"ULTRASONIC MONITORING OF ACTIVELY AND PASSIVELY PROTECTED RC STRUCTURES"

A thesis submitted in partial fulfilment
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Submitted by:

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DECLARATION

The author hereby declares that this thesis entitled **"Ultrasonic Monitoring of Actively and Passively Protected RC Structures",** in whole or part, has not been used to obtain any degree in this, or any other, institute. Except where references have been given in text, it is entirely the authors own work.

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This is to certify that the thesis entitled **"Ultrasonic Monitoring of Actively and Passively Protected RC Structures"** being submitted by Mr. Ashutosh Sharma, Roll No. 801122001 in partial fulfilment for the award of degree of **Masters of Engineering in Structural Engineering** at **Thapar University, Patiala** is a bonafide work carried out by him at **Thapar University, Patiala**, under my guidance and supervision and that no part of this thesis has been submitted for the award of any other degree

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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.

Guided ultrasonic waves offer a potentially attractive solution. In the present study, bars embedded in concrete are subjected to corrosion and also protected with FRP‘s (CFRP and GFRP). These materials have received great attention and their applications to structural repair and retrofit have grown significantly in recent years. CFRP and GFRP fabrics are largely employed because it offers superior performance such as resistance to corrosion, high stiffness- to-weight ratio, high tensile strength, light weight, high durability and easy installation etc.

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 Echo 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 picking up the behaviour of RC Structures when subjected to corrosion and also after protection.

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CHAPTER 1

INTRODUCTION

1.1 GENERAL

Reinforced concrete is one of the most commonly used construction material worldwide. High tensile strength, high stiffness, durability, cost-effectiveness are some of the significant attributes of reinforced concrete that makes it indispensible element in most concrete structures existing today. Many RC structures have given excellent service with minimal maintenance. However, as the structures are exposed to environment , many construction and design problems arise with time, that severely reduce the strength and life of these structures leading to higher maintenance cost than originally envisaged. Some of the problems being faced by RC structures these days are aggressive chemicals such as sulphates and other gases released from the industries in the environment, attack by acid rain, reaction with chlorides and carbon dioxide present in the nature resulting in corrosion, etc. The worst problem that affects the durability of structures is the corrosion of the reinforced steel in concrete .When the reinforcement such as steel is embedded in the concrete, highly alkaline environment is provided by NaOH, KOH and $Ca(OH)_2$ present in the freshly mixed concrete. A passive film is formed around the steel with a pH of around 13 that acts as a protective layer from corrosion. The passivity of the structures is affected mainly by the presence of chlorides and carbonates in the atmosphere. The chloride comes from the de-icing salts sprayed on the marine structures, roads or bridges and, the carbonates come from carbon dioxide present in the atmosphere and carbon emissions by the industries. These atmospheric pollutants (chlorides and carbon dioxide) penetrate into the concrete and once they cross the threshold, they decrease pH of the pore solution at reinforcement depth from 13 to 12-8.5. The passive film is disrupted or destroyed and steel begins to corrode. The resulting corrosion products can take up a volume as much as six times that of the steel. The increased volume induces tensile stresses in the concrete that result in cracking, delamination and spalling of RC structures. The reinforced concrete structure gets weakened to a high degree along with an unpleasant appearance. Moreover, the bond between concrete and steel gets degraded.

The problems associated with corrosion in concrete structures are alarming in India as approximately 80 % of the annual rainfall takes place in two months of monsoon in northern India. The most affected areas are offshore structures, such as marine airports, platforms, bridges, harbours, tunnels and vessels are exposed to harsh marine environment such as tides, storms etc. Typically, restoration work is needed within 15 years of constructing a building in the coastal region. The overall repair and maintenance of RC structures due to reinforcement corrosion cost 1-2 % of the yearly rate of new construction. Thus, corrosion is an obstacle in the economic development of the country. Corrosion is an unavoidable problem being faced by the cement and concrete industry these days and is a matter of great concern. Hence, it becomes necessary to understand the causes of corrosion and how structures can be protected from it.

1.2 AIMS AND OBJECTIVES

It is an established fact that FRP (CFRP and GFRP) protects the reinforced concrete structure from corrosion. The aim of this study is to evaluate the efficacy of ultrasonic guided waves to pick up corrosion of RC cylindrical specimens, when subjected to accelerated chloride corrosion. The guided waves were then used to investigate FRP protected specimens against corrosion. The specimens were both actively and passively protected against corrosion.

1.3 CORROSION MONITORING OF RC STRUCTURES

Due to the adverse consequences of corrosion in RC structures, it is necessary to delay the effect of corrosion as it can’t be stopped. The growing problems in a newly constructed or existing RC structure emphasize the need of corrosion monitoring. Corrosion monitoring or corrosion measurement is a quantitative method that evaluates the effectiveness of corrosion control and prevention methods. The conventional method of visual inspection of corrosion monitoring is based on observing visual symptoms such as cracking, delamination and spalling of concrete cover and, taking the desirable action to delay corrosion. This method is not reliable as corrosion might onset on the reinforced steel much before the visibility of symptoms. There are some alternate techniques of corrosion monitoring that conduct a condition survey on the RC structure suffering from reinforcement corrosion. These techniques can be used in isolation or combination and can be associated with snapshot surveys to give a complete view of the changing condition of structure in time as well as in the three physical dimensions of structure. The rate of deterioration of a structure with time can be observed by embedding corrosion monitoring devices on a new or existing RC structure.

There are a number of devices available in the market to investigate corrosion problems. Each device has a different function and is chosen depending on the requirement of engineer. Corrosion monitoring systems are useful in serving the long lifetime requirements of new structures and in delaying corrosion damage in older structures. These techniques are applied before embarking on repair or rehabilitation of the structure. The corrosion monitoring techniques are classified as non-destructive testing (NDT) techniques and destructive testing (DT) techniques.

The various non-destructive testing techniques for corrosion monitoring are:

- Visual Inspection
- Infrared thermograph Electrochemical measurements
- Open Circuit Potential (OCP) measurements
- Surface Potential (SP) measurements
- Concrete Resistivity measurements
- Linear Polarisation Resistance (LPR) measurements
- Galvanostatic pulse transient method
- Electrochemical Impedence Spectroscopy (EIS)
- Embeddable Corrosion monitoring sensor
- Cover thickness measure
- Ultrasonic pulse velocity techniques
- X-ray, Gamma Radiography measurement

Non-destructive testing techniques monitor material quality without destroying the specimen. Among all non-destructive techniques mentioned above, ultrasonic testing is the most widely used techniques used to measure a variety of material characteristics and conditions. Ultrasonic testing is performed using a device that generates ultrasonic waves with a piezoelectric crystal at a frequency greater than 20 kHz into the piece being examined and analyses the transmitted or reflected signal. The measurements include time taken by signal to locate the defect and, attenuation of transmitted or reflected signal to quantify the defect In this work, it is proposed to use ultrasonic measurements as NDT for monitoring corrosion.

Destructive techniques result in accurate measurements and give specific characteristic of materials by destroying the specimen. Pull out strength, mass loss and compression tests are some of the examples. The inspection of structures using these techniques is limited and costly. So, NDT techniques are preferred over DT techniques to provide valuable and often critical information for same operation of complex systems.

1.4 FRP REPAIR OF RC STRUCTURES

To protect reinforced concrete structures form early damage, several rehabilitation techniques have been identified during the last three decades. Earlier concrete structures were repaired by jacketing with new concrete epoxy bonded steel plates. But this adversely affects the bond between steel plate and concrete because of corrosion. Moreover, such equipments are heavy, difficult to install, and have durability problems. Thus, alternative materials are required. Fibre Reinforced Polymer is one such material that is commonly used for the repair and rehabilitation of corroded RC structures. The use of FRP in the newly constructed structures and, in the repair of corrosion damaged structures has proven to be successful in various investigations. Following properties of FRP are responsible for its extensive use in RC structures –

- Resistance to aggressive corrosion effects of acids, alkalis, salts and similar aggregates under a wide range of temperature
- High strength to weight ratio
- Resistance to electrochemical /electromechanical deterioration
- Easy bondage to reinforced concrete members resulting in a negligible increase in cross-sectional dimensions.

FRP sheets are wrapped around the concrete surface with an epoxy resin. The FRP wrapped structure delay the onset of corrosion to a great extent. The FRP cover enhances the bending capacity and shear capacity of flexural elements and concrete confinement in compressive elements. FRP wraps prevent any further increase in volume by applying confinement pressure on concrete, thus resisting dislodging of concrete cover. Moreover, they are less susceptible to environmental deformation, exhibit increased durability, increased ductility and an improved seismic performance. In addition, FRP is a product of easy installation, high chemical resistance while having a minimum architectural impact. Therefore, it is a commonly used material for the protection of reinforced steel from corrosion. Two common types of FRP materials used are Glass Fibre Reinforced Polymer (GFRP) and Carbon Fibre Reinforced Polymer (CFRP).

GFRP sheets provide passive protection from reinforcement corrosion. GFRP wraps act as a barrier layer that impedes further corrosion of steel. They also compensate the lost steel and improve the confinement of concrete. The barrier layer provided by GFRP slows down the rate of corrosion to a great extent and increase the strength of structure.

CFRP sheets are utilized to provide passive as well as active protection from reinforcement corrosion. CFRP materials are electrically conductive and because of this property, they can be used for active protection. Active protection is provided by passing a reverse current that enables the reinforcement to act as a cathode and CFRP wrap as the inert anode, thus delaying the corrosion of reinforced steel. The decrease in corrosion rate is comparatively more in case of actively protected CFRP wrapped structures than GFRP wrapped structures. Moreover, CFRP sheets are thinner, exhibit greater tensile strength and, tensile modulus as compared to GFRP sheets. But GFRP wraps provide higher electrical resistance in passive protection of reinforced steel. Therefore, both CFRP and GFRP sheets are used in concrete industry depending on the application as they prevent atmospheric pollutants (chlorides, carbon dioxide) to penetrate into the concrete.

The number of FRP wraps and the type of epoxy contribute in further delay of corrosion rate (*Spainhour and Wootten, 2008*). Although, impressed cathodic current method has been suggested as the only effective corrosion preventive method for a contaminated reinforcing concrete member, there exists possible side effects such as bond degradation between steel and concrete (*Chang, 2002*) and hydrogen embrittlement of the high strength steel (*Kim et al., 2003*). *Chang (2002)* investigated that the physical and chemical inhomogeneities and instabilities inherent to the concrete material, may lead to non-uniform distribution of cathodic protection currents and results in localised overprotected areas. The need to preserve the appearance (colour and texture) of the surface and the authenticity in case of historical monuments and other cultural heritage has prevented the use of traditional way of cathodic protection with a distributed anode as the concrete would be covered by the anodic system and its surface would be altered. In this work, the performance of both GFRP sheets and CFRP sheets in delaying the onset of corrosion is observed.

1.5 FORMAT OF THESIS

The thesis has been divided into six chapters.

1st chapter is general introduction of corrosion in RC structures, its monitoring and FRP repair of structures through active or passive protection.

2nd chapter explains in detail the process of corrosion in RC structures, types of corrosion of steel, non-destructive and destructive techniques used for corrosion monitoring, utilization of FRP sheets for corrosion protection and a thorough review of literature on corrosion monitoring techniques as well as FRP wraps.

3rd chapter explains in detail the use of ultrasonic guided waves for structural health monitoring, its modes of propagation, pulse-echo and through methods for ultrasonic testing, some limitations of ultrasonic guided waves and a thorough review of literature on feasibility of ultrasonic guided waves for monitoring of rebar corrosion in concrete.

4th chapter deals with the experimental program wherein all tests, procedures and measures to be followed during experiments are explained in detail.

5th chapter deals with the results and discussions where findings of the experimental program are explained in detail.

6th 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 CORROSION IN REINFORCED CONCRETE

This section explains the initiation of corrosion, its causes, mechanism and common corrosion types.

2.1.1 General

Corrosion of steel in reinforced concrete structures is one of the major obstacles and economic issues faced by concrete industry. It is a threat to the durability of structures. Due to widespread use of RC structures, this problem is so common and has become unavoidable. Normally, the reinforcement (steel) is unaffected by corrosion as concrete ordinarily provides high alkaline environment. Because of the high alkalinity, a thin invisible protective passive film of ferric oxide (Fe_2O_3) with a thickness of approx. 10000 A^o is formed on the steel. When the embedded steel is protected from air by a thick covering of low permeability concrete, it is expected that the corrosion of steel would not arise. But this expectation is not fully met in practice and this is evident from the damage caused in RC structures due to steel corrosion.

The reinforcement corrosion is initiated when the protective layer formed on steel is depassivated and the porosity of concrete is increased. Once it is initiated, it affects both the steel and the concrete. The cross-sectional area of the steel bar reduces eventually due to the formation of expansive corrosion products that create tensile stresses. This introduces notches on the surface of steel bar and results in the reduction of strength and ductility of corroding steel bar. The expansion of the corrosion products also affects the internal structure of concrete resulting in spalling and cracking of the concrete cover (**Fig. 2.1**).

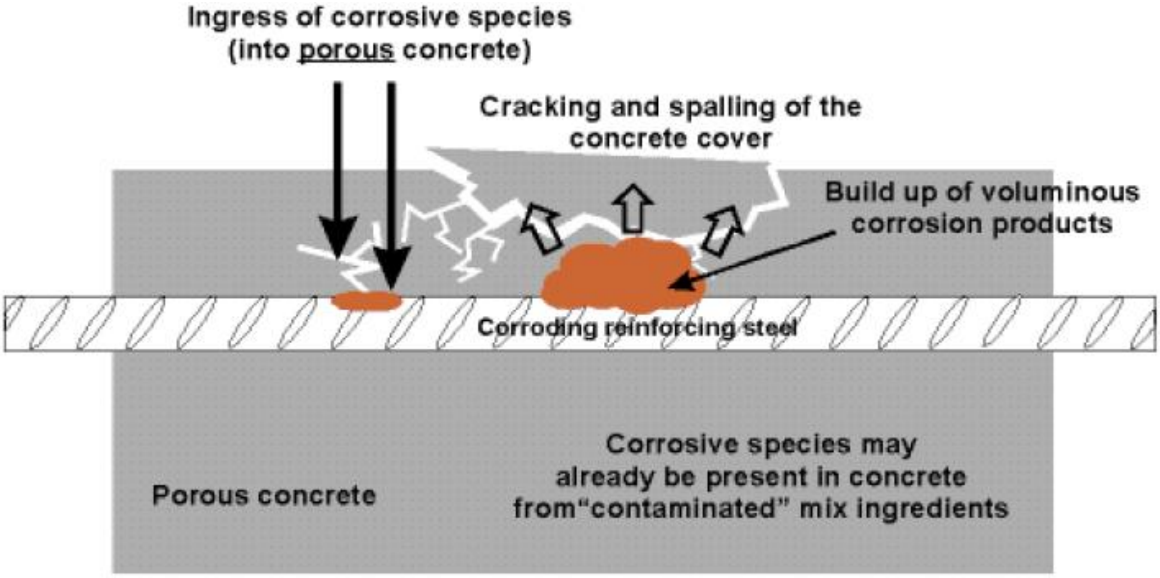


Fig. 2.1: Cracking and spalling of concrete cover due to corrosion of reinforcement (*Ahmad and Shabir, 2005*)

Finally, the lubricant effect of corrosion products and cracking of concrete cover cause bond deterioration at steel-concrete interface which reduces the load carrying capacity and service life of RC structures resulting in a severe damage (*Maaddawy and Soudki, 2005*). **Fig. 2.2** shows the effects of steel corrosion on concrete structures.

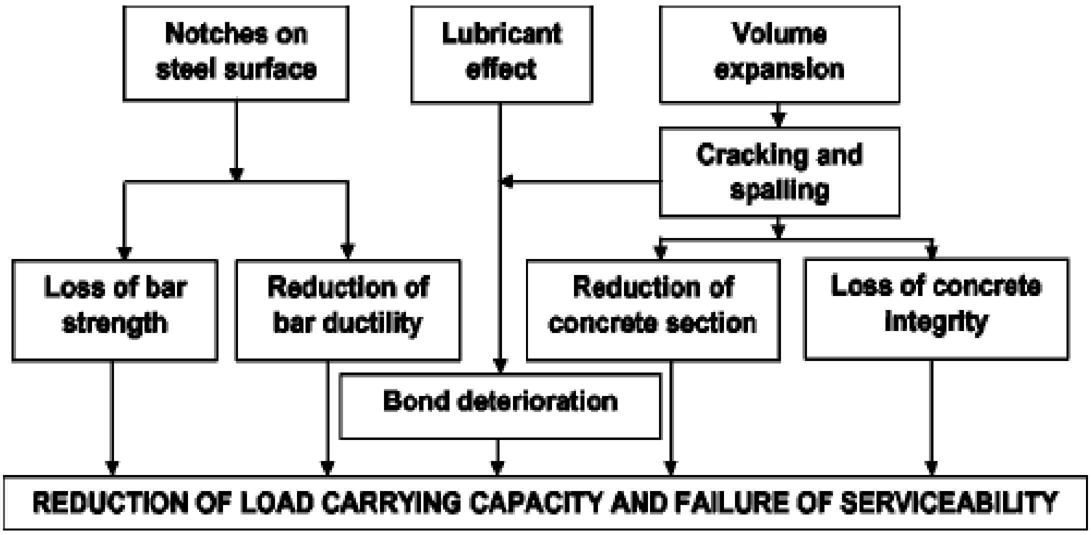


Fig. 2.2: Effect of steel corrosion on concrete structures (*Maaddawy and Soudki, 2005*)

2.1.2 Causes of Rebar Corrosion

The corrosion behaviour of reinforced steel in concrete is determined by the composition of pore solution of concrete and chemical properties of steel. The concrete parameters other than pore solution composition, also affect rebar corrosion. The environmental factors do not directly affect steel corrosion, but cause damage to concrete cover and accelerate the ingress of aggressive species, making pore solution in contact with concrete more corrosive. Among all the environmental factors, the two most important factors responsible for corrosion of steel in concrete structures are the chloride ions and carbon dioxide. Other factors such as temperature, moisture etc. are also responsible for steel corrosion and causes deterioration of reinforced concrete structure. The corrosion of steel in concrete is not determined by a single factor, but the influence of many other factors are also considered. The various factors that are responsible for rebar corrosion are:

1. ***Chlorides:*** Chlorides in concrete is a major cause of steel corrosion. Most of the damage caused in RC structures is due to chloride induced steel corrosion. Chloride enters into the concrete by deliberate addition of chloride as accelerators, use of water containing chloride and contaminated aggregates. The chlorides can also penetrate into concrete through sea-salt spray and direct sea water wetting, de-icing salts and use of chemicals. The ingress of chloride ions lead to a loss of alkalinity of concrete cover and a decrease in pH. Normally, the chloride is present in concrete in two forms :
    - Free chloride, dissolved in pore solution.
    - Bound chloride, absorbed on cement gel or combined with hydrated cement and aggregates.

    As a result, the protective layer around the steel is depassivated and corrosion is initiated. The corrosion of steel is accelerated by the free chloride .The bound chloride is inert to steel before it is dissolved into solution and becomes free chloride. The chloride binding in concrete can be altered by varying factors such as hydroxide concentration in concrete and temperature. The higher is the hydroxide concentration, lower will be the formation of chloride in pore solution. Similarly, higher the temperature, lesser will be the chloride binding capacity. It has been reported that chloride binding is also affected by the kind of sulphate present in cement paste. *Jing and Yao (2010)* investigated that the cement paste containing calcium sulphate has a higher chloride binding capacity than those containing sodium sulphate. As a result, sodium sulphate increases the alkalinity of pore solution and calcium sulphate decreases it. A low concentration of chloride ion in the pore solution does not break the protective passive film around steel. The corrosion of steel is initiated when the chloride content exceeds a certain limit of concentration, called chloride threshold. Once the chloride threshold is crossed, severe damage is caused to reinforced steel and concrete. Federal Highway Administration (FHWA) studies have found that a threshold of 20% chloride by weight of cement could induce corrosion of reinforcement.

2. ***Carbon Dioxide:*** CO_2 is another main cause of steel corrosion. CO_2 present in the atmosphere, penetrates into the concrete and reacts with hydroxides, such as $Ca(OH)_2$ to form carbonates.

$$Ca(OH)_2 \quad + \quad CO_2 \longrightarrow CaCO_3 \quad + \quad H_2O$$

The reaction of carbon dioxide with calcium hydroxide gives calcium carbonate. This reduces the pH of pore solution to as low as 8.5 and affects the stability of passive film on steel.

Carbonation is generally a slow process. However, certain parameters such as high water to cement ratio, low cement content, short curing period, low strength and highly porous paste play a key role in increasing the amount of carbonation. The carbonation of concrete also depends on relative humidity of concrete. The carbonation rate is highest when relative humidity is between 50-70%. The corrosion of steel due to carbonation of concrete often occurs on areas of building that are exposed to rainfall, shaded from sunlight, and have low concrete cover over the reinforcing steel.

3. ***Contact of dissimilar metals:*** Corrosion can occur when two different metals are in contact within concrete for e.g., when Al and steel are in contact and the moist paste of concrete acts as an electrolyte, the current flows. A list of metals in order of electrochemical activity is given below:
   - Zinc

- Aluminium
- Steel
- Iron
- Nickel
- Tin
- Lead
- Brass
- Copper
- Bronze
- Stainless Steel
- Gold

When the metals are in contact in an active electrolyte, the metal that is less active in electrochemical series corrodes. Dissimilar metal corrosion is usually found in balconies where embedded Al railings are in contact with reinforcing steel.

4. ***Moisture:*** There are many factors that lead to moisture migration in structures such as improper design, shoddy construction, or neglected maintenance. Moisture can migrate into a structure through concrete floor slabs, basements walls and flat slab ceilings (*Day, 1996*). In most cases, the moisture that penetrates into the concrete contains dissolved salts and can cause severe damage. Moisture of concrete plays a major role in the corrosion of reinforcing steel. The moisture content also affects the electrical resistivity of concrete and results in the penetration of chloride and carbonates.
5. ***Type of steel:*** The type of steel used for reinforcement in concrete structure also affects the rate of corrosion. Stainless steel is more resistant to corrosion in comparison to plain steel and show much lower corrosion rate. Moreover, excellent corrosion resistance is shown by stainless steel in severe chloride environment. However, stainless steel is expensive and is used only in those concrete structures that don’t permit corrosion. The increase in initial cost is compensated by less maintenance costs and fewer repairs.

6. ***Pore solution of concrete:*** The pore solution of concrete is an electrolyte that is physically absorbed in the pores of water .It contains several ions such as calcium, potassium, sodium, hydroxyl, sulphate and sulphite etc. and the composition of these ions depends on the cement used. The chemical composition of the pore solution affects the conductivity of concrete and can initiate corrosion process. If the water to cement ratio of concrete is more than 0.6, then the structures show lower compressive strength and shorter service life (*Ahmad and Shabir, 2005*). When the pore solution is polluted by chlorides, corrosion process can occur if the chloride threshold exceeds.
7. ***Permeability of concrete:*** The permeability of concrete depends on the porosity of concrete and its pore size distribution. Higher the porosity of concrete, greater will be the corrosion damage caused to reinforced steel. The pores allow detrimental species from environment such as Cl^-, CO_2, O_2, H_2O to penetrate into the concrete. These species affect the corrosion process. However, if the permeability of concrete is low, then these species would find it difficult to react with steel and the possibility of reinforcement would be low. The water-cement ratio influences the porosity of concrete and thus its permeability. Higher the water-cement ratio, greater will be the permeability. Therefore, low water-cement ratio can improve the corrosion resistance of concrete.
8. ***Temperature:*** The corrosion rate is highly influenced by temperature. An increase in temperature leads to an increase in corrosion rate. A 10^o rise in temperature doubles the rate of corrosion of reinforcing steel. When the temperature increases beyond a certain limit, chloride concentration appreciably increases. As a result, reinforcement corrosion is initiated and this can lead to cracking of concrete cover.
9. ***Thickness and defects of Cover Concrete:*** The concrete cover around steel protects it from corrosion. The thickness provided by the cover, delays the ingress of aggressive species in concrete, thus delaying the corrosion process. Compact and defect-free concrete provides greater corrosion resistance to reinforcing steel. However, there are no defect free materials in practice and this is evident from the cracks in concrete cover. The cracks in concrete cover allow the atmospheric pollutants to penetrate into concrete

and react with reinforcing steel, thus causing corrosion. The cracked concrete cover is more vulnerable to corrosion than the un-cracked concrete cover.

