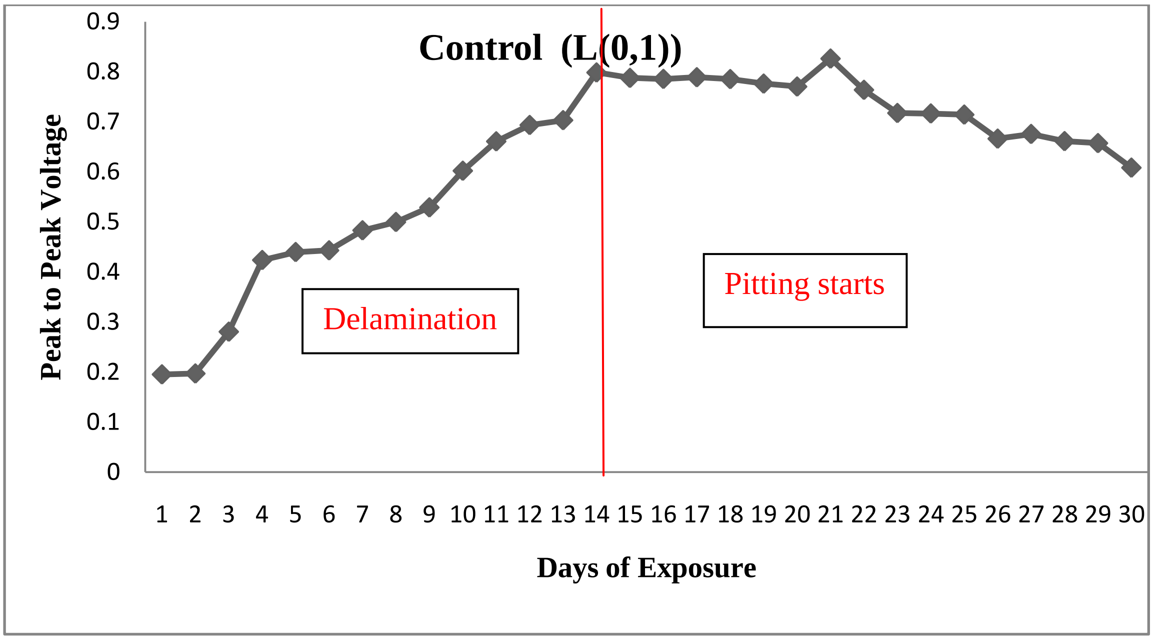


Fig.5.3 : P-T trends for Control sample using L(0,1) mode

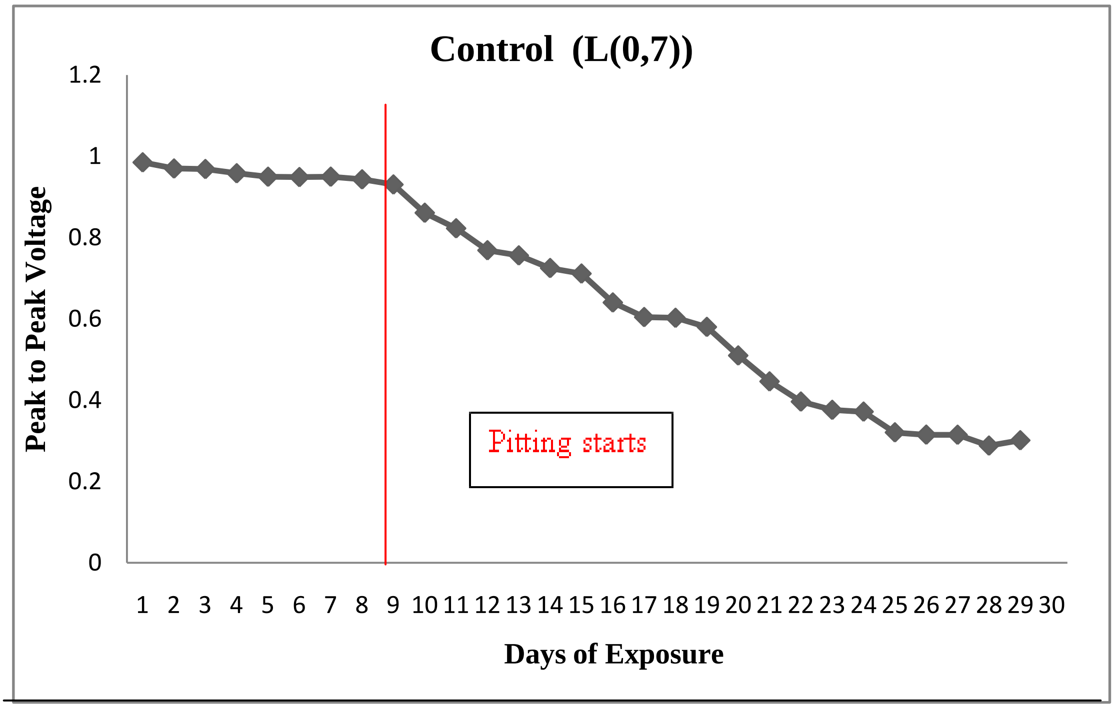


Fig.5.4 : P-T trends for Control sample using L(0,7) mode

Pulse Transmission (P-T) investigations

From P-T investigation of control samples subjected to accelerated impressed current,following observations are made:

- **Surface seeking mode L (0, 1) at 0.1 MHz**

From **Fig. 5.3,** it can be seen that the voltage amplitude of the transmitted signal increases rapidly with the progression of corrosion from 1-15 days which marks the delamination of the rebar due to corrosion. Initially, the reinforcing bar has a good bond with the surrounding concrete. As the corrosion takes place, it results in the formation of corrosion products and gets deposited on the length of bar. This delaminates the rebar from the surrounding concrete. Therefore, as the corrosion progresses, the delamination keeps on increasing which creates a barrier around the rebar and the leakage of the signal ceases. Due to this, the signal keeps on increasing with the increasing rate of corrosion. This is well depicted by the signal rise in initial 13 days of corrosion.

Thereafter corrosion ingresses into the bar and pitting starts causing drop in signal after 13-28 days. Hence, using surface seeking mode L(0,1), initial delamination in first 13 days is well picked up, marked by signal rise. Thereafter, pitting of rebar starts causing drop/attenuation of signal till the end of exposure duration.

- **Core seeking mode L (0, 7) at 1 MHz**

From **Fig 5.4**, it can be seen that initially the transmitted pulse strength is very high. Till 9 days,at the core seeking mode,the peak does not fall. But as the corrosion progresses from 9-28 days, the transmitted signal starts falling. The transmitted signal keeps on falling till it vanishes completely at 28 days. Initially when the corrosion starts, it first delaminates the bar completely from the surrounding concrete. As it progresses further, it starts penetrating into the bar and is marked by the local loss of area in the form of pitting and crevices of the bar which are detected by the core seeking mode. The reduction in the area of the bar due to corrosion causes fall in the amplitude of the signal and the transmitted pulse. There is no drop in initial 9 days and then the signals drops consistently indicating pitting of bar well picked up by L(0,7) mode.

Hence, corrosion of RC slab specimen from 1-13 days is well picked up by the two modes. Initial delamintion is picked by L(0,1) mode whereas pitting is dominantly picked up by L(0,7) mode from (13-28 days). These two modes will be further used for monitoring active protection provided by CFRP wraps.

5.2.2 Ultrasonic Monitoring in Actively Protected samples

- **Surface seeking mode L(0,1) at 0.1MHz**

The following are the **P-T** trends of APC-3,APC-6 & APC-9 specimens using surface seeking L(0,1) mode where APC refers to actively protected corrosion & 3,6 & 9 refers to days of exposure to corrosion acceleration before wrapping with CFRP. **Fig.5.5, 5.6 & 5.7** are the transmitted pulse trends for APC-3,6 & 9 sample using L(0,1) mode.