10. ***Concrete Resistivity:*** The electrical resistivity of concrete, hardened cement paste and mortar also influence the corrosion rate of steel. Normally, the electrical resistivity of concrete is kept between 10^o to 10^7 ohm cm. It is determined by moisture and salt content, pore solution concentration, concrete microstructures (pore size and its distribution), temperature etc. Resistivity decreases with an increase in temperature. It also decreases with a high level of moisture and high concentration of chloride content in concrete. Lower the concrete resistivity, higher is the corrosion rate. (*Song and Saraswathy, 2007*)

2.1.3 Corrosion Mechanism

The corrosion of reinforcing steel in concrete is an electrochemical process .An electrochemical process involves transfer of electrons form one material (anode) to the other (cathode). When no external electrical source is present, two half cell reactions occur, one at the anode and other at the cathode. The anode produces electrons resulting in the oxidation of iron (Fe) and the cathode consumes these electrons i.e. reduction of oxygen takes place to form hydroxyl ions (OH^-). These half-cell reactions take place in the presence of an electrolyte. When these reactions occur close together, or at the same location, it is termed as microcell and when they take place at widely spread locations, it is termed as macrocell.

For any corrosion of metal, three basic processes take place which are as follows:

1. Depassivation reagents, such as dissolved oxygen at the medium surrounding the surface of metal, or H^+ ion present in the aqueous medium arrive at the surface of metal.
2. Electrochemical reactions (i.e. oxidation and reduction reactions) take place at the interface between metal and the medium surrounding it.
3. Some corrosion products are formed on the surface of metal or removed from its surface to medium. For e.g., Fe^{2+} and OH^- ions move into the aqueous solution by anode and cathode respectively and, passive film or

corrosion products are formed on the metal surface. The corrosion process can be stopped by the absence of any of the above process.

Fig 2.3 shows the mechanism of corrosion.

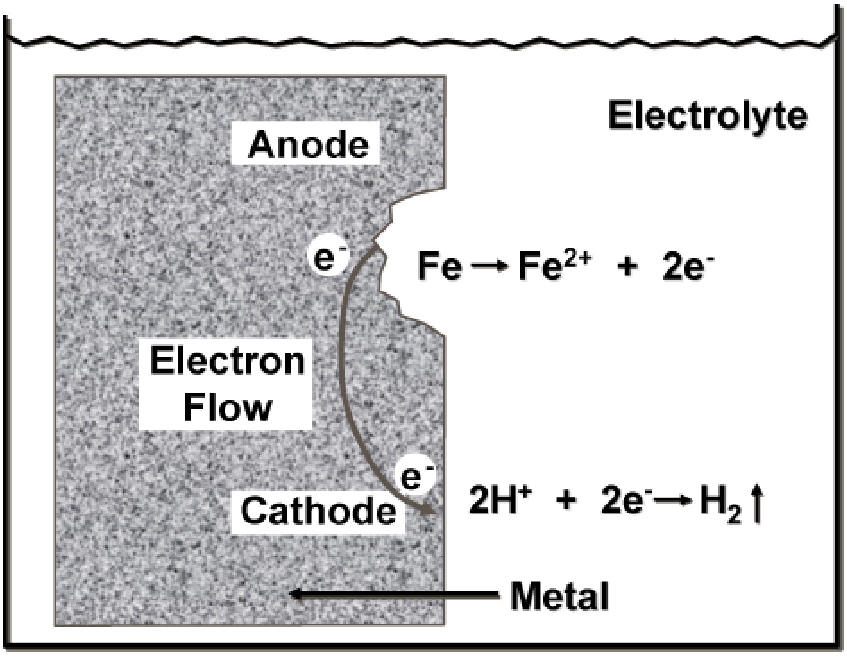


Fig. 2.3: Corrosion Mechanism (*www.octane.nmt.edu*)

The electrochemical half - cell reactions taking place are:

At Anode:

$$\left.\begin{array}{l} Fe \rightarrow Fe^{2+} + 2e^{-} \\ 2Fe^{2+} + 4OH^{-} \rightarrow 2Fe(OH)_2 \\ 2Fe(OH)_2 + \tfrac{1}{2}O_2 \rightarrow 2FeOOH + H_2O \\ Fe + OH^{-} + H_2O \rightarrow HFeO_2^{-} + H_2 \end{array}\right\} \quad (2.1)$$

At Cathode:

$$\left.\begin{array}{l} 2H_2O + O_2 + 4e^{-} \rightarrow 4OH^{-} \\ 2H^{+} + 2e^{-} \rightarrow H_2 \end{array}\right\} \quad (2.2)$$

The anodic reactions release intermediate corrosion product, Fe^{2+} into the solution continuously resulting in a loss of cross sectional area of steel bar. This may lead to external break down of the steel bar. Normally, the pH of pore solution ranges from 13 to 13.5 and only the first two anodic reactions take place. A protective passive layer is formed around the steel because of iron oxide Fe_3O_4 and Fe_2O_3. However, the ingress of chlorides and carbonates reduce the pH, depassivates the protective layer formed by oxides and initiates corrosion. Once the corrosion is initiated, it ultimately leads to delamination and cracking of concrete cover, thus exposing the reinforcement to the outside environment (**Fig. 2.4**)

The various stages of corrosion are:

- Initiation
- Propagation
- Concrete Cracking

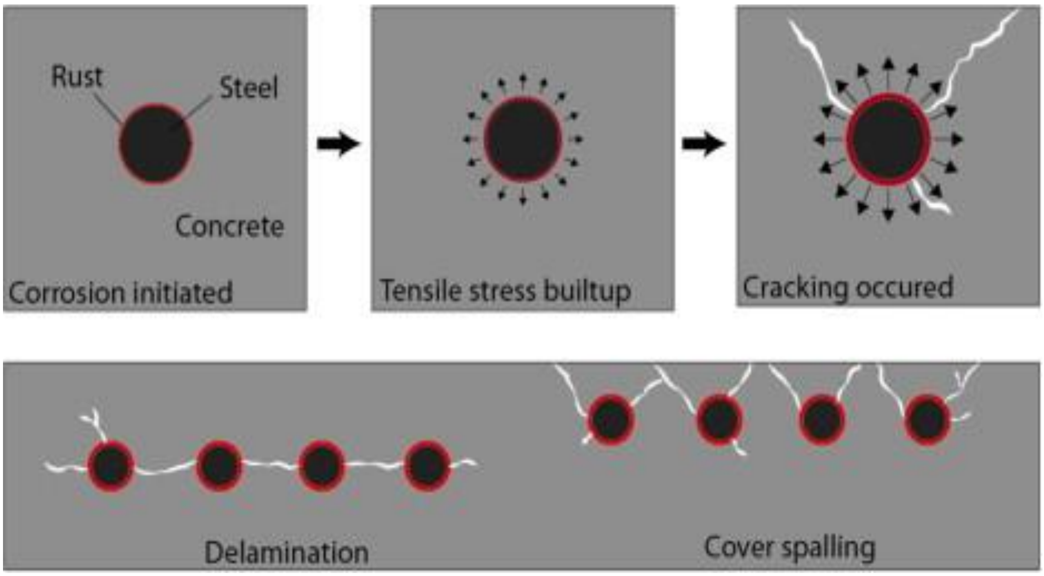


Fig. 2.4: (top) Generally assumed mechanism of corrosion-induced cover cracking, (bottom) cracking modes (*Jamali et al., 2013*)

Fig. 2.5 shows the corrosion model. Initiation Stage describes the time period required for the occurrence of steel depassivation i.e., the time when aggressive species, such as chloride ions, carbon dioxide, etc. penetrate through concrete to the surface of rebar (steel) and build up sufficient concentration of corrosion products to breakdown the passivation layer of steel. Propagation Stage describes the stage where active corrosion has already initiated. The corrosion rates at the propagation stage accelerate significantly once the concrete cover has cracked.

The corrosion products formed on the metal due to transformation of metallic iron to rust is accompanied by an increase in volume that can be as large as 600% of the original metal (**Fig. 2.6**). The increase in volume is responsible for concrete expansion and results in cracking, spalling and delamination in concrete structures.

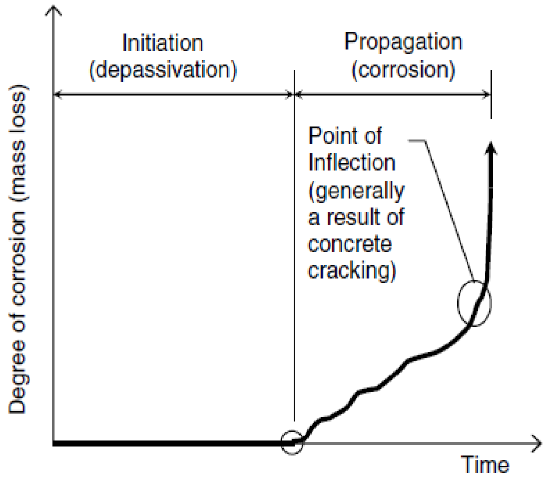


Fig. 2.5: Corrosion process model for steel in concrete (*Spainhour and Wootten, 2008*)

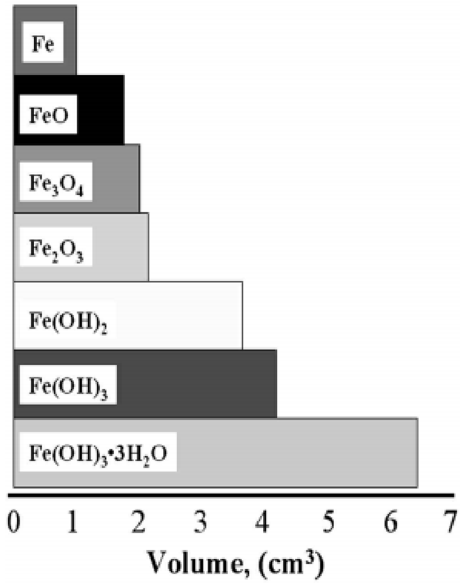


Fig. 2.6: Relative volumes of iron and its reaction product (*Hope, 2002*)

2.1.4 Types of corrosion of steel in RC structures

Based on the corrosion mechanism and partly on the damage caused, corrosion of steel can be classified into following types:

- Uniform Corrosion
- Galvanic corrosion
- Localised Corrosion
- External current imposed corrosion
- Stress corrosion cracking and hydrogen induced constituent

The classification of corrosion types is not absolute but conditional.

1. ***Uniform corrosion:*** When the anodic and cathodic areas are very close to each other such that the distance between them is very small, then the electrochemical reactions would take place uniformly along the steel surface

and the dissolution of steel occurs uniformly on the steel bar. This is termed as uniform corrosion. The term uniform corrosion is a relative concept.

2. ***Galvanic corrosion :*** Practically, the anodic and the cathodic reactions are not uniformly distributed on the steel surface and the rate of these reactions will vary .At some sites, anodic reactions may be faster while at other sites, cathodic reactions may be faster. This happens in case of galvanic corrosion. Galvanic corrosion is dependent on the resistivity of concrete. Higher the resistivity of concrete, lower will be the galvanic corrosion rate. Galvanic corrosion is more common in large dimensioned concrete structures.
3. ***Localised Corrosion:*** It is the most noticeable corrosion. It refers to the most dangerous corrosion damage to reinforcing steel. The various forms of localised corrosion are :
    - Pitting corrosion
    - Crevice corrosion

    The ratio of cathodic area to anodic area is very high resulting in an extremely high corrosion rate at anode. The significant feature of localised corrosion is that the corrosion is triggered and accelerated over a localised area, causing a decrease in pH and severe damage to the structure.

4. ***External current induced corrosion:*** This type of corrosion takes place when an external current is imposed on to a RC structure causing greater corrosion and a heavy loss of steel. Almost all the induced current is conducted by reinforcing steel because steel has greater conductivity than concrete. An example of external current induced corrosion is stray current corrosion. It is found in RC structures where trains or buses run through the structure.
5. ***Stress Corrosion Cracking (SCC) and Hydrogen Induced Embrittlement (HIE):*** SCC and HIE are found in some types of steel due to combination of particular corrosion media and stresses. They result in a sudden breakdown of reinforcement, thus leading to the collapse of RC structures. SCC and HIE are found in materials such as high strength steel. Though these types of corrosion are rarely found, the possible damage caused by them cannot be neglected (*Song and Saraswathy, 2007*).

2.2 CORROSION MONITORING IN RC STRUCTURES

This section gives an overview of the need of corrosion monitoring and various techniques by which it can be done.

2.2.1 Need of Corrosion Monitoring

Reinforced concrete structures are expected to be durable because of high tensile strength and high stiffness of reinforced concrete. However, this expectation is not met in practice and the failure of RC structures occurs when they are exposed to adverse environmental conditions over a period of time. This leads to short service lives and high maintenance and repair costs. Hence, it becomes necessary to monitor the development of corrosion problems in a new or existing RC structure before it is repaired or rehabilitated. Civil engineers need to inspect any possible durability problem before it causes serious damage and therefore, they require such monitoring techniques that give information about how much damage has been caused in the structure due to corrosion and how rapidly the damage will grow with time. Corrosion monitoring techniques are the corrosion measurement methods that give a complete picture of change in the condition of structure in time as well as in all three dimensions of the structure. The corrosion monitoring techniques give an idea about the internal as well as external damage caused, thus enabling the engineer to provide suitable protection measures to the concrete structures.

2.2.2 Techniques used for monitoring of RC Structures

There are a number of monitoring techniques available that satisfy the need for quality control, maintenance and planning for the restoration and retrofitting of RC structures. These techniques detect corrosion at an early stage. A lot of country's expenditure can be saved by identifying the corrosion problem and providing suitable measures at the appropriate time. Corrosion monitoring techniques are broadly classified into destructive and non-destructive techniques.

Destructive testing techniques involve removal or, uncovering of a piece of the RC structure. These tests determine the extent of damage or contamination caused by the penetration of chlorides, carbon dioxides or, fire damage. These tests are frequently carried out to understand the seismic performance of structures in earthquake prone areas. A commonly used destructive technique for corrosion monitoring is pull-out method.

Pull out Method: This method determines the bond strength between reinforcing steel and concrete subjected to corrosion. In this method, RC structures are exposed to anodic current for 24-28 days. A universal testing machine (UTM) is then used to hold these structures from the protruding portion of reinforcing steel bar (**Fig. 2.7**)

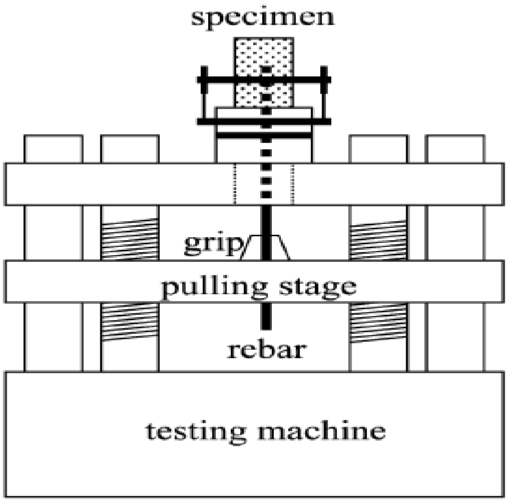


Fig. 2.7: Pullout measurement setup (*Chang, 2002*)

The maximum pull out force is recorded. The reinforcing steel bar may break at the interface because of loss of metal at the top interface due to corrosion. Therefore, the structure is usually cut down to a certain height so as to expose the reinforcing steel bar for holding it in the grip of universal testing machine. (**Fig. 2.8**)

The pull-out tests are carried out again for these structures (*Gadve et al., 2008*). The bond strength can be obtained by dividing the maximum pull out force by the corresponding embedded area (*Chang, 2002*). After carrying out the pull out tests, the concrete structures are cleaned to remove the corrosion product using chemical methods. The reinforcing steel bars are placed in 10 % solution of muriatic acid for a week. As a result, all the corrosion products and the remaining concrete is removed from the steel bar (**Fig. 2.9**).

After cleaning the steel bars, they are weighed to determine the mass loss of corroded steel bar in reference to actual steel bar, that is non corroded (*Spainhour and Wootten, 2008*). It has been reported that the pull out strength is inversely proportional to the mass loss at the reinforcement (*Gadve et al., 2008*). Moreover, as the mass is lost at the reinforcement, it becomes thinner and the bond between steel and concrete is weakened. Therefore, mass loss is an indication of the bond strength between the reinforcing steel and concrete.

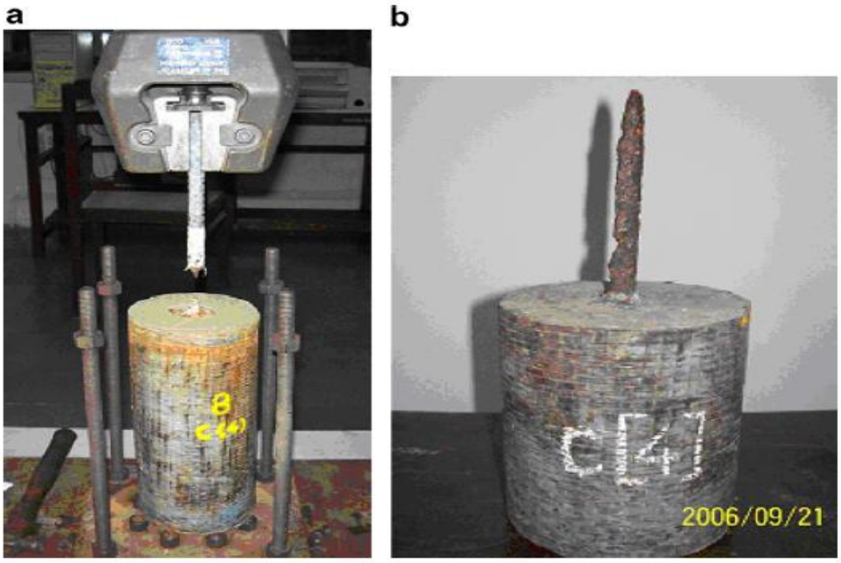


Fig. 2.8: Pullout tests: (a) bar fracture at the interface, and (b) cut specimen for pullout test (*Gadve et al., 2008*)

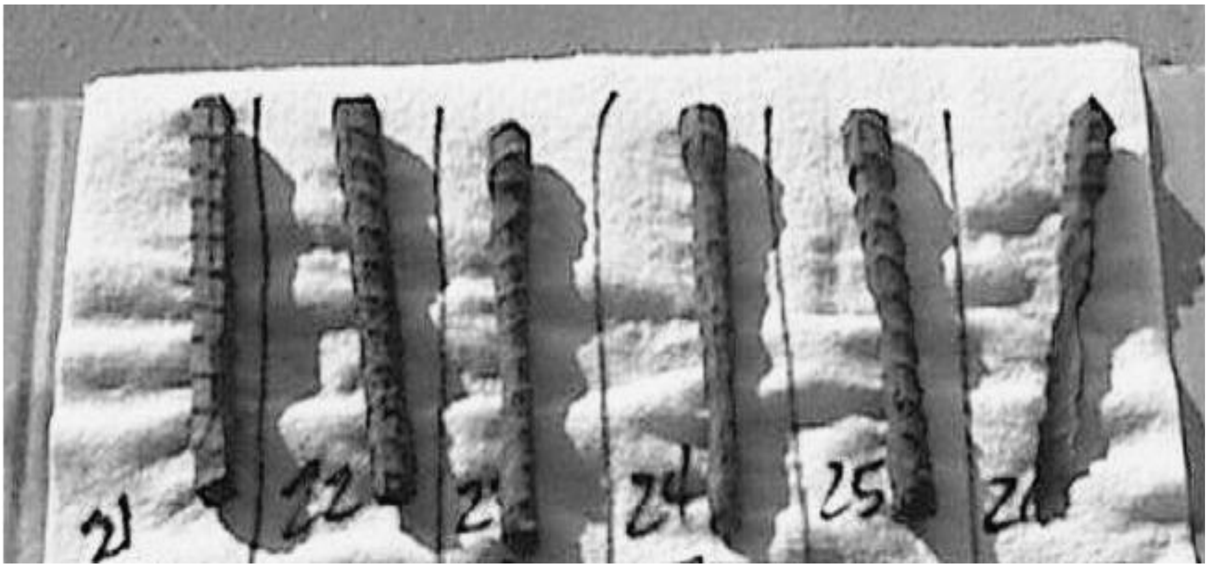


Fig. 2.9: Sample rebars following exposure and cleaning (*Spainhour and Wootten, 2008*)

Destructive testing techniques are rarely applied to building structures or, large non building structures (e.g. bridges and dams) due to the prohibitive cost of constructing a building, or a portion of building again as these techniques destroys the structure. Therefore, non-destructive testing techniques are usually applied to monitor the corrosion in RC structures.

2.2.3 Non-Destructive Testing Techniques

NDT techniques are a wide group of safe analysis techniques as they don't permanently alter the structure being inspected .These techniques are highly valuable as they save both money and time while evaluating the properties of a material or, a system without causing any damage. There are a number of techniques available that can be used in isolation or in combination to provide a complete picture of the overall condition of the structure. Various NDT techniques used for corrosion monitoring of RC structures are given below:

- Visual Inspection
- Infrared thermograph Electrochemical measurements
- Open Circuit Potential (OCP) measurements
- Surface Potential (SP) measurements
- Concrete Resistivity measurements
- Linear Polarisation Resistance (LPR) measurements
- Galvanostatic pulse transient method
- Electrochemical Impedence Spectroscopy (EIS)
- Embeddable Corrosion monitoring sensor
- Cover thickness measure
- Ultrasonic pulse velocity techniques
- X-ray, Gamma Radiography measurement

Visual Inspection: This technique is based on structural analysis of the concrete surface with the help of binoculars or directly through eyes, once a month, an year or once in several years depending on the importance of structure. It uses visual information such as cracks, spalled concrete cover, rust stains, exposed reinforcement, etc. as a measure of corrosion monitoring. This method is not reliable as it is possible that corrosion has been initiated on reinforcing steel, but the symptoms on concrete surface are not visible yet. It might be too late when the symptoms are visible and the structure is severely damaged. Hence, this technique fails to detect corrosion at an early stage. (*Song and Saraswathy, 2007*)

Infrared Thermograph: It is a new NDT technique that provides information about the chloride content in concrete. It uses near-infrared irradiation equipment, imaging spectroscope and near-infrared multi-spectrum camera to acquire information about the chloride content on concrete surface. However, this technique is under development.