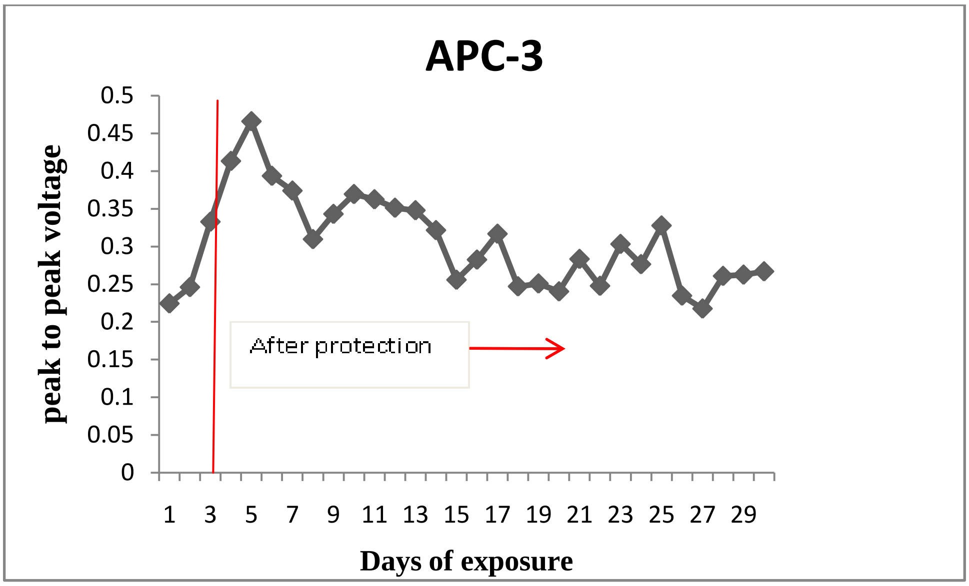


Fig. 5.5: P-T Trends using L(0,1) mode for actively protected samples after 3 days of corrosion by CFRP

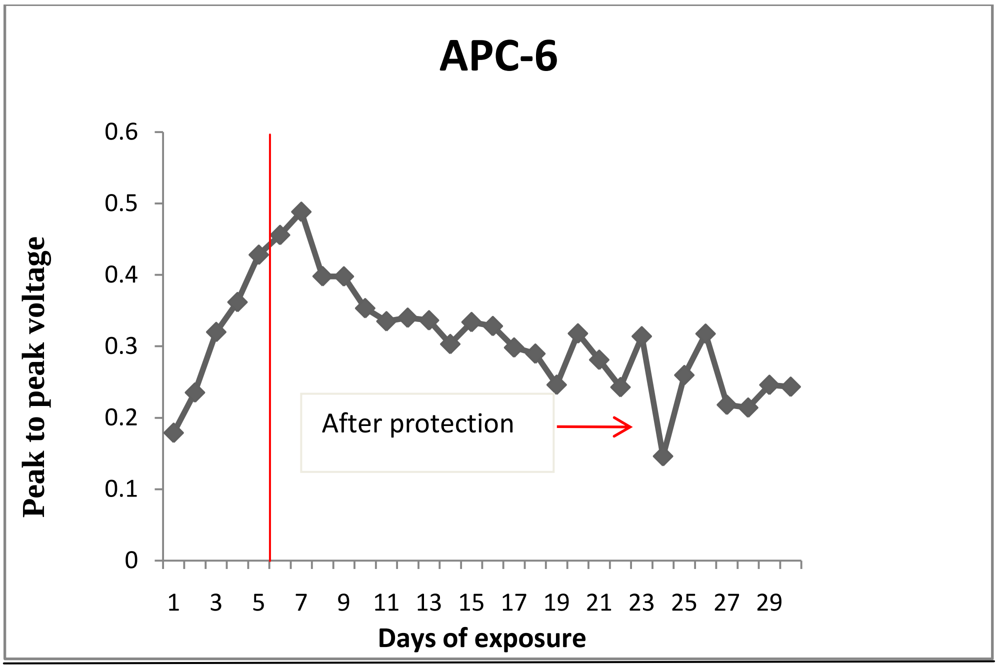


Fig. 5.6: P-T Trends using L(0,1) mode for actively protected after 6 days of corrosion by CFRP

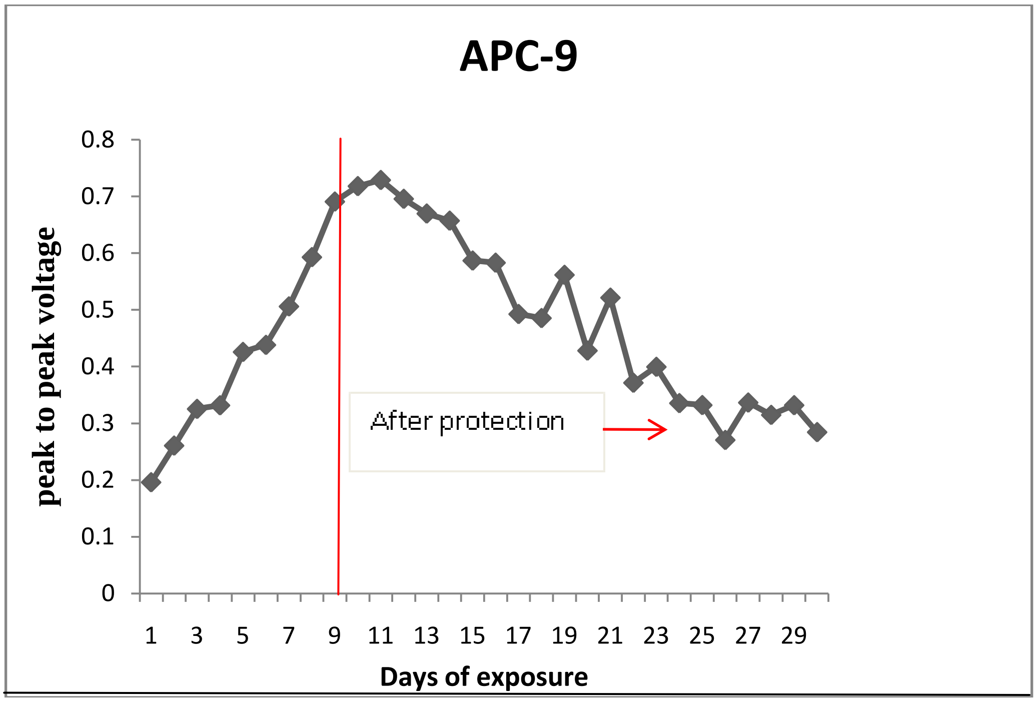


Fig. 5.7: P-T Trends using L(0,1) mode for the specimens actively protected after 9 days of corrosion by CFRP

From the graphs shown in **Fig. 5.5, 5.6** and **5.7**, following observations are made:

1. The peak of amplitude voltage signal rises with the propagation of corrosion upto respective days of corrosion with surface seeking modes. In APC-3,APC-6,APC-9, the signals rises upto 3,6 & 9 days until corrosion progresses as in control sample.
2. After the protection, there is a fall in the signal strength . Surface seeking waves could pick up the active protection provided by CFRP. Hence,in APC-3,APC-6 & APC-9, L(0,1) signal which rises till 13 days in control sample,starts falling immediately after 3,6 & 9 days of active protection offered by wrap.
3. The fall of signal with active protection using CFRP is large and huge in actively protected structures indicating the effectiveness of L(0,1) mode in picking up protection offered by CFRP wraps against corrosion.

This indicates that active protection offered by CFRP impedes the corrosion and delamination stops immediately after wrapping. Active protection offered by CFRP wrapping not only confines the concrete but also prevents the further corrosion.

- **Core seeking mode L (0, 7) at 1 MHz**

The following are the **P-T** trends of APC-3,APC-6 & APC-9 specimens using surface seeking L(0,7) mode where APC refers to actively protected corrosion & 3,6 & 9 refers to days of exposure to corrosion acceleration before wrapping with CFRP. **Fig.5.8, 5.9 & 5.10** are the transmitted pulse trends for APC-3,6 & 9 samples using L(0,7) mode