Open Circuit Potential (OCP) Measurement: OCP measurement is a non-destructive test that diagnoses the corrosion risk in RC structures. In RC structures, the pore solution in concrete acts as an electrolyte and thus, a potential is developed on the reinforcement that may vary from place to place depending on the concrete environment. OCP Measurement is based on the principle of measuring corrosion potential of steel with respect to a standard reference electrode. The reference electrode can be a saturated calomel electrode (SCE), Cu/$CuSO_4$ electrode (CSE), Ag/AgCl electrode etc. A large number of observations are taken from RC structure to deduce the corrosion risk. The schematic representation of OCP measurement is as shown in the **Fig. 2.10** below:

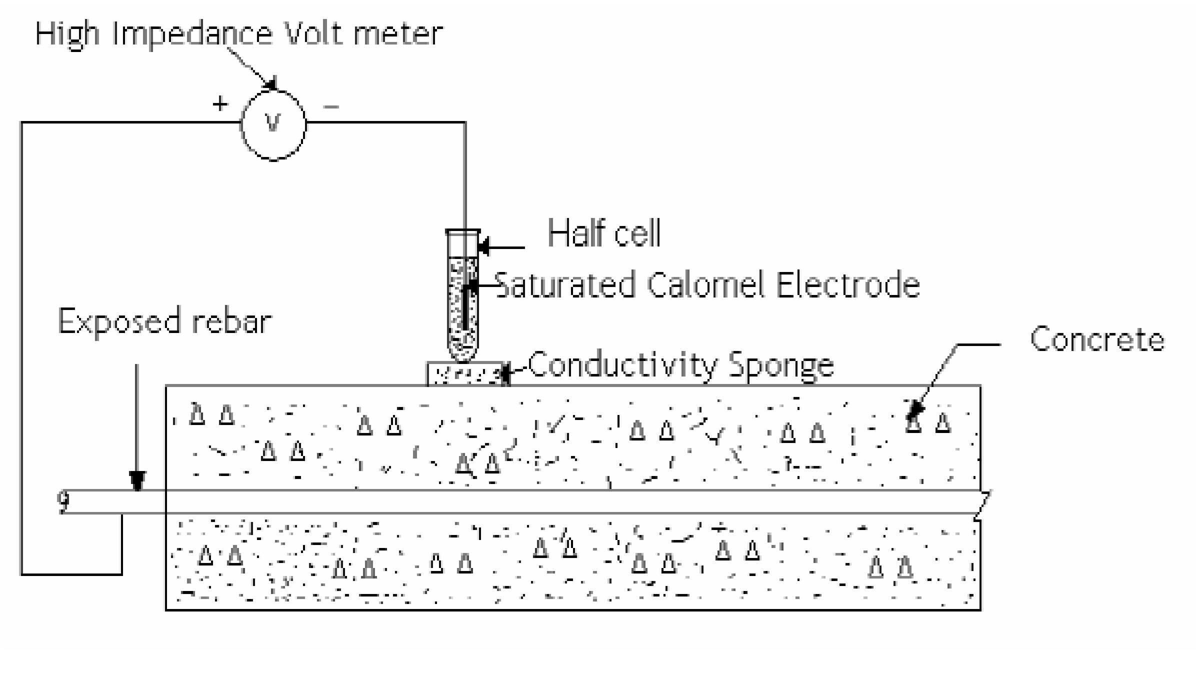


Fig. 2.10: Schematic representation of Open circuit potential (OCP) measurement (*Song and Saraswathy, 2007*)

Although, there are various methods available for detecting corrosion, half cell potential (HCP) measurement is a commonly used detection technique. **Table 2.1** gives an indication of corrosion condition based on the measured potential.

Table 2.1: Corrosion condition related with half-cell potential (HCP) measurements (*Song and Saraswathy, 2007*)

Open circuit potential (OCP) values		Corrosion condition
(mV vs. SCE)	mV vs. CSE	
< -426	< -500	Severe corrosion
< -276	< -350	High (<90% risk of corrosion)
-126 to -275	-350 to -200	Intermediate corrosion risk
> -125	> -200	Low(10% risk of corrosion)

Surface Potential Measurement: SP measurement is a useful technique to identify the anodic and cathodic regions in a RC structure and determines the probability of corrosion reinforcement indirectly. During corrosion process, electric current flows from anode to cathode, i.e., from higher potential to lower potential. SP measurements are based on measuring the potential drop from anode to cathode. The schematic representation of SP Measurement is as shown in F**ig. 2.11** below:-

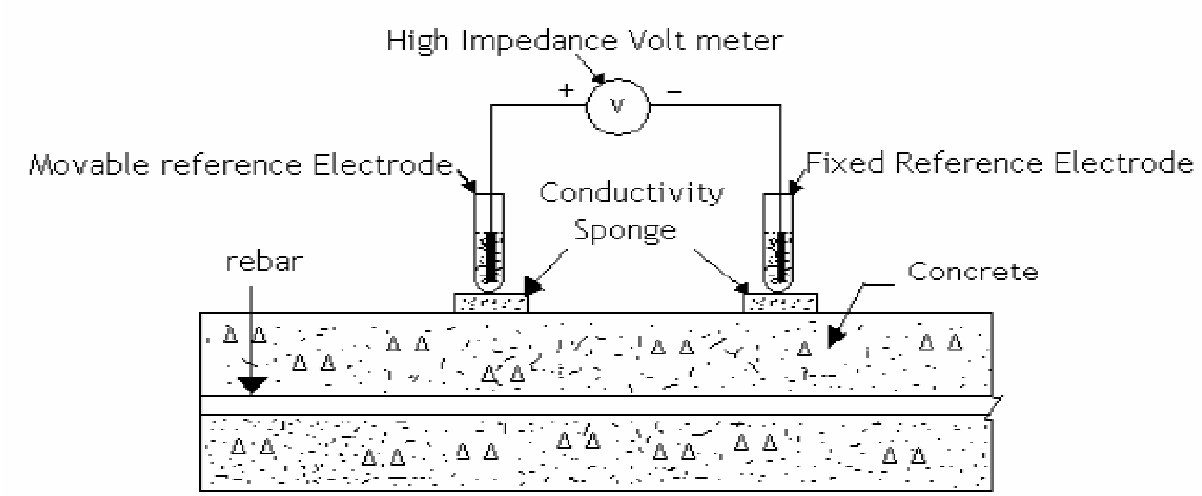


Fig. 2.11: Schematic representation of surface potential (SP) measurements (*Song and Saraswathy, 2007*)

Two reference electrodes are shown in the above figure - a movable reference electrode and a fixed reference electrode. The moving electrode moves on the structure and measures a potential against the standard fixed electrode. The probability of corrosion is determined by the potential difference measured between anode and cathode. The more the potential difference, more is the probability of corrosion.

Concrete Resistivity Measurement: It is a NDT technique that evaluates corrosion risk on the reinforcement based on electrical resistivity measurements. The parameter "electrical resistivity" plays an important role in determining the intensity of corrosion. Greater the electrical resistivity of concrete material, slower will be the corrosion process. It has been reported that electrical resistivity is inversely proportional to the corrosion rate. Electrical resistivity is an important parameter that provides useful information about corrosion performance of steel embedded in concrete. **Fig. 2.12** shows the circuit for electrical resistance measurements.

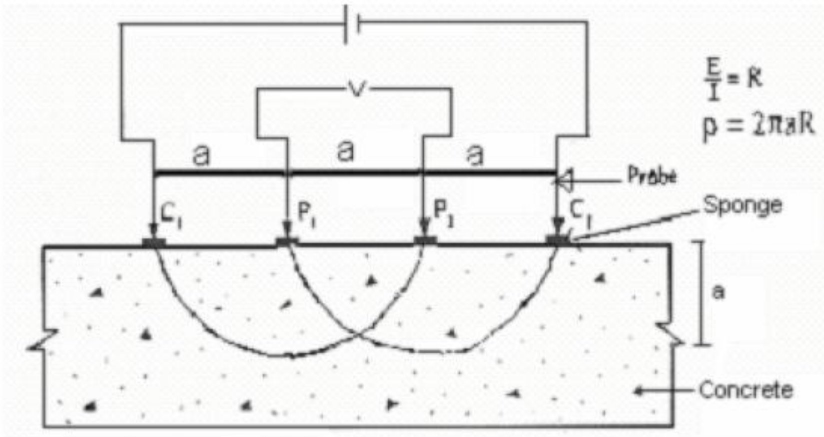


Fig. 2.12: Circuit for electrical resistance measurements (*Song and Saraswathy, 2007*)

Linear Polarization Resistance (LPR) Measurements: It is a useful NDT technique that determines the instantaneous corrosion rate of reinforcing steel. **Fig 2.13** shows the schematic representation of Linear Polarization Resistance (LPR) Measurement. This method provides more detailed information as compared to simple potential survey. Moreover, it is rapid, non-intrusive and enables accurate assessment of the condition of RC structures. However, this technique requires localised damage on the concrete cover in order to enable a concrete connection to the reinforcing steel. In this method, the potential of reinforcing steel is changed by a fixed amount ΔE and the current ΔI is monitored after a fixed time period. The change in potential ΔE should be between 10 – 30 mV (Stern-Geary range).

The polarization resistance, R_p is given as:

$$R_p = \Delta E / \Delta I \quad (2.3)$$

The corrosion rate, I_{corr} is expressed in terms of polarisation resistance (R_p)

$$I_{corr} = B/R_p \quad (2.4)$$

where, B is Stern–Geary constant.

B = 25 mV (for active steel)

B = 50 mV (for passive steel)

The value of corrosion current gives an indication of the condition of rebar.

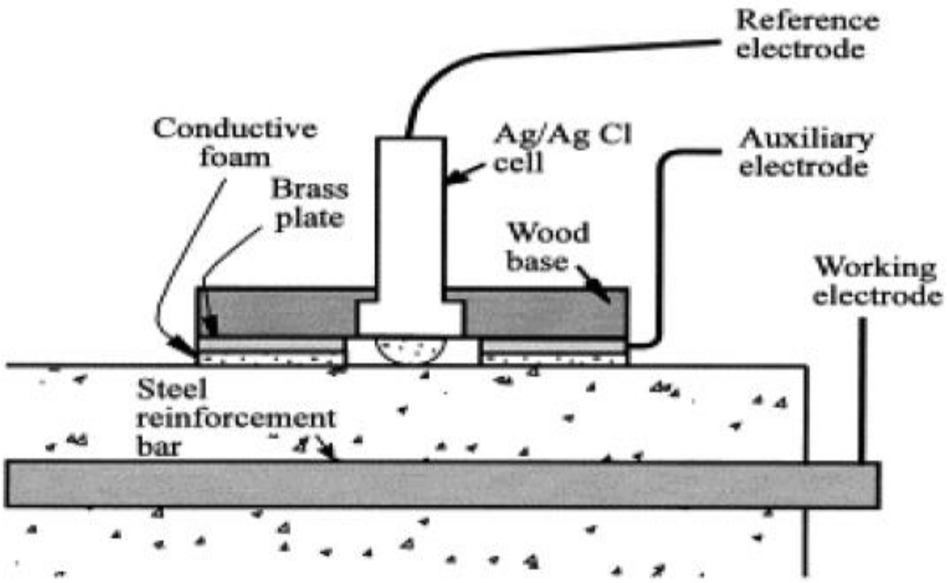


Fig. 2.13: Linear polarization resistance measurement (*Song and Saraswathy, 2007*)

Galvanostatic Pulse Transient Method: It is a NDT technique based on transient polarization that operates in time domain. In this method, a short time anodic current pulse (10-200 µA) is imposed on the reinforcing steel by a counter electrode placed on the surface of concrete. This leads to polarization of the reinforcement with respect to its free corrosion potential in anodic direction. The resulting potential difference is recorded by a reference electrode as a function of polarization time. The set up for galvanostatic pulse technique is as shown in **Fig.**

2.14. A limitation of this technique is that the pulse response must be stabilized to give an accurate value of potential.

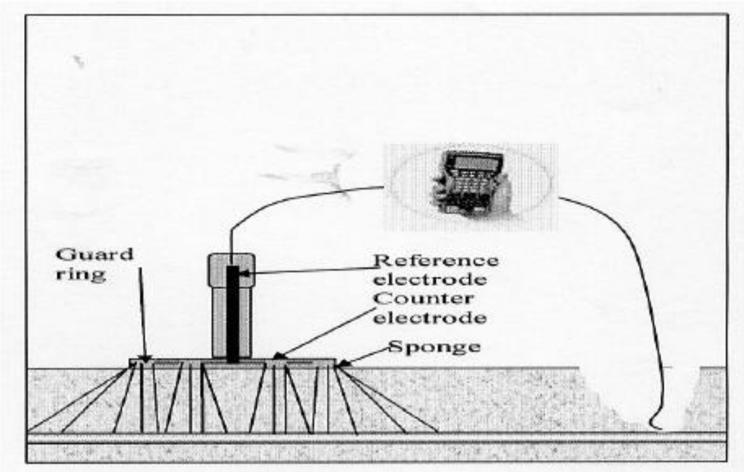


Fig. 2.14: Set-up for galvanostatic pulse technique (*Song and Saraswathy, 2007*)

Electrochemical Impedence Spectroscopy (EIS): EIS is a very powerful and useful NDT technique that can evaluate the corrosion rate of steel over a wide range of frequencies. In this method, an alternating voltage of about 10-20 mV is applied to rebar and the resulting current and phase angle are measured at various frequencies. EIS involves a parameter Z, Impedence which is the ratio of ac voltage to ac current. The variation of impedence with frequency is studied and is used to determine the equivalent electrical circuit which gives the same response as the given corrosion system. Although AC- EIS technique gives more information than DC-LPR measurements, but it is a very time consuming procedure, and is confined to labs instead of structures.

Embedded Corrosion Monitoring Sensor: The Embedded Corrosion Monitoring Instrument (ECI) is a non-destructive evaluation (NDE) sensor that gives a warning of the conditions that can cause steel damage at an early stage. This technique helps the civil engineers to avert crises, save money and build a detailed record of each structure. ACI monitors five key factors in corrosion:

- Linear polarization resistance
- Open Circuit potential
- Resistivity
- Chloride ion concentration

- Temperature

The ECI monitors are connected to form an embedded corrosion sensor that can be easily installed on a structure to provide adequate coverage of the structure during construction. **Fig. 2.15** shows an ECI sensor:

Fig. 2.15: ECI sensor during operation (*Song and Saraswathy, 2007*)

ECI monitors can be used for corrosion monitoring of bridges, dams, buildings, parking garages, roadways, flood control channels, etc.

Cover Thickness Measurement: This NDT technique employs a device known as cover meter or profmeter to measure the concrete cover for detecting rebar size, position and direction. **Fig. 2.16** shows a cover meter to monitor corrosion of reinforcing steel:

Fig. 2.16: Cover meter (*Song and Saraswathy, 2007*)

The parameter used by the cover meter is “cover thickness”. This parameter is essential to preserve the electrochemical stability of steel embedded in concrete contaminated by chlorides.

Ultrasonic Pulse Velocity (UPV) Measurements: Ultrasonic refers to sound energy above the audible frequency of 20 kHz. UPV is a non-destructive technique that can be used to predict material strength and detect internal damage in the structure such as cracking, decay, voids, honeycomb, etc. This technique is readily applied to the concrete structures and is very efficient in finding out the areas of weak concrete in a generally sound RC structure. In this method, electrical energy is converted into pulses of longitudinal, elastic stress waves by a transducer that is in direct contact with the concrete surface to be tested. A good contact between the transducer and concrete surface is made by using a coupling gel. The acoustic pulses generated by the transducer traverse through the concrete and after reflection, the pulses are received by transducer and converted back to electrical energy. The time taken by the wave to travel through the structure and reflect back is measured by electronic means and this is used to calculate the parameter “pulse velocity”.

$$\text{Pulse Velocity, } V = L/T \quad \text{(2.5)}$$

The value of pulse velocity determines the quality of concrete.

X-ray/Gamma Radiography: Radiography technique provides useful information about concrete quality and defects within RC Structure. It uses radioactive isotopes for concrete testing. This technique is classified into X-ray radiography and γ-ray radiography, based on the em wave used for corrosion monitoring. The X-rays and γ- rays provide a radiographic examination of concrete to locate internal cracks, voids and variation in concrete density.

2.3 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.

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. This method is explained in detail in the following section.

2.4 ELECTROCHEMICAL METHODS OF PREVENTION

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

2.4.1 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.

2.4.2 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, discussed as follows:

1) ***Galvanic anode systems:*** These are based on the principle of connecting an external metal (anode) higher in the electrochemical series to the metal to be protected (steel) as shown in **Fig. 2.17**. This creates a potential difference between anode and steel and causes a positive current to flow in the electrolyte from anode to steel. Thus, the surface of steel becomes negatively charged and behaves as cathode. The corrosion process is stopped and there is no further dissolution of metal (steel) into ions. The metals commonly used as an external anode are zinc, aluminium and magnesium. The sacrificial anode systems are inherently simple, requires no monitoring or maintenance. However, they have shorter anode life and non-adjustable current.

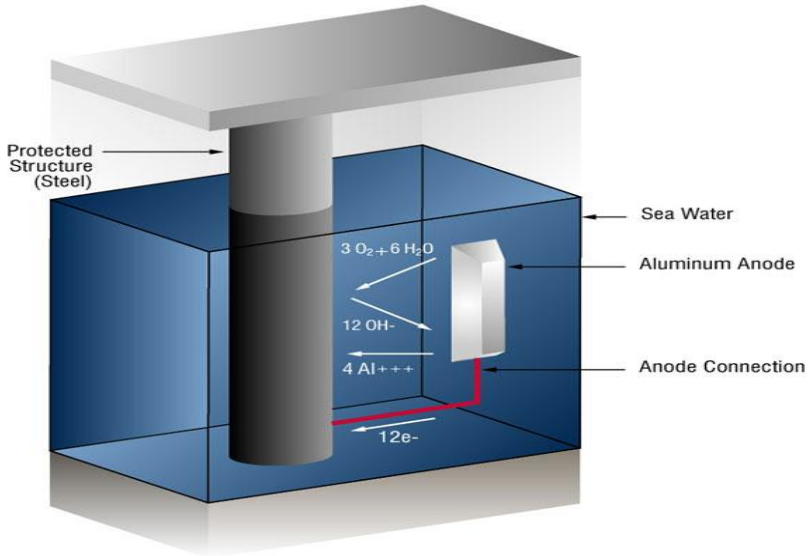


Fig. 2.17: Cathodic Protection using Galvanic anode systems (*www.cathodicprotection101.com*)

Generally, galvanic systems are used for localized protection or for small well-coated and low current demand structures, and impressed current systems are used for large complex structures (*Daily, 2001*).

2) ***Impressed current systems:*** These are based on the principle of impressing current from an external anode to the metal to be protected by employing an external dc power source as shown in **Fig. 2.18**. The anode used in these systems is inert. Although, impressed current systems are complex in design and require monitoring and maintenance, they have the advantage of

providing longer anode life, extensive track record, high dc driving voltage (up to 50 V), and capability of supplying relatively large current.

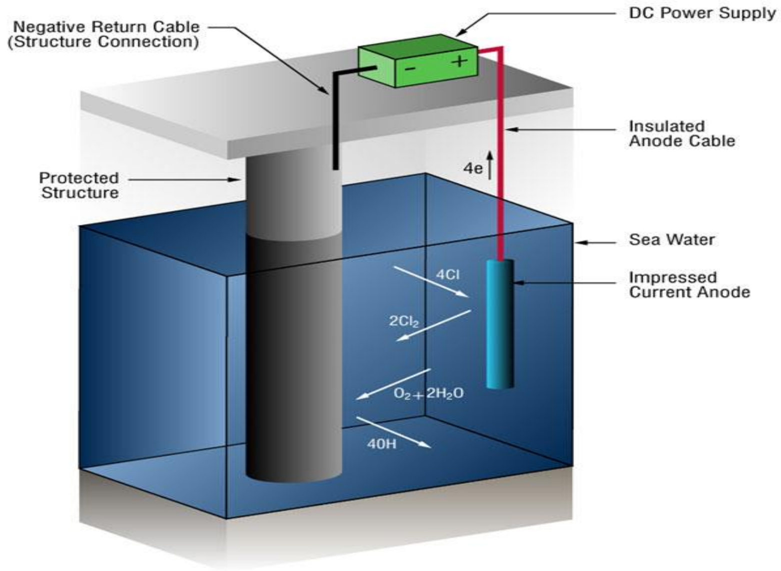


Fig. 2.18: Cathodic Protection using Impressed current systems (*www.cathodicprotection101.com*)

Limitations of Cathodic Protection: Although Federal Highway Administration has suggested Impressed Cathodic Current Method as the only effective corrosion prevention method for a corroded RC member, there exist certain limitations such as:-

- The localized overprotection created by the impressed current cathodic protection results in hydrogen embrittlement of high strength steel. It has been reported that mechanical properties of the material such as strain to failure ratio, time to fracture, and elongation decreases due to hydrogen evolution at the metal (*Kim et al., 2003*).
- The overprotection cathodic current also softens C-S-H gel in concrete and reduces the compressive strength and durability of structures.
- The major drawback of cathodic protection is the bond degradation at the interface between rebar and concrete due to cathodic protection current (*Chang, 2002*)
- Activated titanium anodes that are used as inert anodes, ensure a uniform current distribution on the concrete surface, supply high current densities

and exhibit long service life. But, they are expensive and add weight to the protected structure.

- Conductive Polymer Sheets such as CFRP are cheaper, but they suffer from poor wear resistance, high thermal expansion coefficient, high contact resistivity between underlying concrete and covering, and inability to supply sufficient current densities for long time.

2.5 PROTECTION USING FRP's

This section provides an overview of common types of FRP materials used for providing passive and active protection against corrosion.

2.5.1 General

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.

2.5.2 Suitability of FRP for use in Structural Engineering

Several factors have facilitated the use of FRP's for the repair and rehabilitation of RC Structures. Some of them are:

- Ease of installation
- High strength to weight ratio
- High durability
- Low permeability
- High thermal resistance
- Minimal architectural impact

FRP's can be laminated on the concrete surface using epoxy resin or can be used as inert anodes to delay corrosion of reinforcing steel in RC structures. When a structure is wrapped with FRP laminates, the corrosion activity is greatly reduced as FRP wraps act as a barrier to further penetration of water, oxygen and other aggressive species present in the environment. Moreover, FRP wraps provide an external pressure that resists the displacement caused by the expansion of corrosion products and reduce the cracking and spalling of concrete (*Maaddawy and Soudki, 2005*). The FRP wrapped structures show an increase in axial compressive load capacity, improved flexural and shear load carrying capacity, increased ductility, increased torsional strength, increased fatigue resistance and an improvement of seismic performance (Fonseca, 2000). FRP's are used as inert anodes instead of laminates, for the repair and maintenance of historical monuments and other heritage structures in order to preserve their physical appearance. Also, FRP protected structures are highly resistant to corrosive effect of salts, acids, alkalis under a wide range of temperature and are unaffected by the electrochemical and electromechanical deterioration.

2.5.3 Types of FRP's

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.

(i) ***Glass Fibre Reinforced Polymer (GFRP):*** It is used in the form of sheets that are wrapped around the concrete surface of the RC structure (**Fig. 2.19**). The GFRP covering act as a physical barrier that hinders the ingress of aggressive species such as chlorides and carbon dioxide present in the environment and strongly delays the corrosion onset. The properties of GFRP are shown in **Table 2.2**

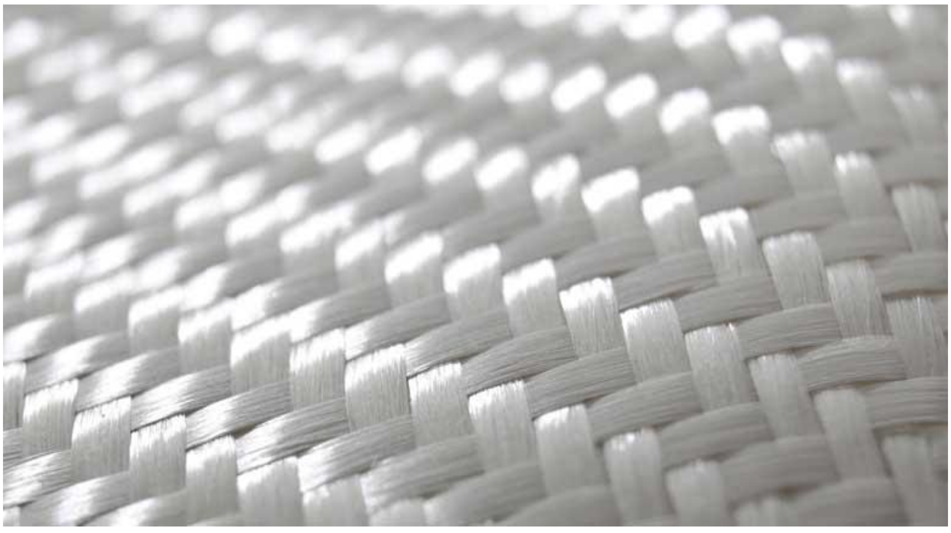


Fig. 2.19: GFRP sheet (*www.fassmer.de*)

(ii) ***Carbon Fibre Reinforced Polymer (CFRP):*** CFRP sheets are thinner than GFRP sheets and exhibit a greater tensile strength, greater tensile modulus and lower ultimate strain. The properties of CFRP are shown in **Table 2.2**. **Fig. 2.20** shows CFRP sheet.