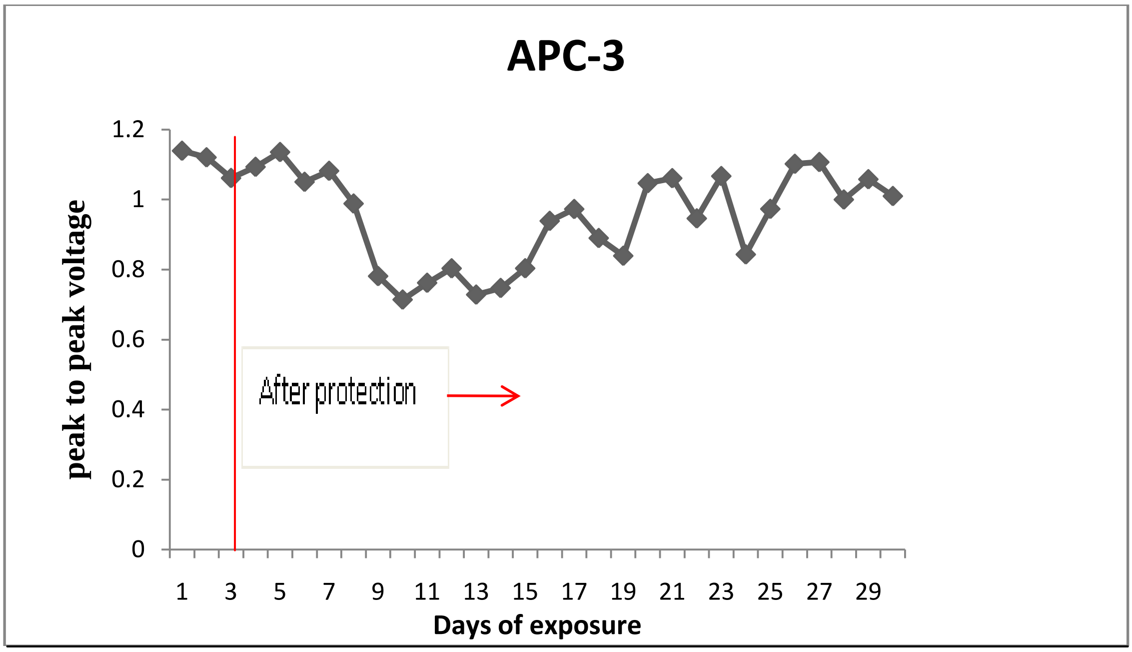


Fig. 5.8: P-T Trends using L(0,7) mode for the specimens actively protected after 3 days of corrosion by CFRP

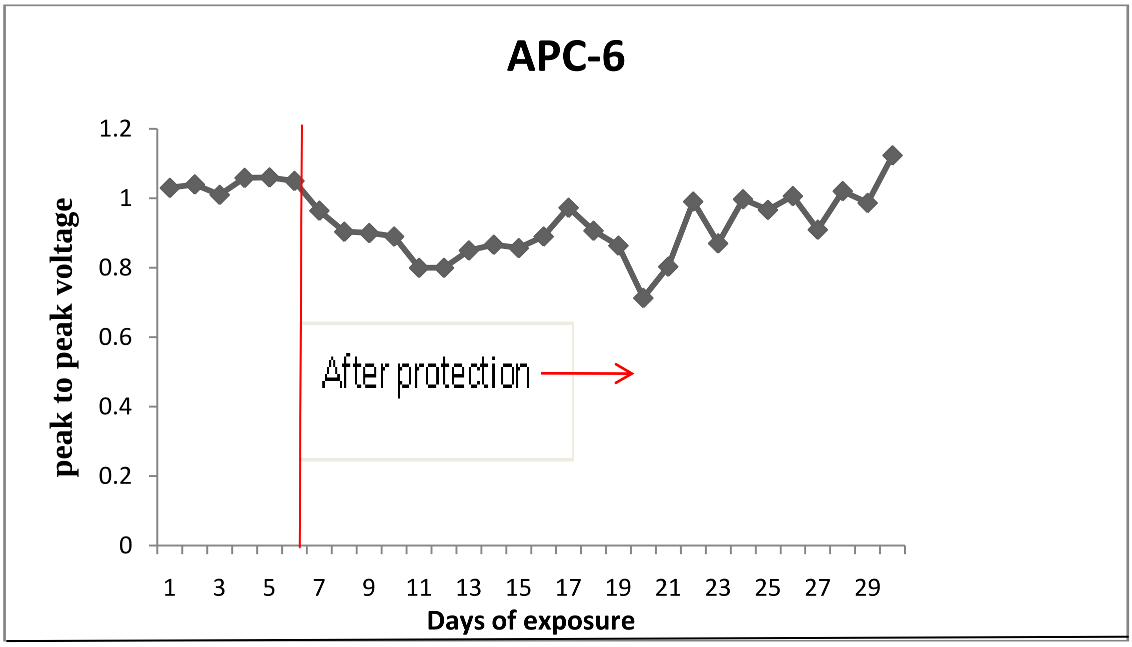


Fig. 5.9: P-T Trends with L(0,7) mode for the specimens actively protected after 6 days of corrosion by CFRP

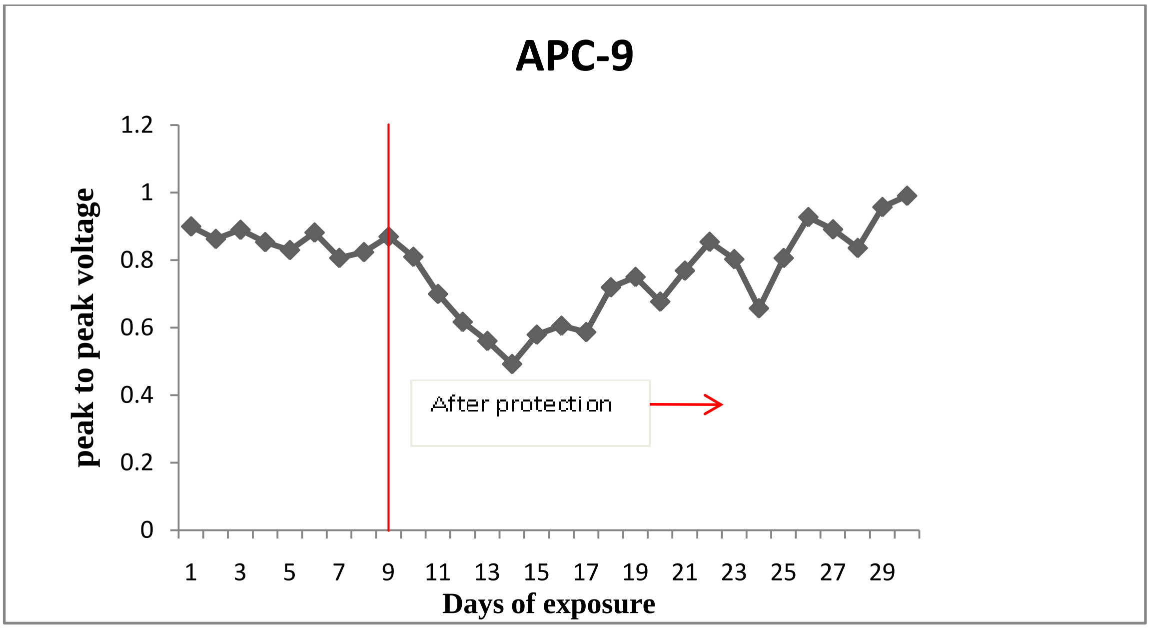


Fig. 5.10: P-T Trends with L(0,7) mode for the specimens actively protected after 9 days of corrosion by CFRP

From the graphs shown in Fig**. 5.8, 5.9, 5.10**, following observations are made with L(0,7) mode:

1. Before active protection, signal remains almost constant upto 3, 6 & 9 days respectively as in control sample where it remains constant till 9 days.
2. In APC-3,after active protection is applied, the fall in the peak is not so drastic as in the control sample. But the peak starts rising again after 15 days of active protection.
3. In case of APC-6, there is not so steep fall in the peak after active protection as in control sample and it starts rising from 20 days of protection. Similarly,in APC-9,the fall in L(0,7) signal due to pitting falls but not so steeply as in control sample. But after 16 days after the active protection causes signal indicating the effect of active protection preventing pitting of rebar.

   Hence,due to active protection using CFRP wrapping ,the L(0,7) mode points towards slow effect of pitting due to corrosion. The signal fall is not drastic as in control samples but starts rising indicating the positive effect of CFRP active protection which impedes corrosion.

5.3 Observations

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 L(0,1) mode, 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 L(0,7) mode is used for monitoring the peak of signal decreases with increase in corrosion but not so drastically as in control samples but after wrapping the signal starts rising after sometime.

Hence,ultrasonic guided waves using both L(0,1) and L(0,7) modes can effectively not only pick up onset and progression of corrosion but also protection offered by active protection using CFRP wraps. CFRP provides active protection successfully and impedes corrosion. It is well guided by guided waves. It can go a long way in developing a non-destructive monitoring methodology for RC structures.

5.4.1 Destructive Test Measurements

5.4.1 Pull-out strength test : Destructive pull-out strength test is performed when the specimen has been subjected to exposure of corrosion for respective days and protected actively. This was done by securing the slab in a Universal Testing Machine (UTM) and attaching the grip to the protruding portion of the reinforcing bar.

Table 5.1 & Fig.5.11 shows that from the pull-out strength observation, it is observed that the pull out strength of control sample is highest due to confinement offered by concrete which increases the force required to pull out the reinforcing bar.