Fig. 2.20: GFRP sheet (*www.mechanicalengineeringblog.com*)

Table 2.2: Properties of CFRP and GFRP (*Gadve et al., 2008*)

Material	Thickness (mm)	Tensile strength (GPa)	Tensile modulus (GPa)	Ultimate strain
Carbon sheet (Net fiber) (CS)	0.13	3.79	230	0.015
Glass sheet (Net fiber) (GS)	0.35	2.30	76	0.018
Adhesive	–	15	4.3	0.02

It has been reported in latest literature that CFRP is used for providing cathodic protection to RC Structures. CFRP act an external inert anode that enables the deposition of negative charges on the reinforcing steel. Thus, reinforcement starts to behave as a cathode and corrosion process is stopped. *Maaddawy and Soudki (2005)* investigated that CFRP repaired structures show greater flexural strengthening and a prolonged life as compared to unrepaired RC Structures, but significantly reduce the deflection capacity. *Masoud and Soudki (2006)* reported that FRP repaired structures show a higher rate of decrease in corrosion potential than the unrepaired structures.

Spainhour and Wootten (2008) reported that by increasing the number of CFRP wraps, corrosion rate is slowed down. *Spainhour and Wootten* also reported that the type of epoxy used for wrapping CFRP sheets affects the corrosion rate and found that the epoxy Sikaguard 62 is helpful in reducing corrosion rate.

2.5.4 Use of FRP for Active and Passive Protection

The active and passive protection techniques are discussed as follows:-

1) ***Passive Protection:*** The pressure exerted by FRP sheets wound on the concrete surface prevents further increase in cross-sectional dimensions. This technique of providing protection against corrosion is termed as 'passive protection'. The passive protection provided by GFRP and CFRP wrapped structures exhibit greater strength and a reduction in mass loss as compared to non-wrapped structures. Thus, FRP's solve a dual purpose-decreasing the corrosion rate and increasing the strength in a RC structure.
2) ***Active Protection:*** CFRP material is electrically conductive and because of this property it can be used to provide 'Active Protection' besides Passive Protection. In active protection of reinforcing steel in concrete, the steel act as a cathode and electrically conductive CFRP wraps serve as anode. This reverses the direction of current i.e., current flows from CFRP(anode) to steel(cathode) now and this prevents the dissolution of metal into ions, thus hampering the corrosion process. Thus, CFRP provides both a physical barrier to restrict the ingress of chloride ions and carbon dioxide into concrete, and reverse the direction of current to stop the dissolution of metal into ions.

2.6 LITERATURE SURVEY

Assessment of the effect of GFRP on the corrosion of steel reinforcement in confined RC by EIS (2000)

Fonseca (2000) investigated the effect of GFRP sheets on the corrosion of reinforcing steel in the presence of chloride ions. The experimental work was done on cylindrical concrete specimens with two ribbed steel bars used as electrodes. Two different w/c ratio mixtures were used. GFRP sheets were wrapped on half of the specimens and then, all the specimens were partially immersed in 3% NaCl solution. Two types of electrochemical techniques were used for corrosion monitoring- Open circuit potential (OCP) and Electrochemical Impedence Spectroscopy (EIS). The results indicated that the specimens that were not wrapped with GFRP sheets show a fast corrosion onset and an increase of corrosion activity. The different w/c ratio mixtures had no significant effect on corrosion in non-GFRP samples. The OCP monitoring revealed the passive state characteristic of GFRP samples, which was confirmed by EIS measurements. The barrier effect of GFRP layer was highlighted by the increased resistivity of these samples. The corrosion process was delayed by decreasing the penetration of chloride ions through GFRP wraps. The results indicate that the corrosion rate of reinforcing steel reduces by more than 200 times when the samples were wrapped with GFRP sheets. It was concluded that GFRP layers act as a physical barrier between the concrete surface and the aggressive environmental species, and helps in maintaining the passive state of rebar by reducing the electrochemical activity.

The use of permanent corrosion monitoring in new and existing reinforced concrete structures (2002)

Broomfield et al. (2002) encouraged the use of permanently embedded corrosion monitoring devices to monitor the development of corrosion problems and a new or existing RC Structure before repairing or rehabilitating the structure. Corrosion Monitoring systems comprising of concrete resistivity and other probes were installed in new as well as old RC structures. As the chloride ions and carbon dioxide were penetrated into the concrete structure, it was found that the corrosion monitoring systems provide quantitative information about the development of corrosion. Ii was observed that the service lives of the new structures were extended, thus preventing premature repair requirements. The old structures were also benefitted from corrosion monitoring systems as these systems were effectively used to access the effectiveness of repairs already done and future repair cycle. It was found that sensors can be used in corrosion monitoring systems to measure corrosion rate and concrete condition.

Cathodic Protection of Reinforced Concrete Structures- A Practical Method of Arresting Rebar Corrosion (2002)

Bird (2002) investigated Cathodic Protection (CP) to treat corrosion damaged reinforced concrete structures, and found that it is a practical technique for halting corrosion of reinforcing steel. It was reported that cathodic protection has numerous advantages over other short term rehabilitation techniques such as path repairs and protective coatings. The life of CP was found to be 4.5 times longer than the conventional path repair. The ability of CP to delay the corrosion process and extend the service life of RC structures was highlighted. It was observed that CP can be employed as a long term and economical solution (in excess of 25 years) to the problem of rebar corrosion with minimal maintenance requirements. CP was also recognized as a means of prevention of corrosion damage in new structures. It was concluded that CP is a widely used technique to halt corrosion of reinforcing steel in order to protect RC structures.

Using Cathodic Protection to control Corrosion of Concrete Infrastructure in Marine Environments (2002)

Funahashi et al. (2002) provided a review on the corrosion process in marine environments and the types of systems that are available to control corrosion in the atmospheric, splash, tidal and submerged zones. It was observed that corrosion is most prominent in partially or semi-submerged zones due to high chloride concentration, wet-dry cycling, high moisture content and oxygen availability. Conventional methods such as path repairs were proven to be ineffective in controlling corrosion. CP using both impressed current and galvanic (sacrificial) were proven to be effective in providing long-term corrosion control for marine RC structures. It was observed that when impressed current technique was used, CP current distribution was affected by variations in steel density. Therefore, a rectifier was used to adjust and control the current. It was found that titanium mesh and ribbon mesh anode systems used for cathodic protection, has a significant design life of over 75 years.

A Study of Bond degradation of rebar due to cathodic protection current (2002)

Chang (2002) studied the bond degradation between rebar and concrete due to cathodic protection current. Possible side-effects of cathodic current method were highlighted such as non-uniform distribution of cathodic protection current due to physical and chemical instabilities in concrete material, resulting in localized overprotected areas; increase of hydrogen permeation current non-linearly with concrete thickness; softening of C-S-H gel in concrete due to overprotection cathodic current resulting in reduction of compressive strength and durability of concrete and, weakening of bond strength between reinforcement and concrete. However, the effect of current density and polarization time on bond strength degradation was examined. The experiments were performed on three different mix designs of concrete (different w/c ratios). It was found that potassium and sodium ions move towards the steel-concrete interface during cathodic polarization of rebar, thus resulting in the softening of C-S-H gel. The experimental results indicate that the compressive strength increases as the age of concrete increases and water-cement ratio decreases (**Fig. 2.21**).

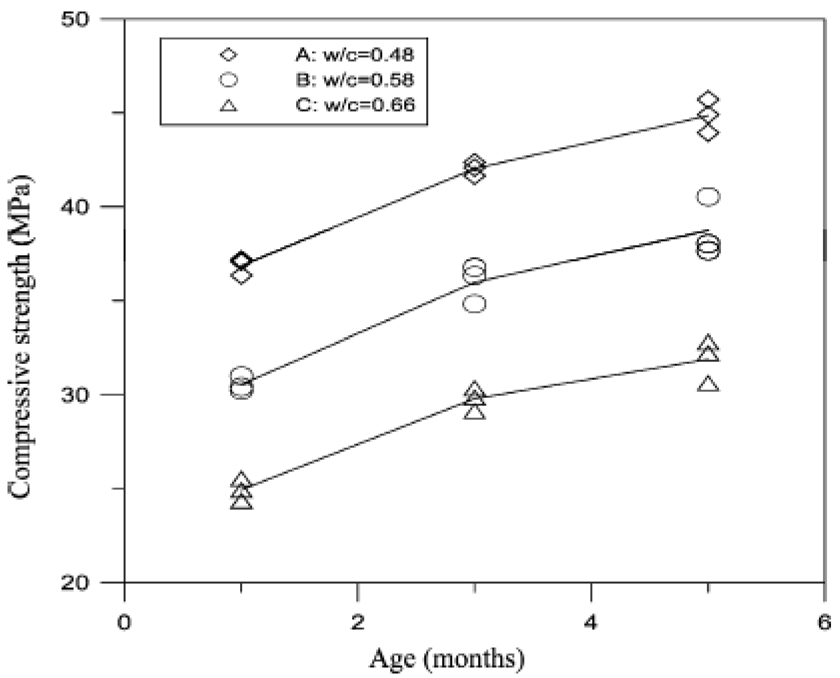


Fig. 2.21: Development of compressive strength

It was observed that bond strength decreases with an increase in polarization time and cathodic current density, and the mixture with highest w/c ratio showed the worst bond strength. As shown in **Fig. 2.22**, a new parameter ϕ (i_c*t_P) was defined, and conclusions were made that bond strength reduces to the critical value when ϕ = 2400 µA/cm^2.

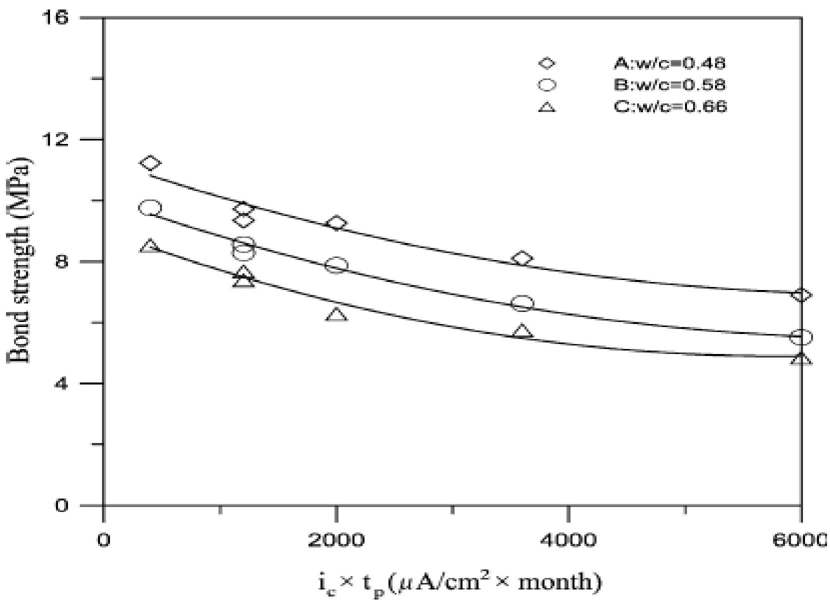


Fig. 2.22: Regressive curves for bond strength versus polarization parameter ϕ

Microscale experiments were also carried out to examine the relation between hardness value and parameter ϕ. It was observed that micro-hardness value decreases as parameter ϕ increases (**Fig. 2.23**).

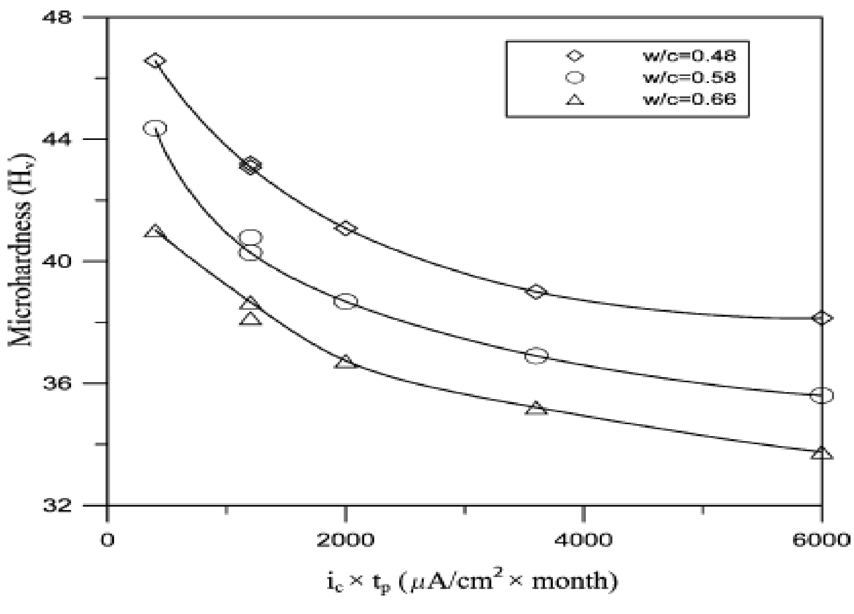


Fig. 2.23: Micro-hardness values versus the polarization parameter ϕ

It was also observed that concentration of potassium and sodium ions decrease with an increase in parameter ϕ (**Fig. 2.24**)

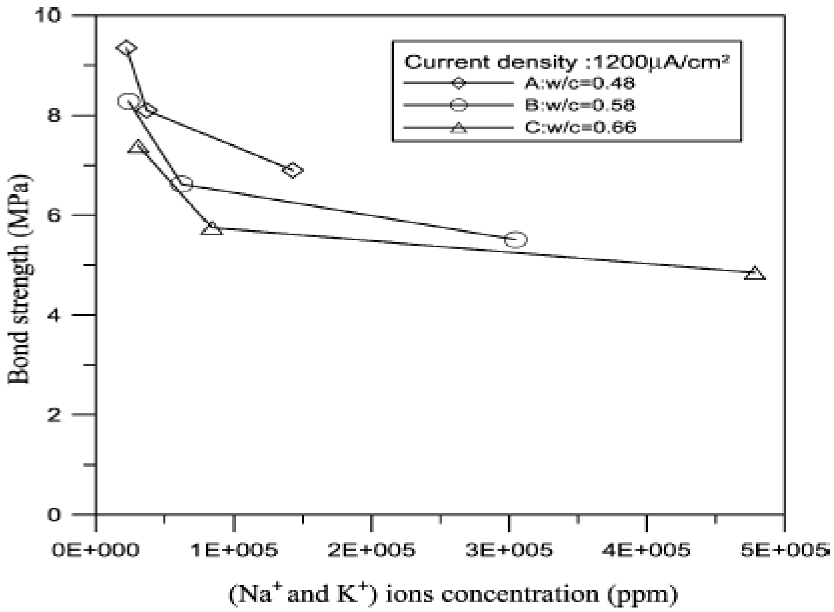


Fig. 2.24: Bond strengths versus total concentration of potassium and sodium ions

It was concluded that degradation % of bond strength is more for concrete with higher w/c ratio than the concrete with lower w/c ratio, when impressed cathodic protection technique is used.

An Electrochemical Study of Cathodic Protection of Steel used for Marine Structures (2003)

Kim et al. (2003) studied the effect of hydrogen embrittlement caused due to the overprotection during impressed current cathodic protection of high strength steel used in marine structures. Slow- Strain Test (SSRT) was used to investigate the effect of post weld heat treatment (PWHT) in order to reduce galvanic corrosion on marine structural steel. A correlation was investigated between mechanical properties of steel and hydrogen embrittlement. The test specimens used for both SSRT and PWHT was high strength steel. An Al alloy was used for providing cathodic protection. Electrochemical tests were carried out to examine the relationship between Al anode weight loss and PWHT conditions at flow rates of 0 and 3 cm/sec. It was found that anode weight loss is comparatively more when flow rate is 3 cm/sec than at 0cm/sec due to larger anode current. The SSRT examination showed that the optimum PWHT temperature with minimal weight loss is 550^o C. (**Fig. 2.25**)

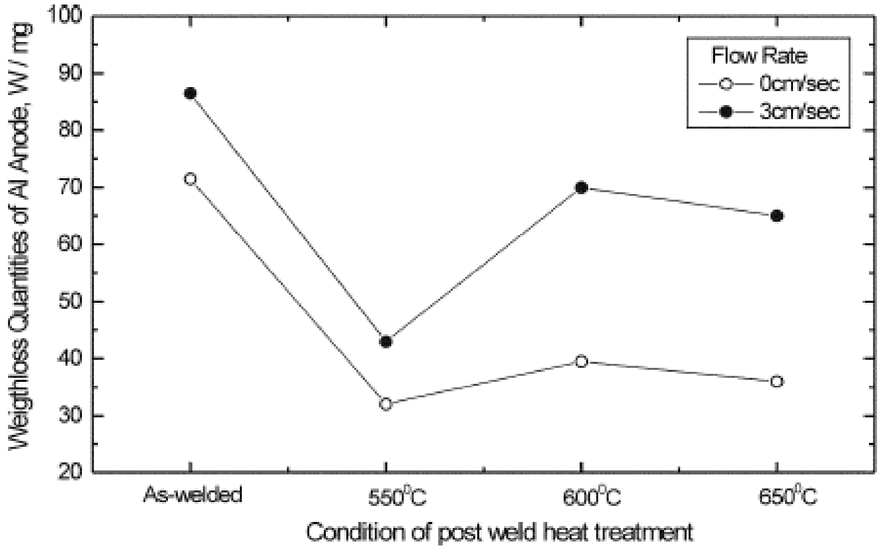


Fig. 2.25: Relationship between Al anode weight loss quantity and PWHT conditions in the case of flow rate 0 cm/sec, 3 cm/ sec

Due to reduction in dissolved oxygen, potential difference between Al alloy and cathode was decreased with an increase in concentration polarization. The experiments showed no correlation between maximum tensile strength and hydrogen embrittlement. However, relationships were found between hydrogen embrittlement and each of the mechanical properties (elongation, time to fracture, strain to failure ratio) as shown in **figures 2.26, 2.27 and 2.28**.

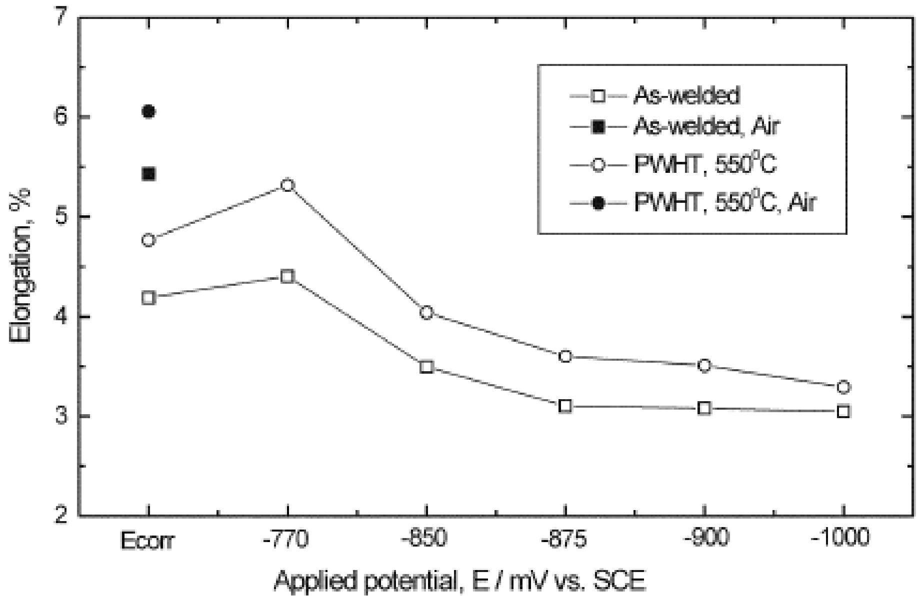


Fig. 2.26: Relationship between elongation and applied cathodic potential in as-welded and post-weld heat treated specimen

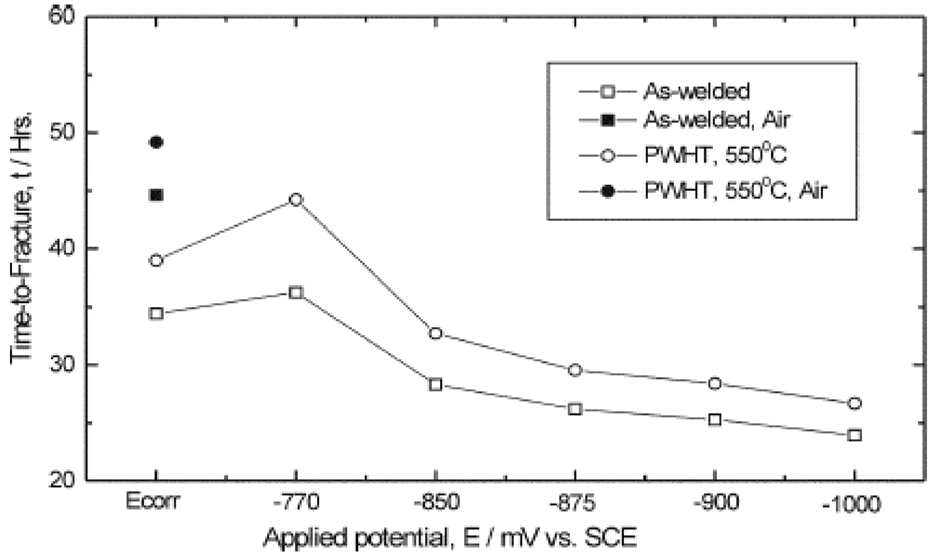


Fig. 2.27: Relationship between time-to-fracture and applied cathodic potential in As-welded and post-weld heat treated specimen

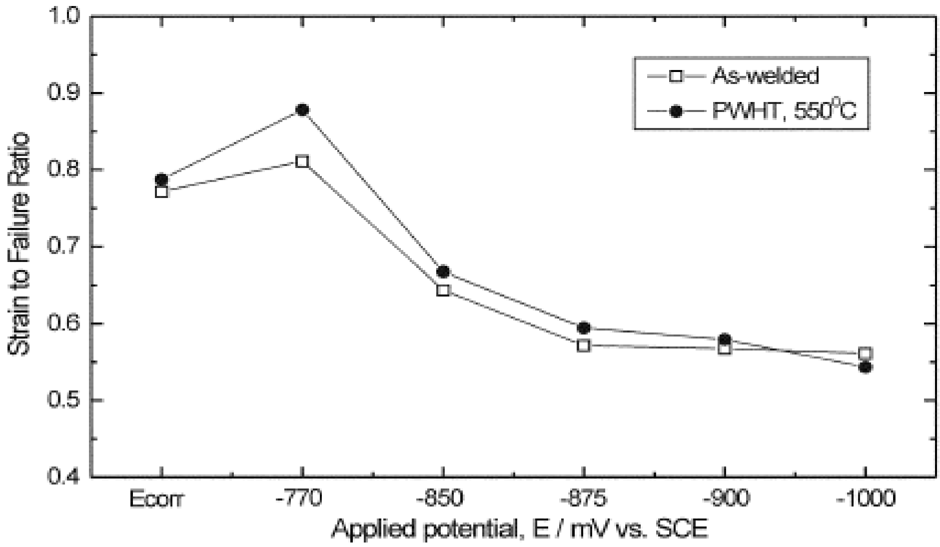


Fig. 2.28: Relationship between strain to failure ratio and applied cathodic potential in as-welded and post-weld heat treated specimen

It was observed that elongation time, time to fracture and strain to failure ratio shows a maxima corresponding to cathodic potential of -770 mV and after that reduces as cathodic potential is lowered. This reduction in the material properties was due to hydrogen evolution. SEM fractography analysis indicate that the optimum potential range for cathodic protection is -770 to -850 mV (SCE) with PWHT at 550^{o} C, and within this range, there is no hydrogen embrittlement.

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 wwre 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 potentiodynamic 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 renforced 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 n 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 fibre 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. 2.29** shows that standard deviation of protection current distribution initially increases as corrosion current increases, but is non-uniform after the inflexion point.