Table 5.1: Pull-out strength measurements for all the specimens

Specimen	Pull-out Strength (MPa)
Control	7.82
APC-3	5.8
APC-5	5.93
APC-9	6.14

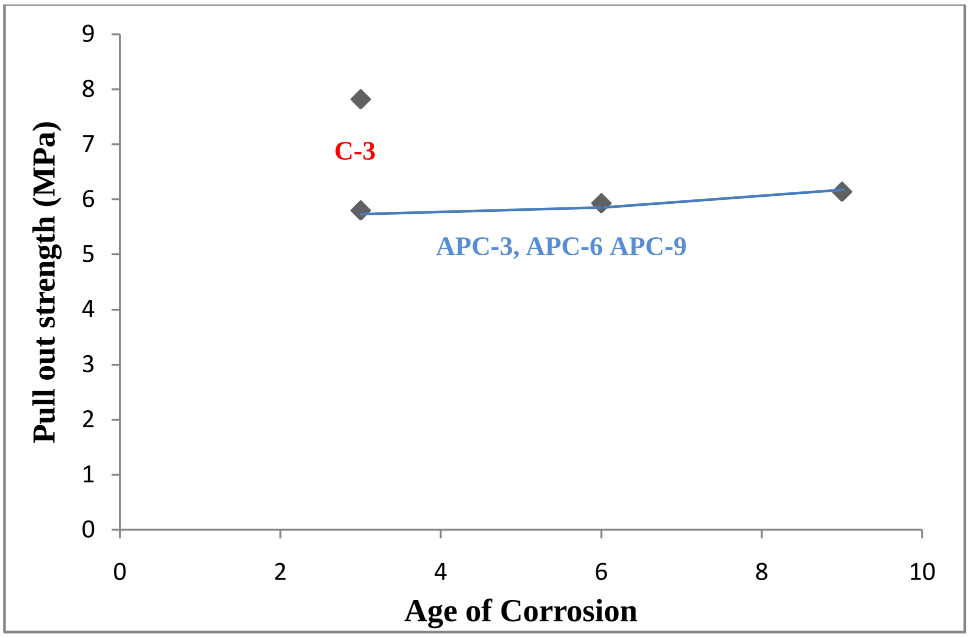


Fig. 5.11: Variation of pull-out strength with corrosion for all specimens

As the samples are wrapped with CFRP and active protection is done, the Pull out strength decreases significantly as compared with the control sample. This is basically due to continuous flow of current due to active protection which softens the C -S-H gel in concrete and the compressive strength and durability of concrete is reduced. It has also been proven that the alkali silica reaction would be accelerated by protection current. This causes decrease in pull-out strength with active protection. In APC-3,the sample is actively protected for larger no. of days and hence pull-out strength is minimum. In APC-9,the protection is offered for least number of days so pull-out strength is highest. This illustrates the effectiveness of active protection.

5.4.2 Mass Loss: After carrying out the pull-out test, the extracted bars were cleaned of all corrosion products and weighed to determine their mass loss. **Table5.2** shows the variation in mass loss for different samples.