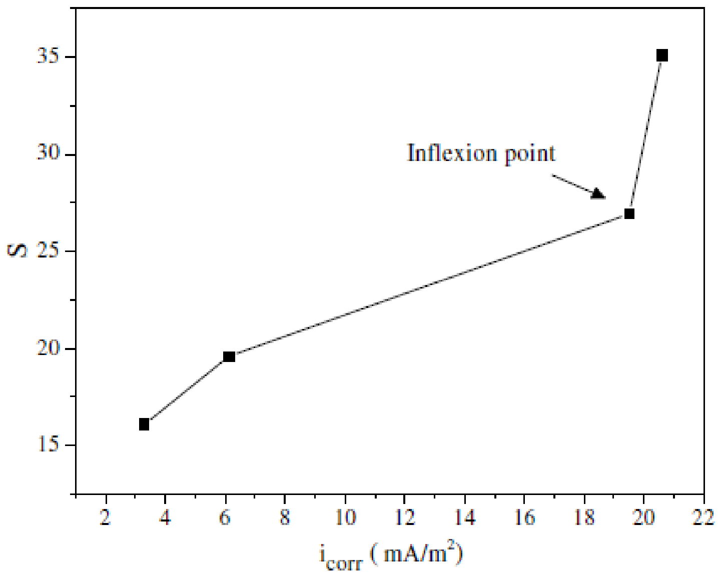


Fig. 2.29: The relationship between corrosion rate and standard deviation of protection current distribution values

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. 2.30**, 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.

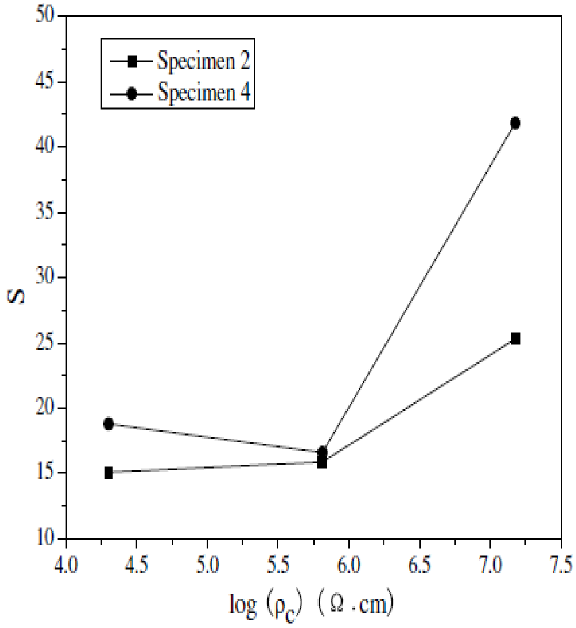


Fig. 2.30: The relationship between concrete resistivity and standard deviation of protection current distribution values

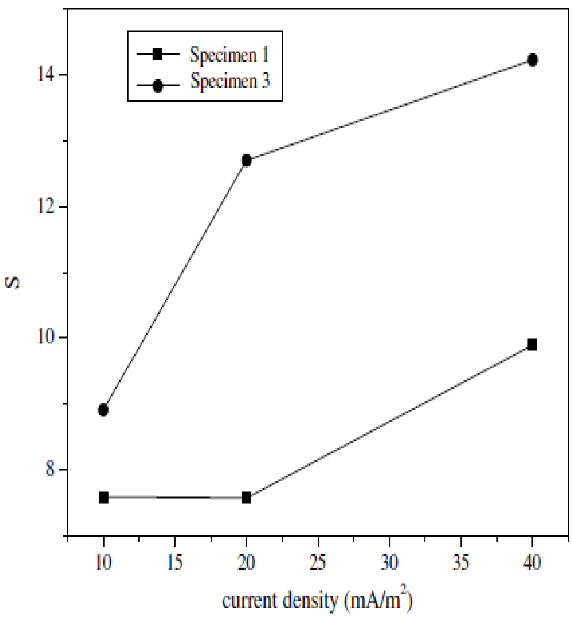


Fig. 2.31: The relationship between impressed current density and standard deviation of protection current distribution values

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. 2.31**.

Conductive Mortar as Anodic Material for Cathodic Protection of Steel in Concrete (2010)

Jing and Wu (2010) studied the behaviour of carbon fibre reinforced cement as a secondary anode material used for cathodic protection of steel in concrete. The mechanical, electrical and electrochemical properties of this conductive mortar were investigated. The experiments were performed on two different sizes of specimens- one was a cylindrical specimen and the other was a rectangular bar specimen. It was observed that the mechanical performance of mortar was improved by the addition of carbon fibres. Both compressive and flexural strength were found to increase with the fibre content (**Fig. 2.32**). Ductility of mortar was also increased on addition of carbon fibres.

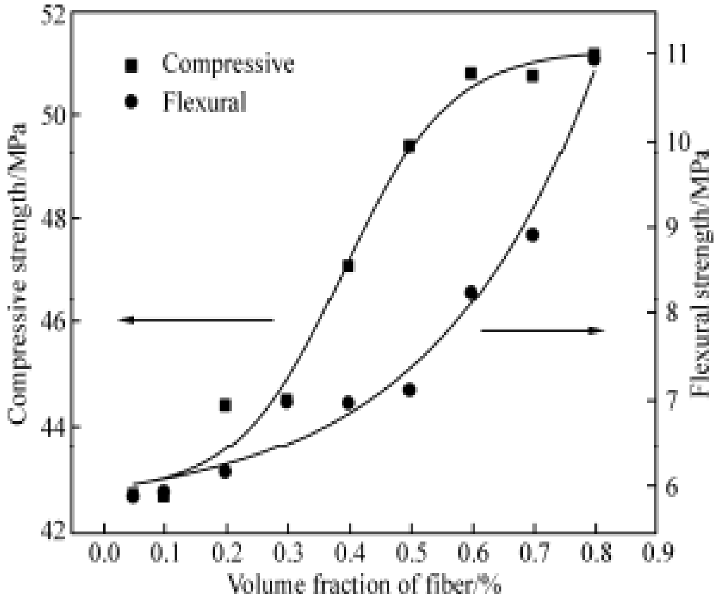


Fig. 2.32: Compressive strength and flexural strength as functions of fibre content

The electrical properties of the mortar were also affected by the fibre content (**Fig. 2.33**). For specimens with over 0.3 vol % of fibre, the electrical resistivity was decreased. However, at higher fibre content (over 0.6 vol %), the additional fibre had no significant effect on the decrease of resistivity.

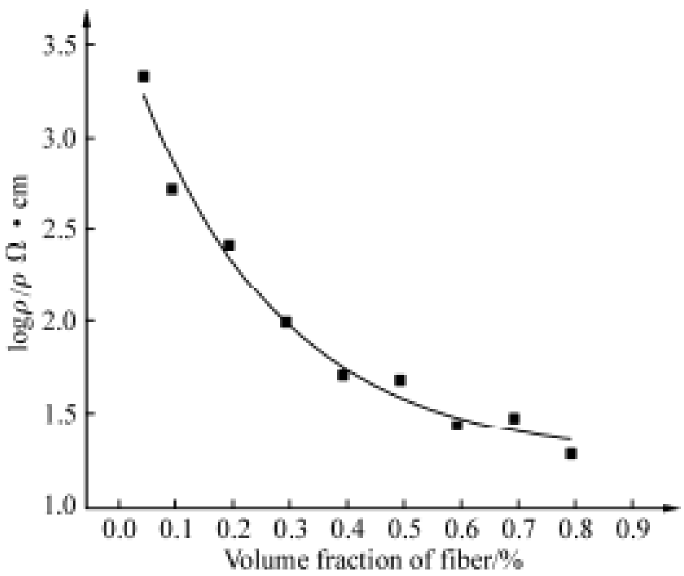


Fig. 2.33: Resistivity versus carbon fibre content for mortar systems

The anodic polarization behaviour of the specimens immersed in aqueous solution of saturated $Ca(OH)_2$ was studied in the absence and presence of 3% NaCl. The electrochemical parameters of conductive mortar were calculated based on EIS measurements. It was found that the electrochemical behaviour was influenced not only by the fibre content, but also by the solution composition. The mortar containing greater fibre content was characterized by lower resistance and higher potential stability during anodic polarization. However, the electrochemical property of mortar had more inclination to deteriorate when the chloride ions were present. Based on the study of mechanical, electrical and electrochemical parameters, it was concluded that the optimum fibre content in the conductive mortar should lie in the range of 0.5 vol% - 0.7 vol%.

Active Protection of Fibre 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 non-destructive techniques such as potentiodynamic 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 provided an overview of various factors affecting rebar corrosion, the mechanism involved in corrosion, various DT and NDT corrosion monitoring techniques, active and passive protection provided by CFRP and GFRP, use of cathodic protection and its limitations. The current research involves impressed current cathodic protection technique for the protection against rebar corrosion. The pull-out strength technique and ultrasonic pulse velocity technique are used as performance metrics of corrosion monitoring.

CHAPTER 3
ULTRASONICS FOR HEALTH MONITORING

3.1 GENERAL

In spite of the use of better materials, design practices and corrosion inhibiting systems for RC structures, a large cost and heavy damage is associated with the problem of rebar corrosion. The public demands for RC structures that are functional, cost effective, reliable and safe. This emphasizes the need for the inspection of RC structural health. To date, numerous on-site non-destructive and semi-destructive testing methods are available for detecting corrosion (discussed in the previous chapter). However, many of these methods are time-consuming and require the structure to be temporarily shut down. The closure will create indirect costs associated with the use of the method. Direct costs associated with the use of the methods are the human task force sent out to inspect the structure and the equipment involved. Most of the methods rely heavily on the inspector's expertise to visually assess damage and their knowledge of the equipment to inspect the structure. For some structures, the demand of having an inspector on-site poses safety risks. Other methods that can avoid on-site inspections, such as a ground penetrating radar from a moving vehicle, are generally structure specific, allowing for inspection of only certain parts of a structure (e.g., bridge deck). Therefore, a demand exists for smart structural health monitoring systems. The development of an embeddable corrosion monitoring system for RC structures can be one such method.

Embeddable sensors, in conjunction with artificial intelligence systems (e.g., neural networks, case based reasoning and fuzzy logic) for the processing and interpretation of data, would allow for continuous updates of structural health and real-time decision-making capabilities to ensure serviceability and safety requirements. Since the corrosion process occurs in multiple stages, it is doubtful that one particular method or technique can monitor the entire process. Within recent years, several embeddable sensors for detection and monitoring of corrosion in reinforced concrete have been or are currently being developed. A need still exists for an embeddable sensing method that will allow for a more direct assessment of the condition (e.g., steel cross-sectional loss and bond loss) of the reinforcing steel. Towards the development of such a methodology, a guided wave approach has been undertaken. An ultrasonic approach has been chosen because of the relative feasibility of using an embedded ultrasonic network for monitoring corrosion in real structures (*Ervin and Reis, 2008*).

The ultrasonic approach refers to the study of sound waves having frequencies higher than the human audible range i.e., above 20 kHz. Upper range of these waves can be as high as 15-30 GHz. However, for most SHM applications, the upper bound of frequency rarely exceeds 20MHz. Ultrasonic monitoring is based on the ability of ultrasonic waves to "see through" solid/opaque material and detect surface or internal flaws without affecting the material adversely. It is noteworthy that there are no changes in the dimensions of the structure that is examined by ultrasonic test. This can be achieved only when the maximum applied stress do not exceed the elastic limit so that the resultant strain is proportional to the applied stress. Hence, it is necessary that the ultrasonic intensity is sufficiently low for the elastic limit not to be exceeded. It involves introducing a very low energy level, high frequency stress pulse or 'wave packet' into a material and observing the subsequent propagation and reflection of this energy. The means for introducing and detecting the stress waves are based generally on the piezoelectric effect. The ultrasonic waves are sensitive to the location, extent and character of defects in a structure and, the wave characteristics change accordingly. By studying the propagation, reflection, and attenuation of these waves, it is possible to determine the fundamental properties of the materials such as elastic constants and damping characteristics and employ them for damage diagnosis. Thus, non-destructive ultrasonic technique can be used as a means for monitoring the soundness/ health of structures by the propagation of acoustic waves through structures.

3.2 ULTRASONIC GUIDED WAVES

This section provides an understanding of ultrasonic guided waves

3.2.1 Introduction

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.

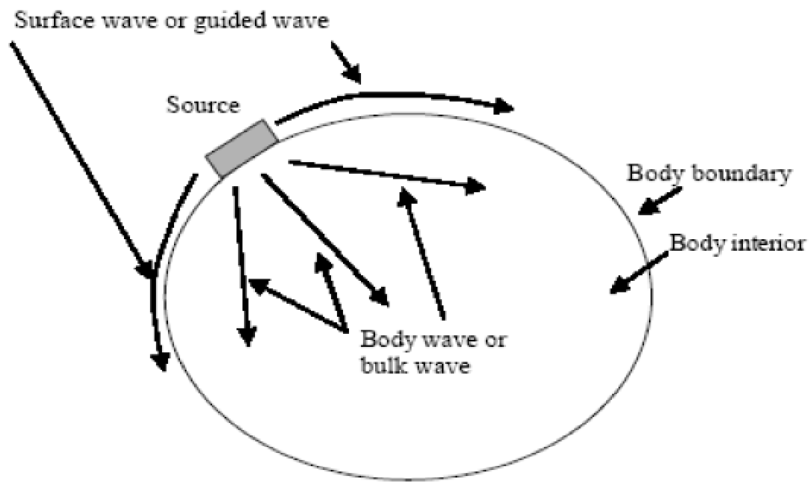


Fig. 3.1: Body waves and Surface waves generated by an ultrasonic source (*Kundu, 2004*)

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**).

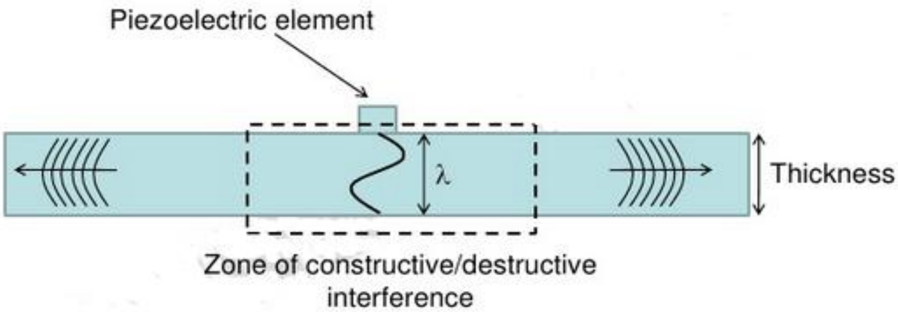


Fig. 3.2: Propagation of guided waves through a structure (*www.wins-ndt.com*)

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.

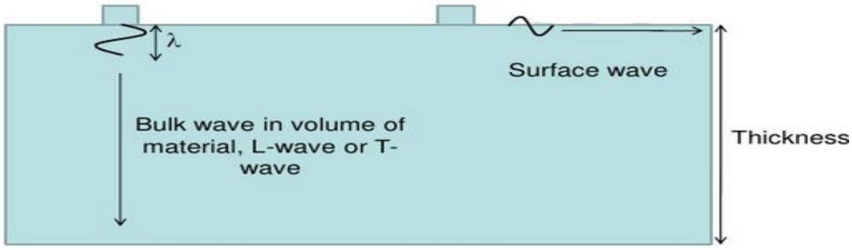


Fig. 3.3: Wave Propagation when thickness of material >> wavelength

(*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:

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

3.2.2 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

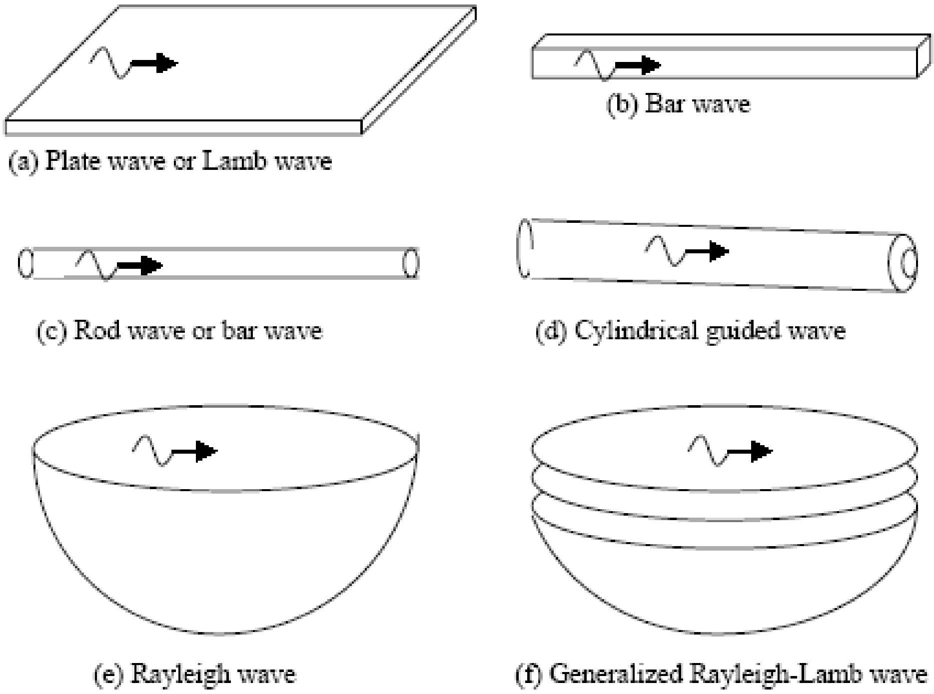


Fig. 3.4: Different types of guided waves (*Kundu, 2004*)

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.

3.2.3 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 cylindrical guided waves as the test specimens are cylindrical RC structures. There are three types of propagating waves, or modes in a cylindrical 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) and F(m,n) respectively. In this notation, 'm' represents the circumferential displacement and is a function of cos(mθ) , 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.

3.2.4 Limitations of Guided Waves

There are few limitations of guided waves such as:

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

3.3 ULTRASONIC TESTING

3.3.1 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 focussing, 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 NDE 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 ultrasonic waves require a transducer that is made of piezoelectric ceramics, composites or polymer. The transducer has the capability of converting a high voltage electrical pulse to a burst of sound waves and vice-versa. There are five types of transducers commonly used for ultrasonic flaw detection: Contact Transducers, Angle Beam Transducers, Delay Line Transducers, Immersion Transducers and Dual Element Transducers. The current research uses Contact Transducers. As the name implies, contact transducers are kept in direct contact to the surface of the material (**Fig. 3.5**). Sometimes good contact requires the use of a coupling 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.

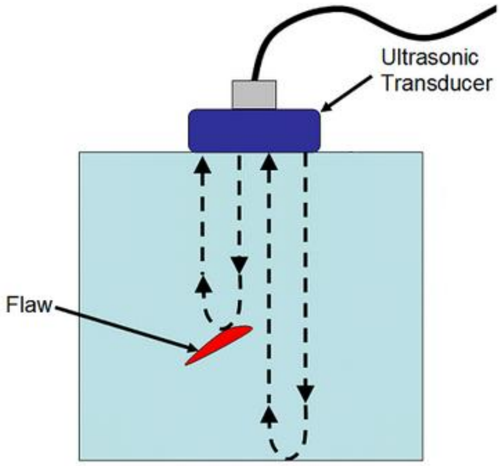


Fig. 3.5: Principle of Ultrasonic wave generation and detection (*www.ni.com*)

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:

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

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:-

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

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**.

Table 3.1: Longitudinal Pulse velocity v/s concrete (*Song and Saraswathy, 2007*)

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.

3.3.2 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.

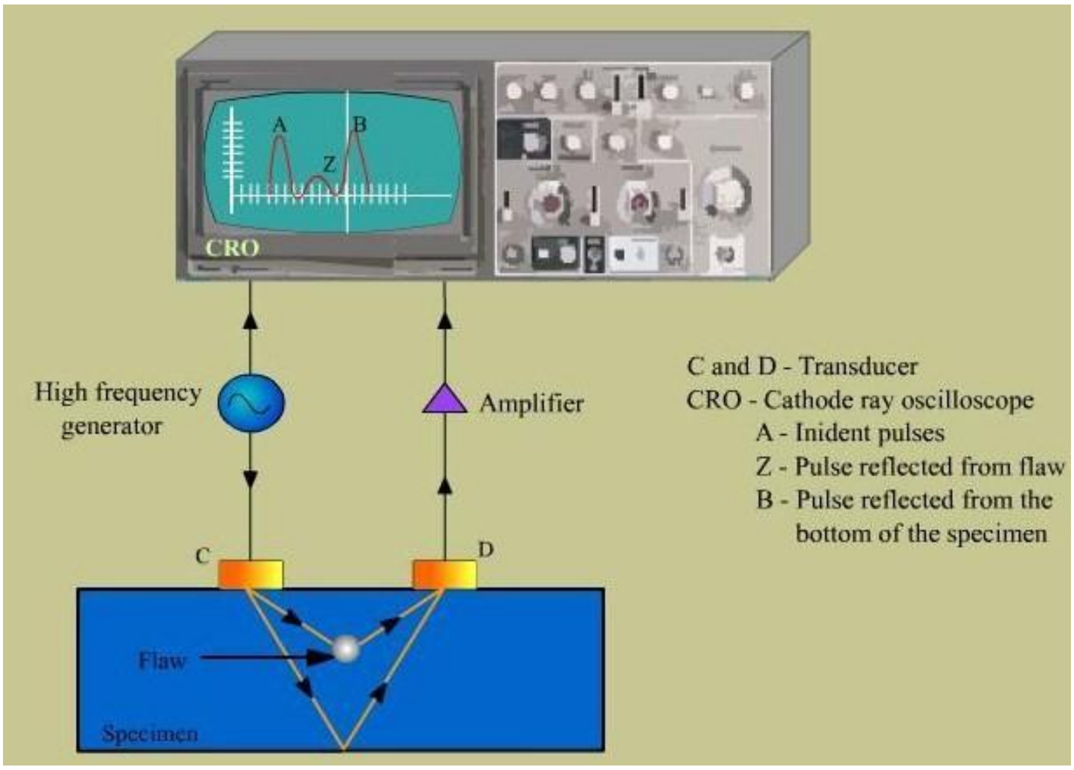
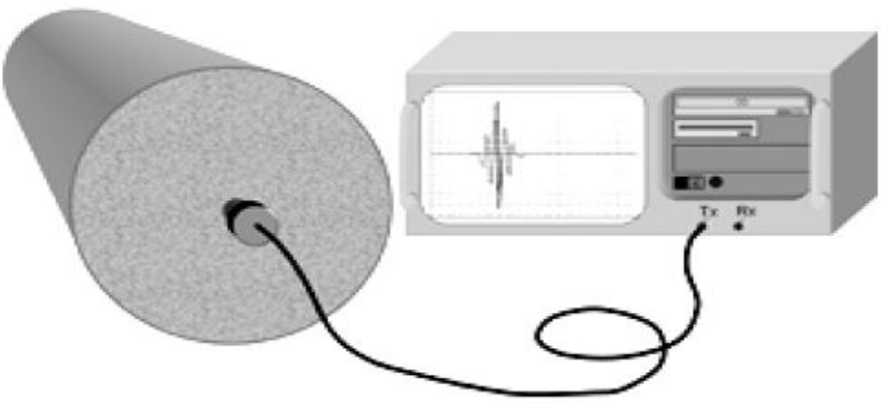


Fig. 3.6: Pulse Transmission method of testing

(www.*msheiksirajuddeen.blogspot.in*)

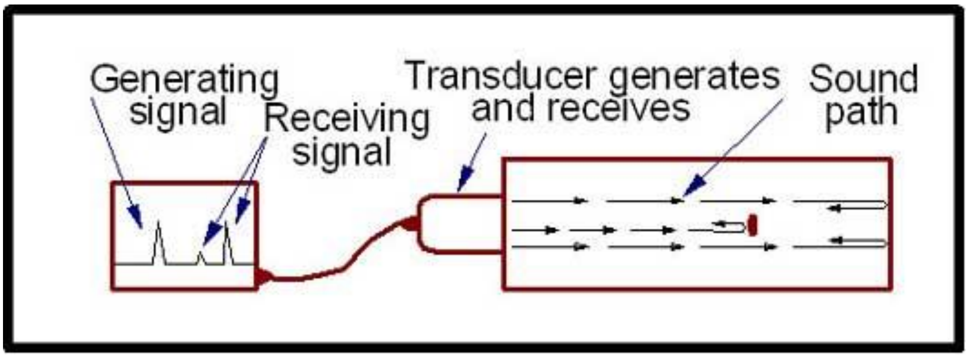
(a) Pulse Echo method

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**).



(a)

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



(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:

$$D = V\,t \qquad (3.3)$$

where,

D = Distance of defect from transducer end,

V = Velocity of wave and,

t = Time of Flight

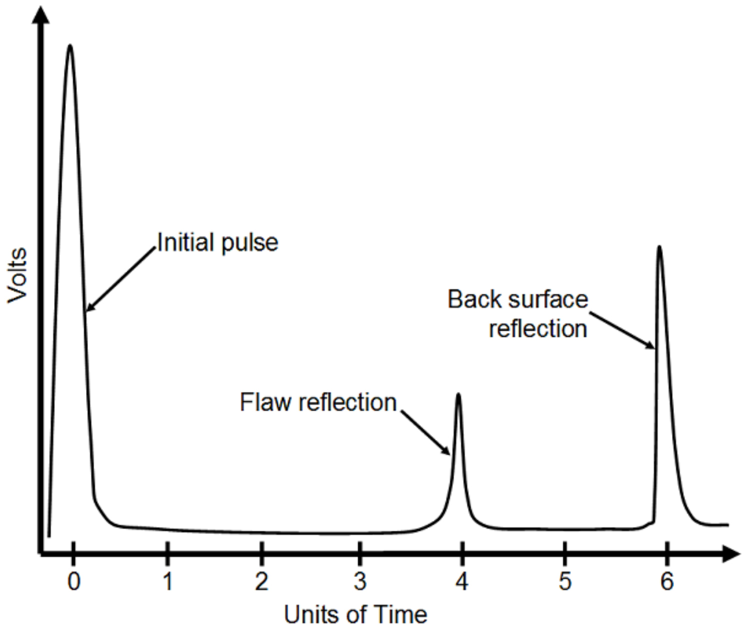


Fig 3.8: Pulse Echo method of testing (*www.ni.com*)

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.

3.3.3 Limitations of Ultrasonic guided wave testing

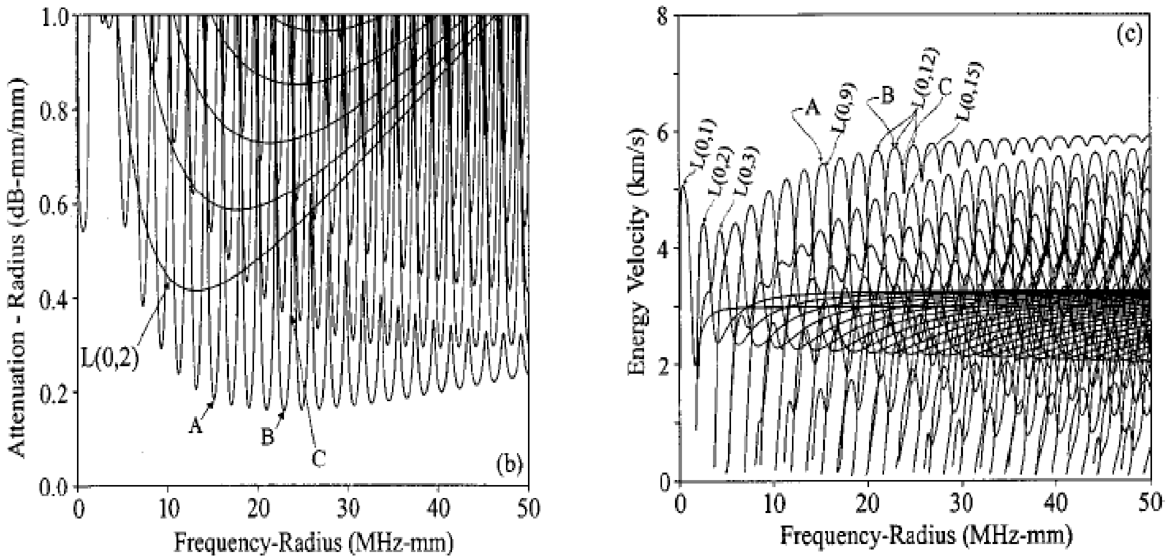
One disadvantage of guided waves for monitoring corrosion in reinforced concrete is the limitation of inspection range for certain modes and frequencies. Unlike guided wave propagation in other multilayered systems, such as a metal pipeline in air, wave energy in steel bars embedded in concrete is lost (i.e. attenuated) at high rates due to leakage into the surrounding concrete. Apart from leakage of guided waves, the reflection coefficient of defects such as breaks and patches also causes a problem. The recent discovery of high frequency, low-leakage guided modes (*Pavlakovic et al., 2001*) has the potential to reduce the attenuation due to leakage, although the reflection coefficients from defects need to be determined. In addition, lower frequency modes may offer an alternative to the high frequency modes for detection of surface/interfacial damages. Hence, in the present work, it is proposed to use high and low frequency guided wave modes for corrosion detection in steel embedded in concrete. Another disadvantage of ultrasonic guided wave technique is the difficulty to find flaws in complex sized or shaped structures, where reflections from multiple features are not resolved in time, and it becomes impossible to detect an individual reflection or an extra reflection from a defect. Hence, a reliable structural health monitoring system for complex structures requires a great deal of research to find a method that can compensate the benign changes such as temperature variations, moisture uptake, ageing, etc. (*Cawley, 2007*). Some other limitations of ultrasonic guided wave technique are extensive technical knowledge required for efficient monitoring, difficulty to inspect materials that are rough, irregular in shape, very small or non-homogenous and requirement for couplants to provide effective transfer of ultrasonic wave energy between transducer and the inspected structure.

3.3 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 axisymmetric L(0,n) modes of steel bar imbedded in grout (a) attenuation; (b) energy velocity

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,

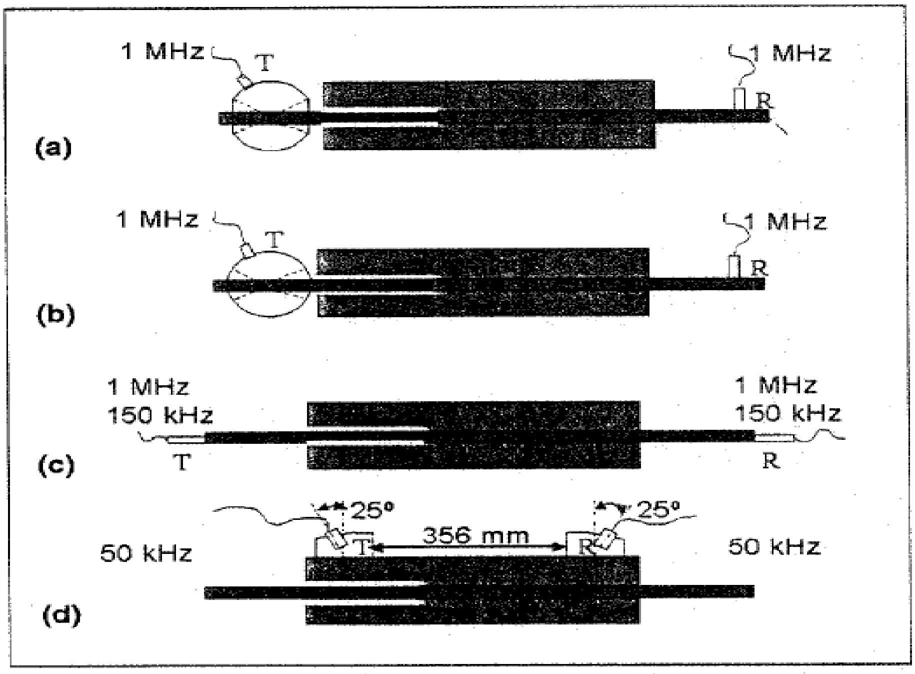


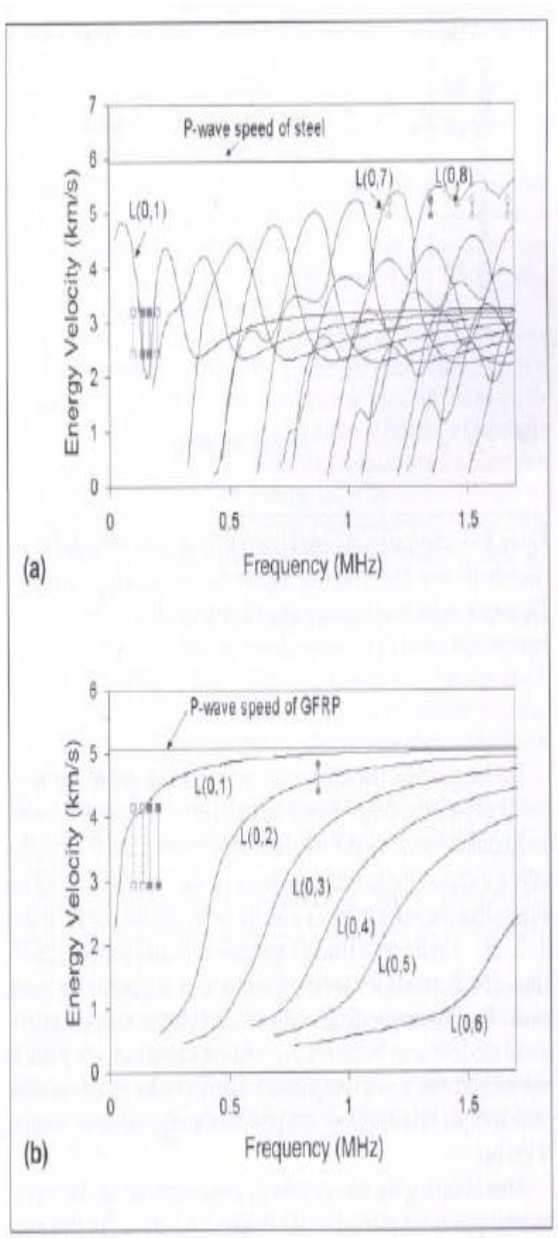
Fig. 3.10: Different transmitter/receiver arrangements for experimental investigation: (a and b) spherical solid coupler transducer holders; (c)transmitter and receiver in direct contact at the ends; (d) solid coupler transducer holder on concrete with 25 degree incident and reception angles

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.

A Comparison of Steel / Concrete and Glass Fibre Reinforced Polymer / Concrete Interface Testing by Guided Waves (2002)

Na et al. (2002) investigated the feasibility of using ultrasonic guided wave testing technique for detecting delamination at GFRP rod- concrete interface. The experimental investigations involved ultrasonic testing in through transmission mode for both glass fibre reinforced polymer and steel bars embedded in concrete to study the effect of high attenuation shown by GFRP. Two transmitter-receiver arrangements with transducer's center frequency of 50 kHz, 150 kHz and 1 MHz, were applied to propagate guided waves through the specimens, and Ultrasonic tests were carried out. Frequency v/s signal amplitude curves i.e., V(f) curves were obtained after ultrasonic testing. It was observed that the testing sensitivity was not affected by the high attenuation of GFRP bar and therefore, guided wave technique can be applied equally well for detecting delamination at GFRP/Concrete and Steel/Concrete interface.

The dispersive behaviour shown by the guided waves was also studied. The specimens were modelled as GFRP bars of finite diameter embedded in an infinite concrete medium, for wave mode identification. Ultrasonic testing was done to obtain the material properties, and these were used to plot energy velocity curves (**Fig. 3.11**) and attenuation dispersion curves (**Fig. 3.12**). The experimental observations from the curves conclude that ultrasonic guided wave technique can be used for GFRP-concrete interface testing.



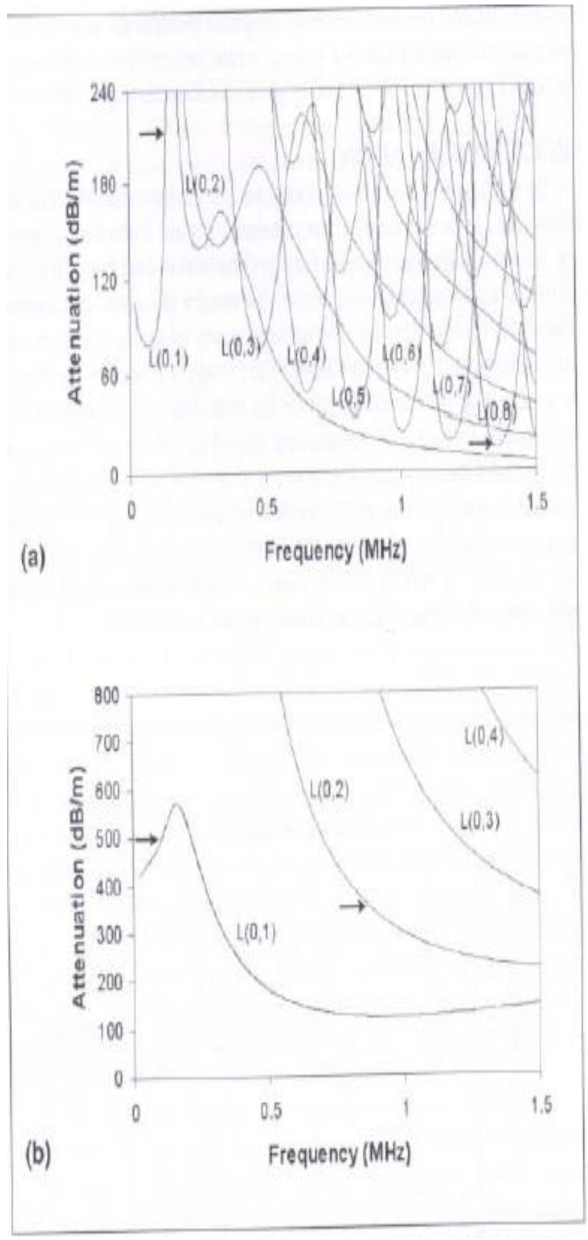


Fig3.11: Energy velocity dispersion curves (a) Steel embedded in concrete (b) GFRP embedded in concrete

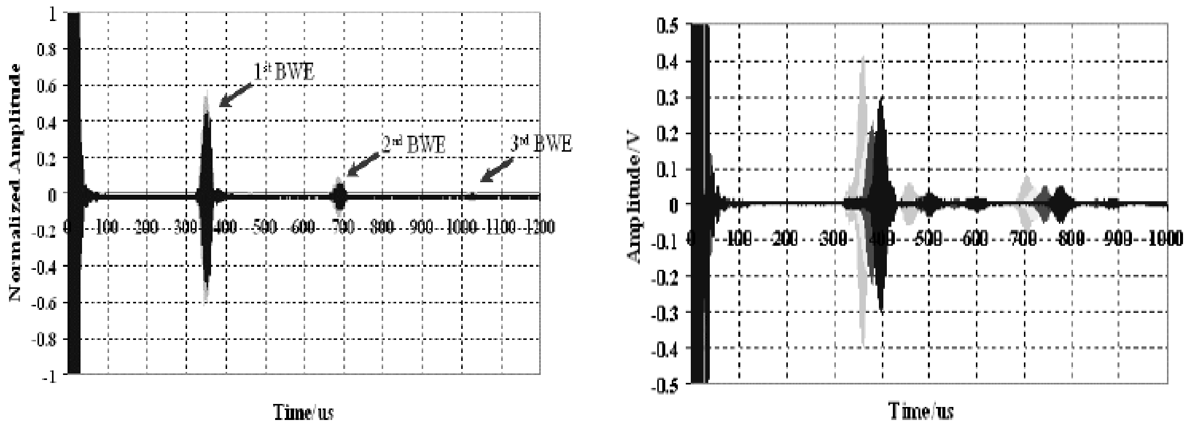
Fig3.12: Attenuation dispersion curves (a) Steel embedded in concrete (b) GFRP embedded in concrete

Ultrasonic Guided Waves for Inspection of Grouted Tendons and Bolts (2003)

Beard et al. (2003) proposed a method using guided ultrasonic waves to inspect grouted steel tendons, anchors and rock bolts for corrosion and fracture. Two types of reinforcing tendons were constructed- single wire (5 or 7 mm in diameter) and 15 mm seven wire strands. A pulse-echo technique was carried out from the free end of the structure to measure the attenuation experienced by the wave in short lengths of grouted tendons. The amount of attenuation that the wave experienced because of leakage into the embedding material and material losses, was used to evaluate the reflection coefficient of the modes from different geometry breaks. The measurements of attenuation and reflection coefficients were used to determine the maximum length of tendon that can be inspected using this method. The experimental results illustrated that the inspection range for a complete break was limited to about 1.2 and 0.8 m for 7 and 5 mm dia wires respectively. For 15 mm stranded tendons, the inspection range was limited to about 1.5 m for the center wire and about 0.5 m for the six outer wires. This indicate that the use of guided waves for the inspection of small diameter tendons would be limited to provide confirmation of defects in localized areas, due to high level of attenuation and poor reflection of modes. However, it was seen that with an increase in tendon diameter (25-30 mm), the attenuation reduces considerably. The rebars and grouted bolts with a large steel diameter, generally have flat ends which are good reflectors of low-leakage modes. And, it was found that the inspection range of such structures could be as much as 5 m.

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

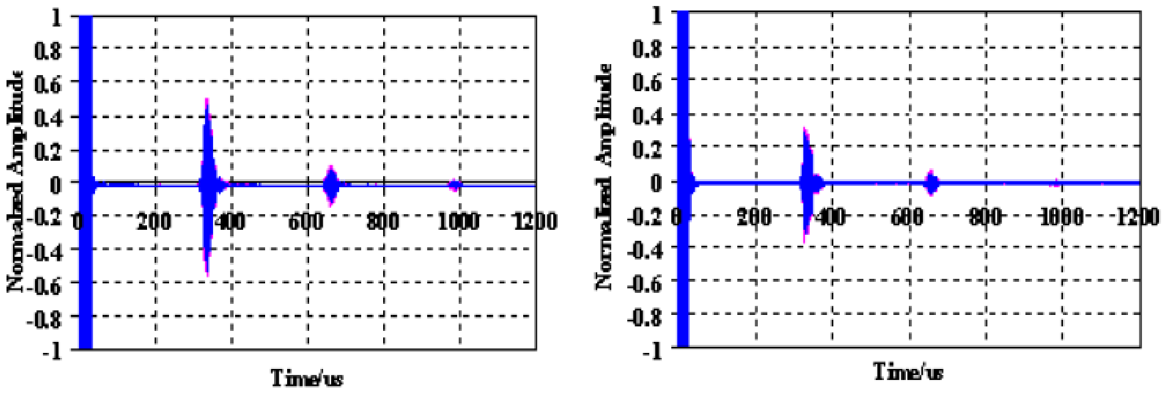
He et al. (2006) investigated the use of ultrasonic guided waves in a two-layered structure (composed of solid steel and semi-infinite layer of concrete) to measure the length of steel rod embedded in concrete and to estimate the amount of delamination between a steel rock bolt and concrete. A Semi-Analytical 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 3.13**.



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

Fig. 3.13: 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

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. 3.14** 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. 3.14: 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.

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 realise 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. 3.15**).

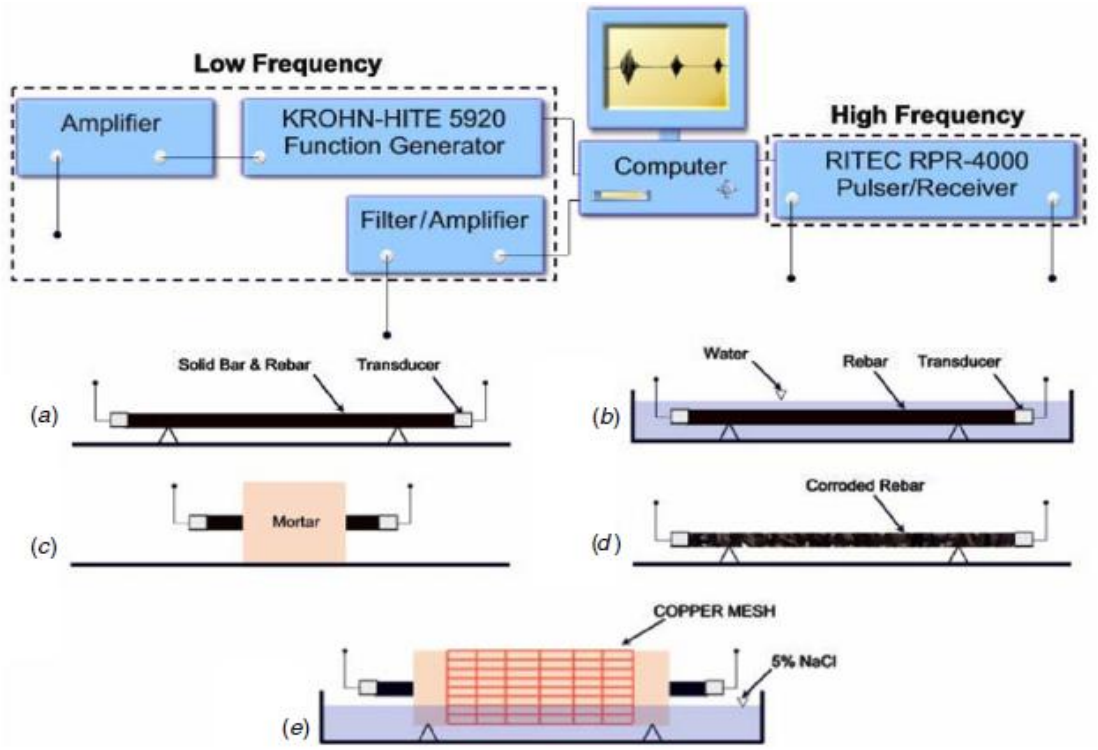


Fig. 3.15: Through-transmission testing for low- and high-frequency longitudinal wave testing on (a) a solid bar and rebar in air, (b) rebar immersed in water, (c) rebar embedded in mortar, (d) corroded rebar in air and (e) reinforced mortar specimens undergoing accelerated uniform corrosion.

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. 3.16**.

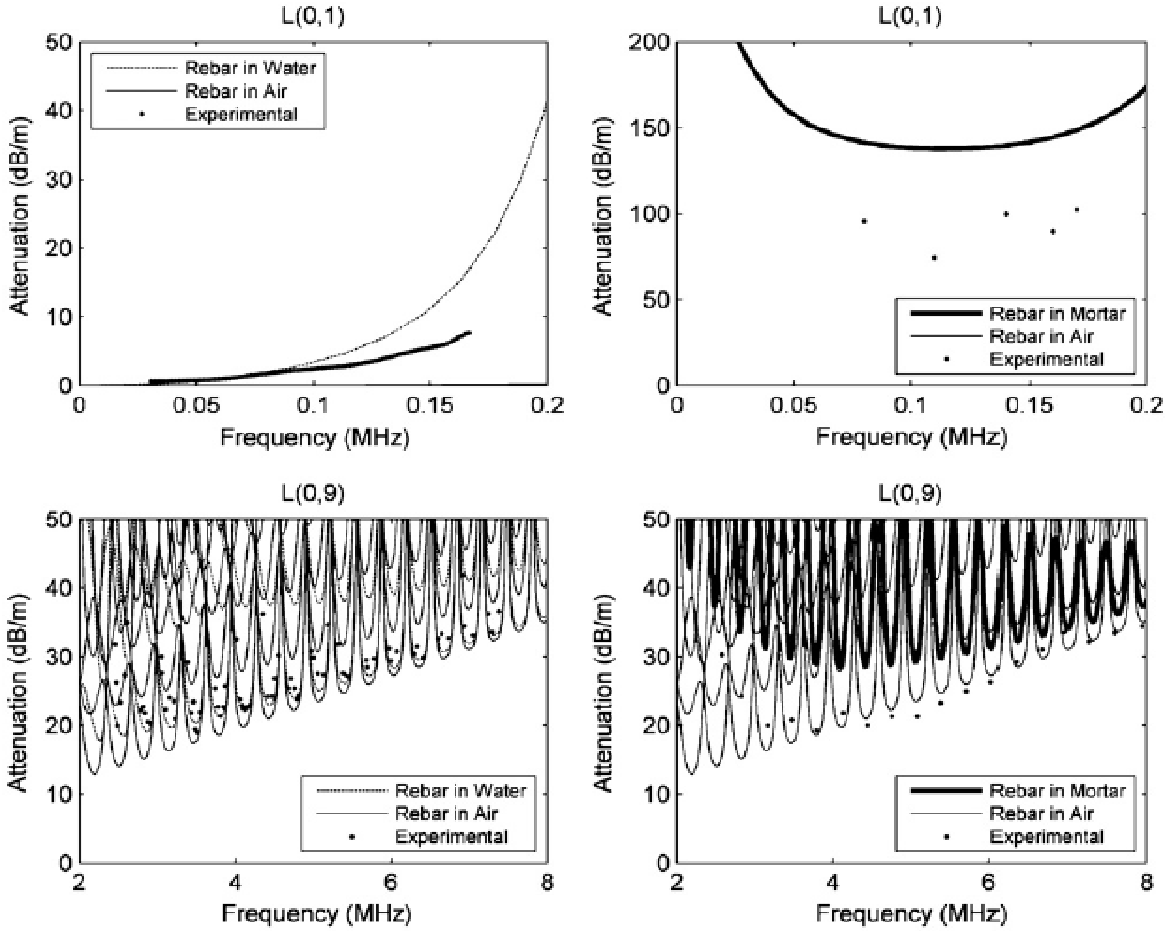


Fig. 3.16: Theoretical attenuation curves with experimental attenuation measurements for rebar in air, immersion in water and embedment in mortar at low and high frequencies

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. 3.17**).