Table 5.2: Mass loss measurements for all the specimens

Specimens	Mass loss (%)
Control	5.9
APC-3	1.11
APC-6	1.9
APC-9	2.35

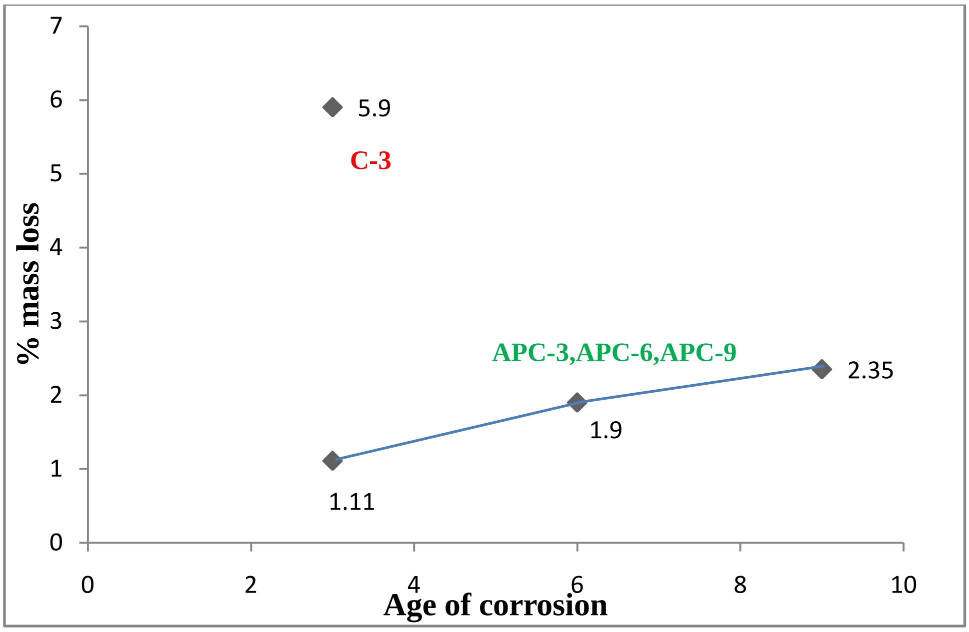


Fig. 5.12: Variation of mass loss with corrosion for all specimens

From **Table 5.2** and graph in **Fig. 5.12**, following conclusions can be drawn from the mass loss tests :

1. For control sample, mass loss is highest which is simply because of easy ingress of chloride ions and due to the absence of any physical barrier by wraps since it is unwrapped. It experiences maximum corrosion and hence maximum mass loss.
2. For actively protected samples, the mass loss decreases in comparison with the control sample. This implies that the active protection has been able to decrease the rate of corrosion i.e., active protection is effective in impeding and slowing down the progression of corrosion.
3. Comparison of variations in mass loss and pull out strength for all specimens show that pull out strength varies directly with the mass loss. Due to corrosion, the bars exert a bursting pressure on the concrete and the bond strength is maximum for control sample. Thus, for the success of active protection technique, it is imperative that an optimum protection current density is achieved such that the loss of bond strength is avoided. But active protection causes fall in bond strength due to C-S-H gel. But as the days of protection increases,pull out strength also increases indicating the increase in affect of active protection. Similarly it happens with the mass loss.

5.5 Closing Remarks

The experiments conducted in this research establish the effectiveness of ultrasonic guided waves methodology for monitoring the progression of corrosion and also of the protection to corrosion offered by CFRP wraps against corrosion.

CHAPTER 6

CONCLUSIONS

From the results obtained from ultrasonic investigation and destructive tests carried out in this research work for evaluating the efficacy of ultrasonic guided waves to monitor actively protected RC structures from corrosion using CFRP wraps can be summarized as follows :

1. Ultrasonic guided waves has proven to be very effective in monitoring the actively protected RC structures from accelerated corrosion using CFRP sheets.
2. The surface seeking modes and the core seeking modes are very much able to explain the behavior of RC specimens undergoing accelerated corrosion and also when subjected to active protection by CFRP wraps. Corrosion of RC control slab specimen in 12 days is well picked up by the two modes. Initial delamintion is picked by L(0,1) mode whereas pitting is dominantly picked up by L(0,7) mode from (13-28 days). These two modes will be further used for monitoring actively protected slabs by CFRP.
3. Active protection offered by CFRP impedes the corrosion and delamination stops immediately after wrapping. Wrapping not only confines the concrete but also prevents the further corrosion.
4. After the protection,there is a fall in the signal strength. Surface seeking waves could pick up the active protection provided by CFRP. Hence,in APC-3,APC-6 & APC-9, L(0,1) signal which rises till 13 days in control sample,starts falling immediately after 3,6 & 9 days of active protection offered by wrap.The fall of signal with active protection using CFRP is large and huge in actively protected structures indicating the effectiveness of L(0,1) mode in picking up protection offered by CFRP wraps against corrosion.
5. Due to active protection using CFRP wrapping ,the L(0,7) mode points towards slow effect of pitting due to corrosion. The signal fall is not drastic as in control samples but starts rising indicating the positive effect of CFRP active protection which impedes corrosion.
6. Although the active protection proves to be superior to other methods of protection but the pull out strength in this case is lower. This indicates the poorer bond strength between concrete and steel. Prior literature has also reported loss of bond because of active protection and postulated the softening of interface as responsible phenomenon.

7. Results from destructive tests also show that the active protection has successfully been able to impede the process of corrosion to a great extent. The mass loss in the case of control samples is far greater than the protected samples.

FURTHER SCOPE OF WORK

Comparison of various NDT like AET,UGW and electrochemical monitoring corrosion under various environments and in different types of concrete,like slag furnace concrete,silica fume ,etc.

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