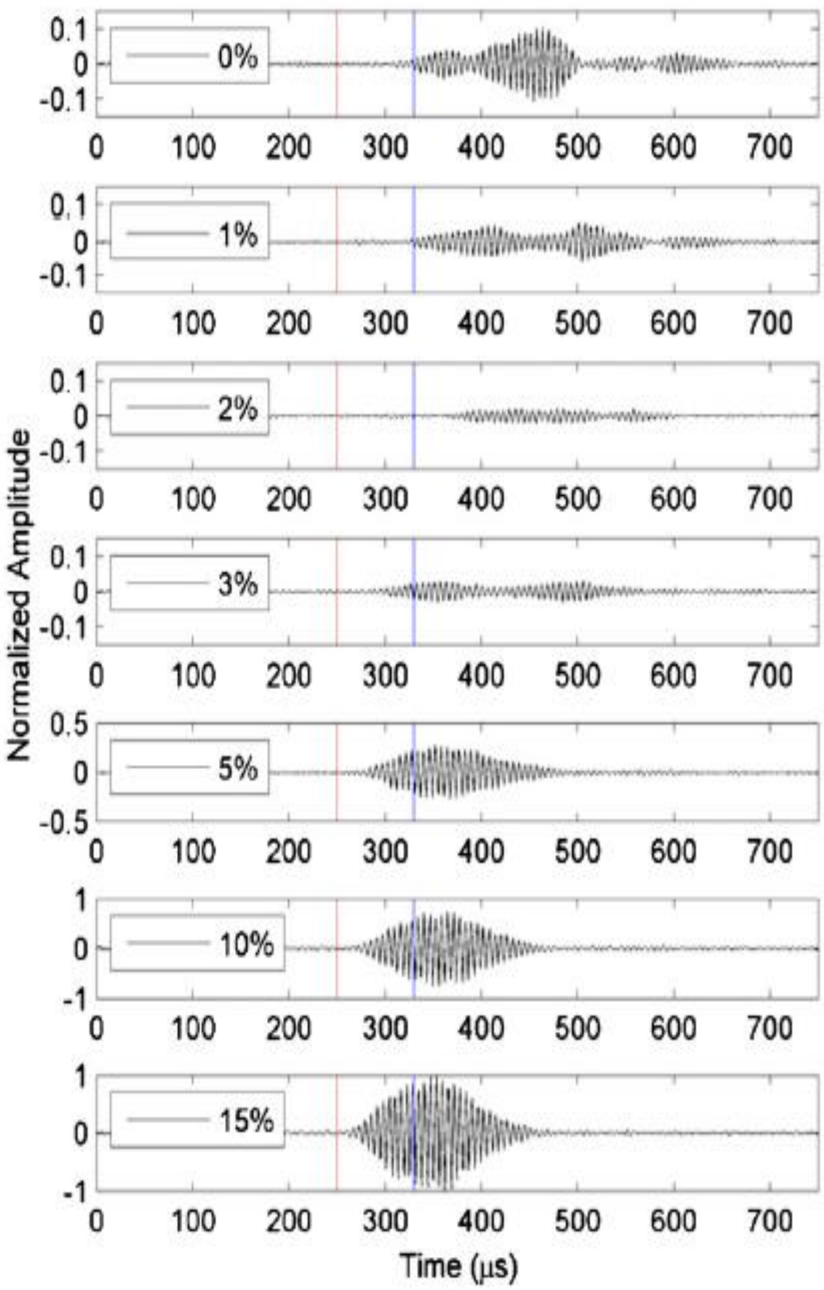


Fig. 3.17: Time domains at different levels of mass loss for low-frequency monitoring of accelerated corrosion. Left and right vertical lines are the arrival times for the L(0, 1) and F(1, 1) modes, respectively. The input signal was a 164 kHz 15-cycle pulse, with a band pass of 159 kHz and 169 kHz.

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. 3.18**).

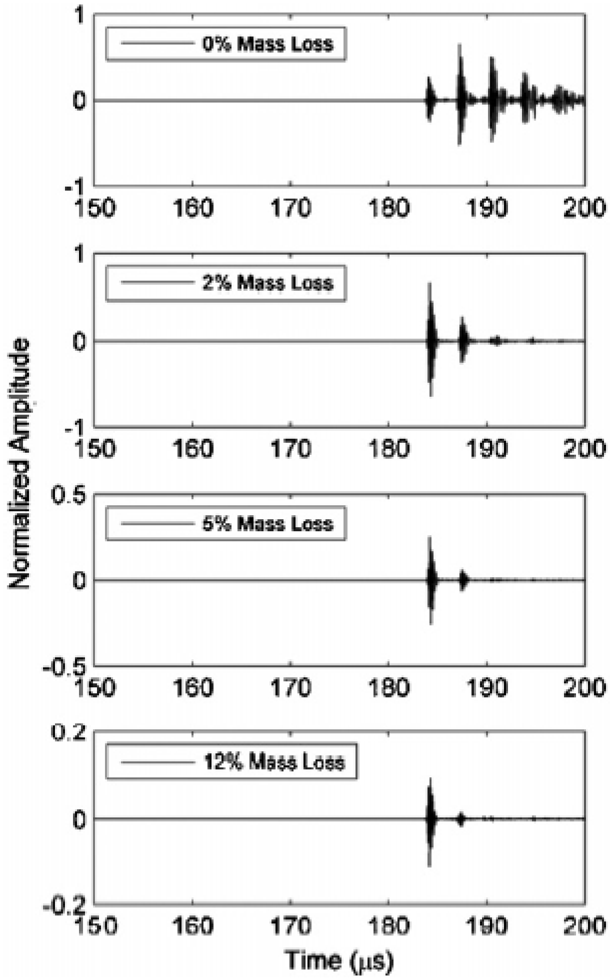


Fig. 3.18: Time domain response at different levels of mass loss for high-frequency monitoring of accelerated corrosion. The input signal was a 5.08 MHz single cycle pulse, with a bandpass of 2 MHz and 10 MHz.

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 (P_{avg}), maximum amplitude (P_{max}) and maximum power- frequency ratio ($(P/F)_{max}$) 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 G_F , fracture energy was obtained. A correlation analysis was performed at each ageing temperature, between the non-destructive parameters (P_{avg} , P_{max} , $({}^{P}/_{F})_{max}$) and destructive parameter (G_F , as shown in **Fig. 3.19**.

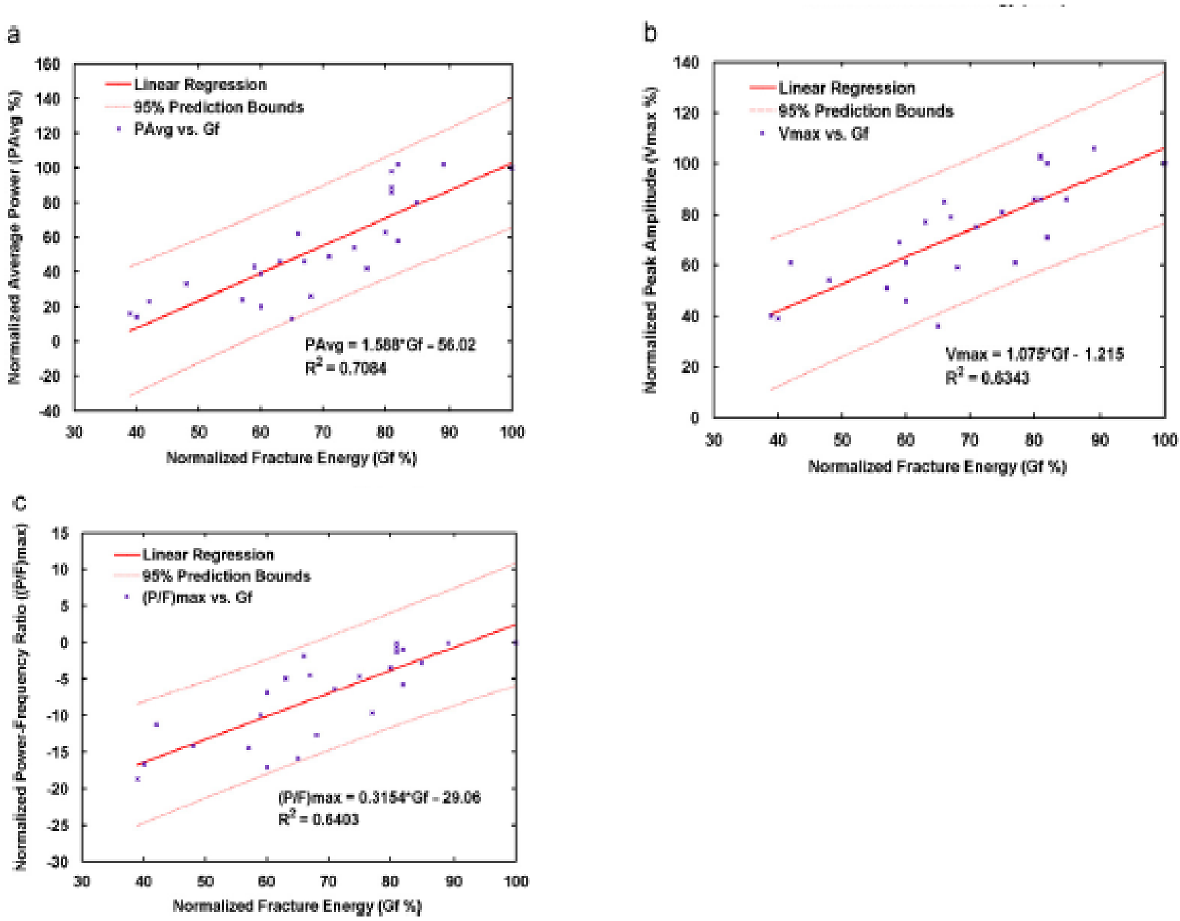


Fig 3.19: Linear regression of non-destructive ultrasonic parameters vs. fracture energy results of CFRP–concrete samples subjected to accelerated aging temperatures: (a) average power(P_{avg}) vs. Fracture energy(G_F), (b) peak amplitude(Vmax) vs. Fracture energy(G_F), and (c) maximum power–frequency ratio of PSD ((P/F)max) vs. fracture energy(G_F). Linear equations and 95% prediction bounds are shown.

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 sch 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 3.20 (a) and (b)** respectively.

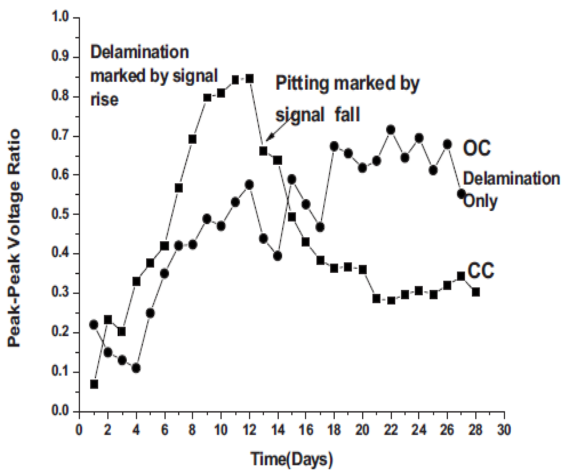


Fig. 3.20(a) : Peak-peak voltage ratio with surface-seeking mode

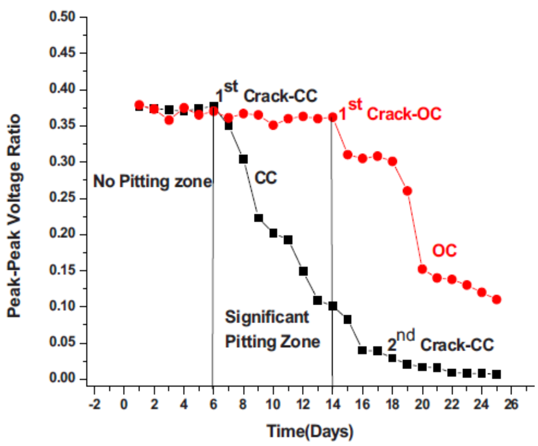


Fig. 3.20(b) : Peak-peak voltage ratio with core-seeking mode

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.

3.5 CLOSING REMARKS

This chapter highlights the basics of ultrasonic waves, different types of guided waves, modes of propagation of ultrasonic guided waves in reinforcing bars, ultrasonic testing techniques available and the limitations of guided waves. The current research uses Ultrasonic guided wave technique for monitoring corrosion in actively and passively protected RC Structures.

CHAPTER 4

EXPERIMENTAL PROGRAM

4.1 GENERAL

The objective of this study is to evaluate the efficacy of ultrasonic guided waves to be able to monitor the behaviour of RC cylindrical specimens during various stages i.e., after the initiation of corrosion, and after the protection of cylindrical specimens with the help of FRP's (Glass Fibre Reinforced Polymer and Carbon Fibre Reinforced Polymer). Also, the destructive tests (pull-out tests) 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 test program involved:

1. Determination of basic properties of constituent materials namely cement, fine aggregates, coarse aggregates and steel bars as per relevant Indian standard Specifications.
2. Casting of concrete cylinders of diameter 150 mm and height 300 mm with a 600mm steel rod embedded in it such that 300 mm of steel rod is inside the concrete cover, using M20 grade concrete.
3. Subjecting the specimens to accelerated corrosion at a constant voltage of 5V. 0.3 ampere current was continuously monitored to ensure that corrosion is taking place.
4. Corrosion is continued for 3, 6 and 9 days of protection.
5. Retrofitting the specimens, corroded to different levels with CFRP and GFRP sheets debond protection.
6. Ultrasonic monitoring of the specimens after every 24 hours till the signals vanish.
7. Destructive tests of pull-out and mass loss of the cylindrical specimens after corrosion.

Fig. 4.1 shows the complete test procedure in the form of flow chart.

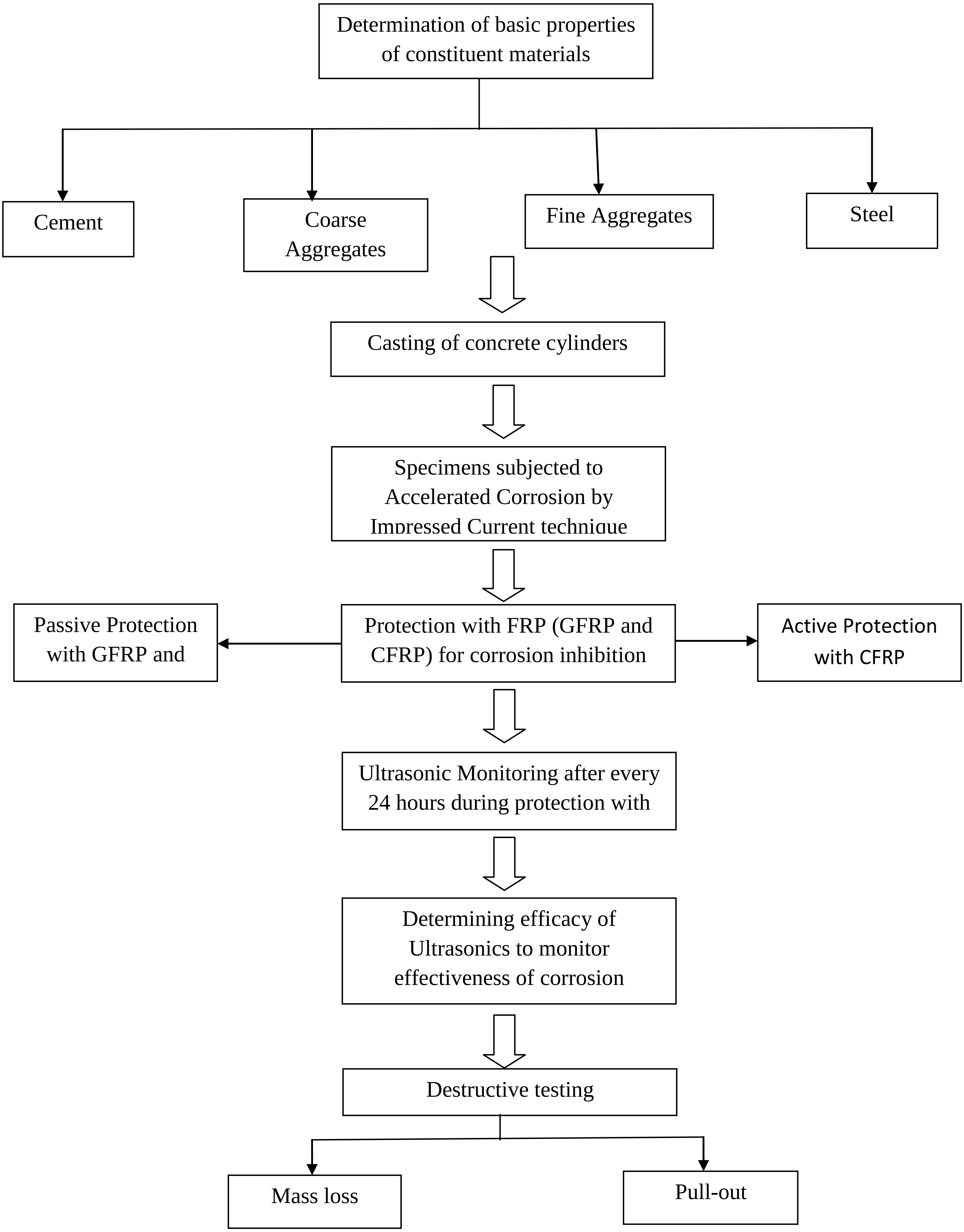


Fig. 4.1: Flow chart of test program

4.3 MATERIALS USED

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

- ***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.
- ***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	3.09	_
6	Compressive strength		
S. No.	**Days**	**Values Obtained Experimentally**	
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

- ***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= (195.73+500)/100 = 6.95

- ***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.
- ***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 cylindrical 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

- ***Fibre Reinforced Polymer:*** The FRP materials used are CFRP (Carbon Fibre Reinforced Polymer) and GFRP (Glass Fibre Reinforced Polymer) as shown in F**ig. 4.2** and **Fig, 4.3** below:

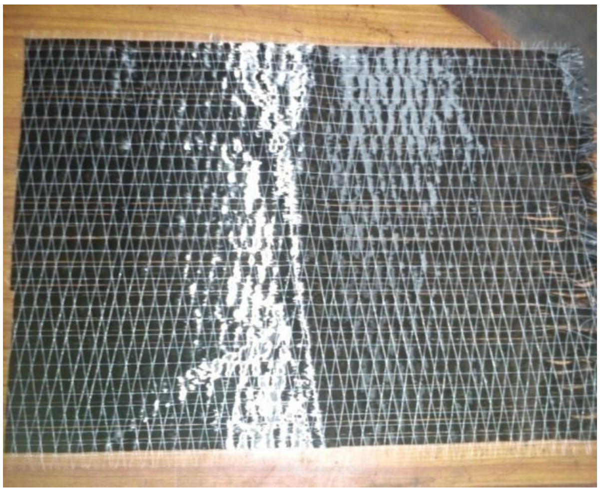


Fig. 4.2: CFRP laminate

Fig. 4.3: GFRP laminate

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

Table 4.7: Properties of CFRP and GFRP

Material	Thickness (mm)	Tensile Strength(MPa)	Tensile Modulus(GPa)	Ultimate strain	Electrical conductivity
CFRP	0.1176mm	3800	240	0.015	551
GFRP	0.35	2.30	76	0.018	-

- ***Adhesives:*** The adhesive used for bonding FRP sheets with concrete is a compatible epoxy system (MBrace) as shown in **Fig.4.5**. 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 saturant

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

Fig. 4.4: Adhesive used for bonding FRP with concrete

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 is 0.5 and compressive strength of concrete after 28 days 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 standard cylinders are cast in mould of dia 150 mm and height 300 mm with 300 mm of steel bar embedded in concrete cover and 300 mm of length exposed to the surrounding environment. First of all, interior of the cylinder mould is oiled, so that cylinders 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 vibrations are given so that the mix gets compacted. The vibration is done until the moulding is completely filled and there are no gaps left. The cylinders are then removed from the mould after 24 hours. After demoulding, the cylinders are cured for 28 days using a open tank. The concrete surface of the cylinders 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 cylindrical specimens were kept fully saturated by keeping each sample immersed in a bucket with 3.5 % NaCl solution. (**Fig. 4.5(a)**)

The rebar was made anode. A stainless steel (SS) mesh is rolled around the circumference of the concrete cylinder and tied together with metal ties in order to assure electrical continuity and is used as cathode (**Fig. 4.5(b)**). The constant voltage of 10 mV is impressed in order to accelerate corrosion. The DC power supply (Aplab) was used as a voltage source (**Fig. 4.6**). 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 along with time.

Fig. 4.5: (a) Cylindrical Specimens (b) Specimen wrapped with stainless steel

Fig. 4.6: Power Supply (Aplab)

4.5.5 Protection against corrosion by FRP wraps

Two fibre materials are popular in the rehabilitation of structures in India – Glass and Carbon Because of the electrical conductivity of carbon fibre, only CFRP has been used for active protection. However, comparison has been made between the active and passive protection offered by both glass and carbon fibre sheets. The fibres are applied in the form of unidirectional sheets. Glass fibre sheets are thicker than the carbon fibre sheets .In this investigation ,two often used, commercially available, unidirectional CFRP and GFRP sheets and compatible epoxy adhesive are used.

Method of applying wraps: The samples are air dried prior to the application of FRP wraps. Manufacturer's specifications are followed in the application of the wraps. A mixture of two components of epoxy resin and hardener is mixed in the ratio of 100:40 fro wrapping the carbon fibre sheets into concrete. Out of four specimens in a group, one was kept unwrapped .One layer of either CFRP or GFRP sheet was wrapped around the specimens with fibre along the circumferential direction of the cylinder (**fig. 4.7**). The entire length of the cylinder was covered. A 25 mm overlap was provided at the ends of the sheets. The remaining specimens were used for active protection. These CFRP wrapped test specimens were provided with additionally adhesive bonded 25 mm to 30 mm wide, vertically oriented carbon sheet to facilitate uniform distribution of direct current throughout the specimen for effective active protection. The epoxy adhesive used was modified to be conductive.

(a)

(b)

Fig. 4.7: Specimens wrapped with (a) CFRP (b) GFRP

Table 4.9: Test Matrix for Specimens

Wrap Material	Exposure in days	Protection	Nomenclature
Unwrapped samples	3	No	C-3
	6	No	C-6
	9	No	C-9
Wrapped with Glass fibre	3	Passive	PAG-3
	6	Passive	PAG-6
	9	Passive	PAG-9
Wrapped with carbon fibre	3	Passive	PAc-3
	6	Passive	PAC-6
	9	Passive	PAC-9
Wrapped with carbon fibre	3	Active	APC-3
	6	Active	APC-6
	9	Active	APC-9

4.5.6 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 fibre sheets that were wrapped around the cylindrical 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. One of the requirements of the system was to make its electrical conductivity uniform. A ribbon of carbon fibres was stitched through the CFRP sheet in the perpendicular direction of the fibres. 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 fibres 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 current of 50 mA was impressed between the carbon fibre (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.

4.5.7 Destructive Tests

(a)Pull-out test: Pull out test was conducted on all the specimens. When the specimens have been completely exposed to corrosion for about 40 days, the pull out test is carried out on them. This is done by securing the cylinder 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-echo (PE) testing method is adopted. In the pulse-echo method, a piezoelectric transducer with its longitudinal axis located perpendicular to and mounted on or near the surface of the test material is used to transmit and receive ultrasonic energy. The set-up for ultrasonic guided wave investigation is shown in **Fig. 4.8.** 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 digital to analog converter (DAC) digitizes the input and received pulse and is displayed on the display. The signals received are in form of voltage-time (V-t) graphs. The ultrasonic test set-up in this study uses DPR-300 pulse receiver system (**Fig. 4.9**) and Karl deutsch contact transducers (**Fig. 4.10**)

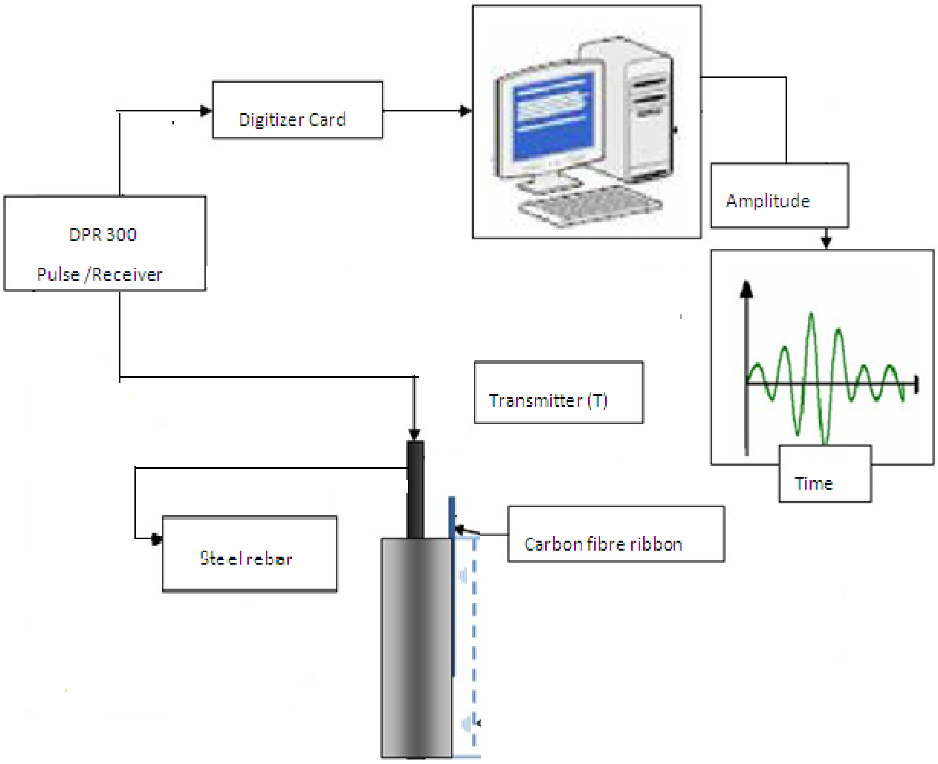


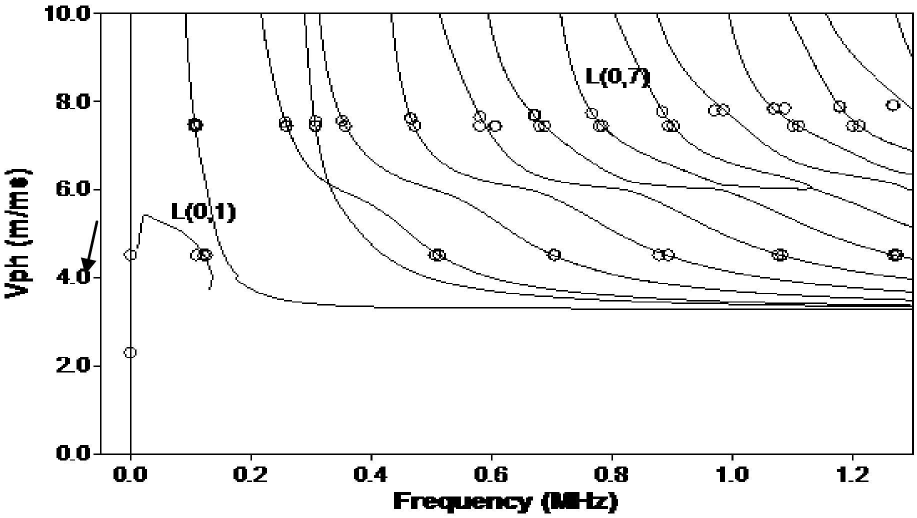
Fig. 4.8: Set up for P-E Ultrasonic investigations

Fig. 4.9: Contact type transducers (Karl deutsch)

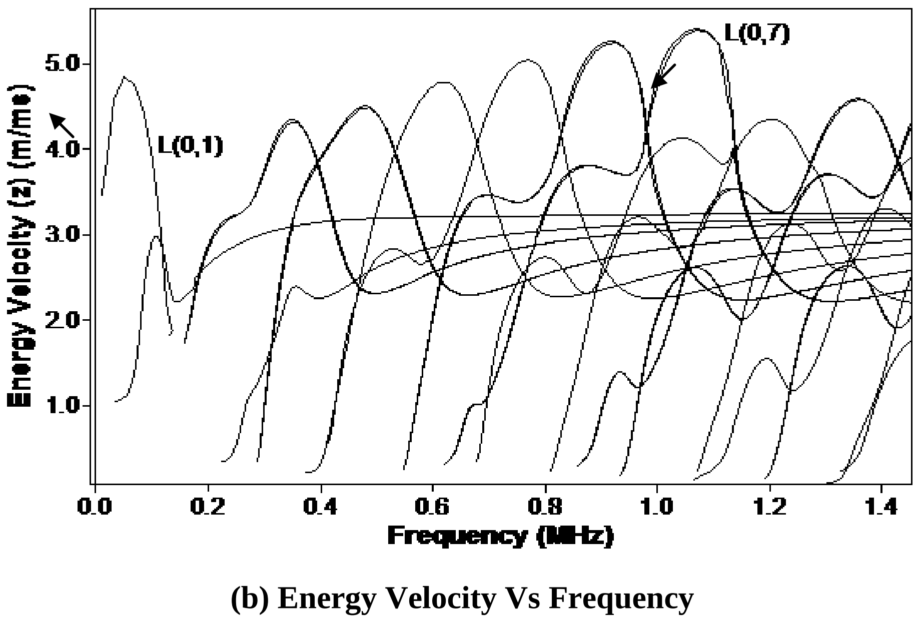
Fig. 4.10: Pulse Receiver (DPR 300)

4.6.2 Selection of Excitation mode and Frequency

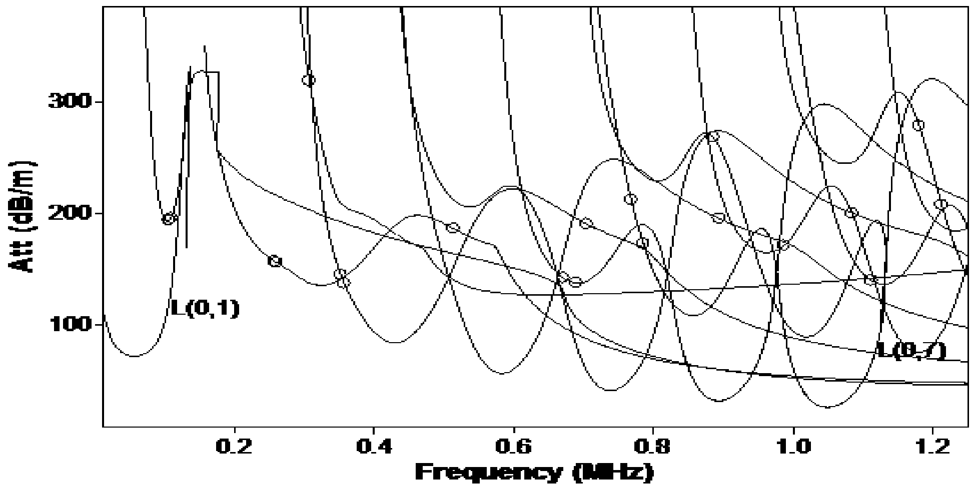
The selection of a suitable test mode and frequency is done after analyzing the dispersion curves using the software Disperse. According to *Sharma and Mukherjee (2010)*, modes that have lowest signal attenuation and at the same time are easily distinguishable are selected. Generally, modes at low attenuation 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. Dispersion curves for a mild steel bar of 25mm diameter are shown in **Fig. 4.11**.



(a) Phase velocity Vs Frequency



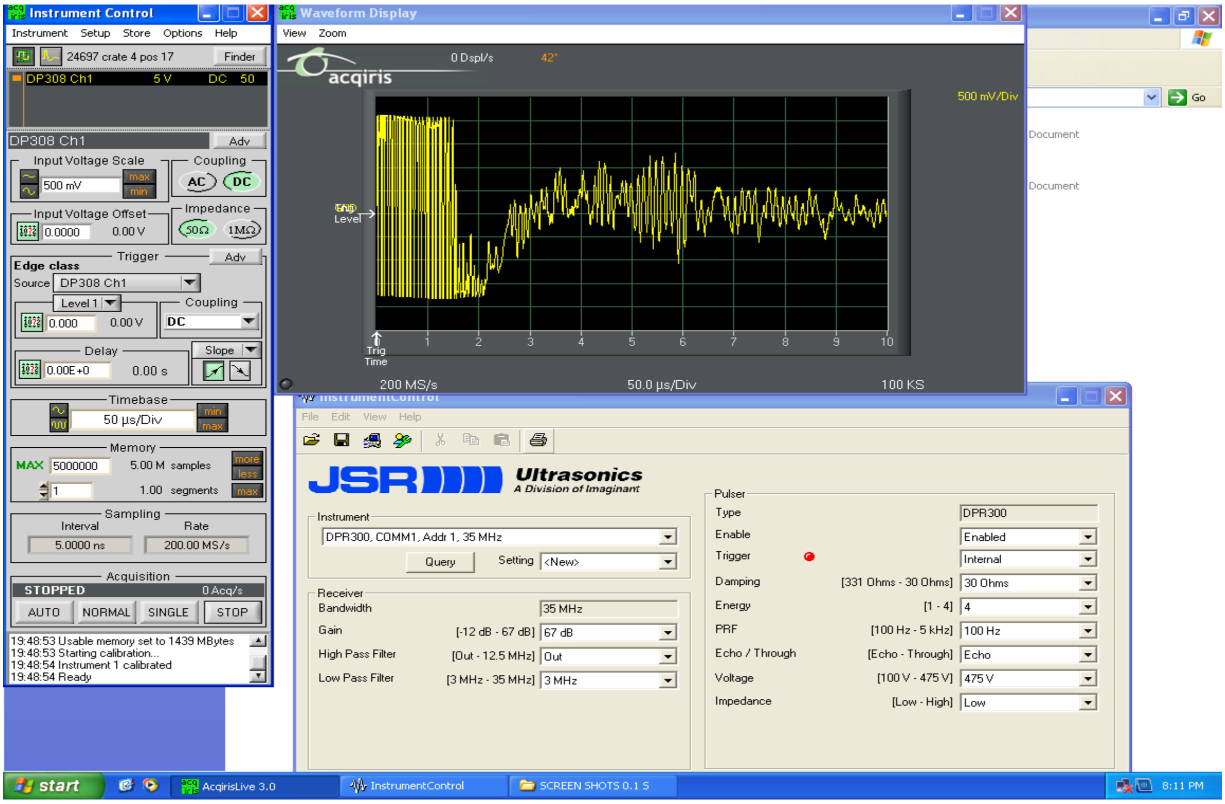
(b) Energy Velocity Vs Frequency



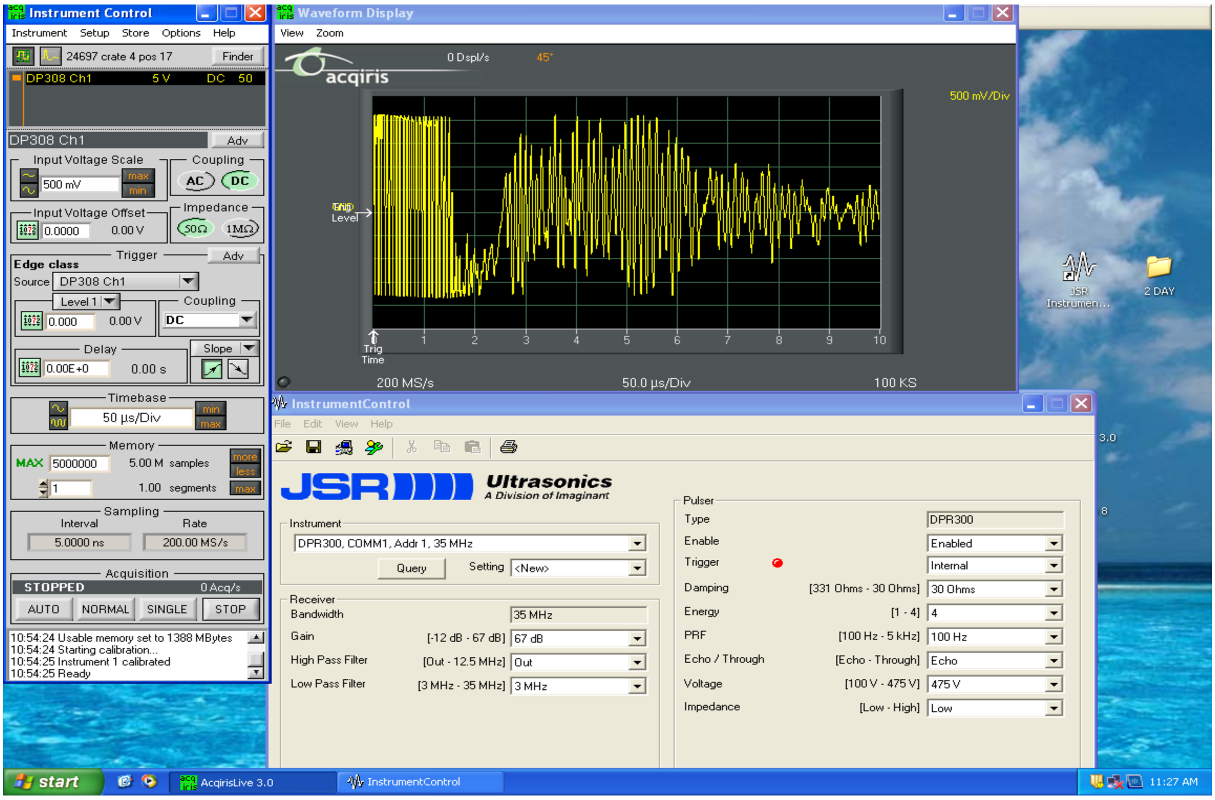
(c) Attenuation Vs Frequency

Fig. 4.11: Dispersion curves for 25mm dia bar (*Sharma & Mukherjee, 2010*)

4.6.3 Ultrasonic Signatures:

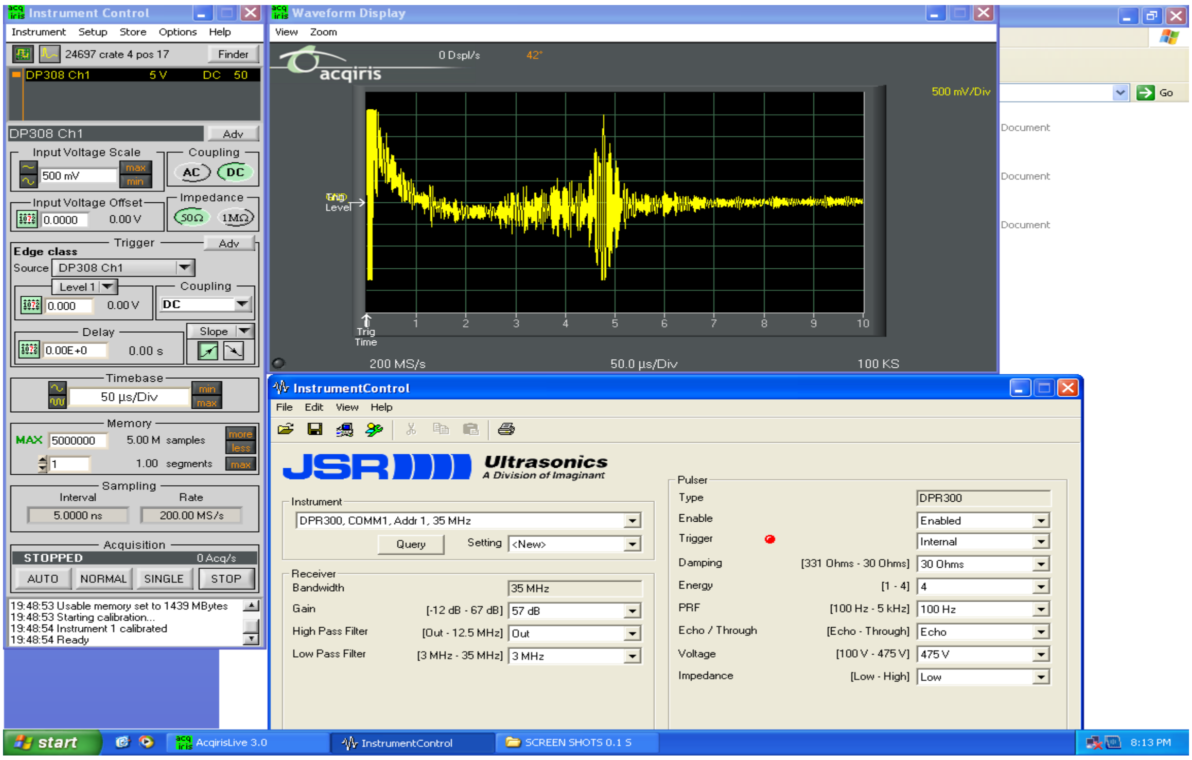


(a)

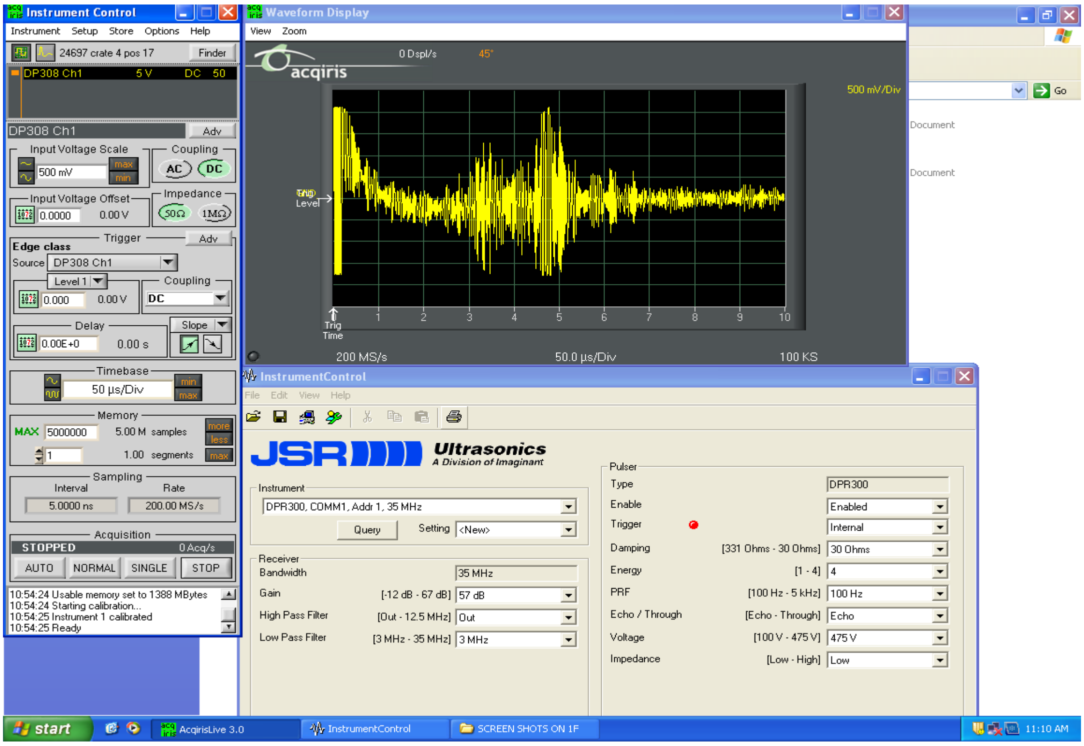


(b)

Fig. 4.12: Pattern of Signature peak with 0.1 MHz transducer



(a)



(b)

Fig. 4.13: Pattern of Signature peak with 1 MHz transducer

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. From the display, the time of flight between the excitation and reflected pulse is measured. Knowing the velocity of the wave, the location of the defect can be calculated as follows:

$$D = Vt \quad \text{\_ \_ \_ \_ \_ \_ \_ \_ \_ \_ \_ \_ \_ \_ \_ \_ \_ \_} \quad (4.1)$$

where,

D = Distance of defect from transducer end,

V = Velocity of wave

t = Time of Flight.

4.7 CLOSING REMARKS

In this chapter, monitoring of corrosion in RC cylindrical 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 cylinders before and after protection. Efficacy of guided waves to monitor effectiveness of anodically and cathodically protected RC structures is investigated in the study. Destructive tests of mass loss and pull out tests were also carried out.

5.2 NON-DESTRUCTIVE TEST MEASUREMENTS

Along with the destructive tests that were carried out at the end of the exposure, each specimen was non-destructively monitored. Ultrasonic techniques have been used for FRP wrapped concrete structures because of their safety, low-cost, and flexibility, in addition to high sensitivity. *Mahmoud et al. (2010)* utilized the ultrasonic pulse velocity to assess damages within FRP encased concrete. In this work, ultrasonic guided waves have been used to monitor corrosion progression in structures which are protected against corrosion by electrochemical techniques. 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.

Fig. 5.1(a), 5.2(a) and **5.3(a)** shows P-E Trends for control samples monitored with 0.1 MHz transducer and **Fig. 5.1(b), 5.2(b)** and **5.3(b)** shows P-E Trends for control samples monitored with 1 MHz transducer.

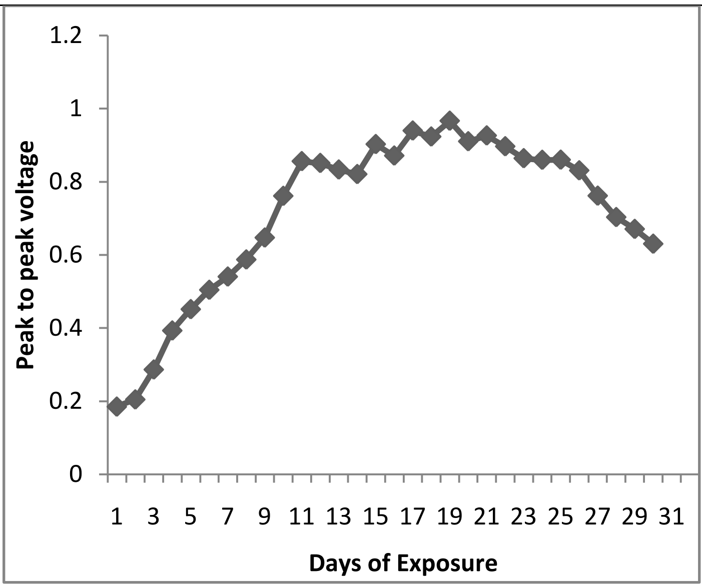
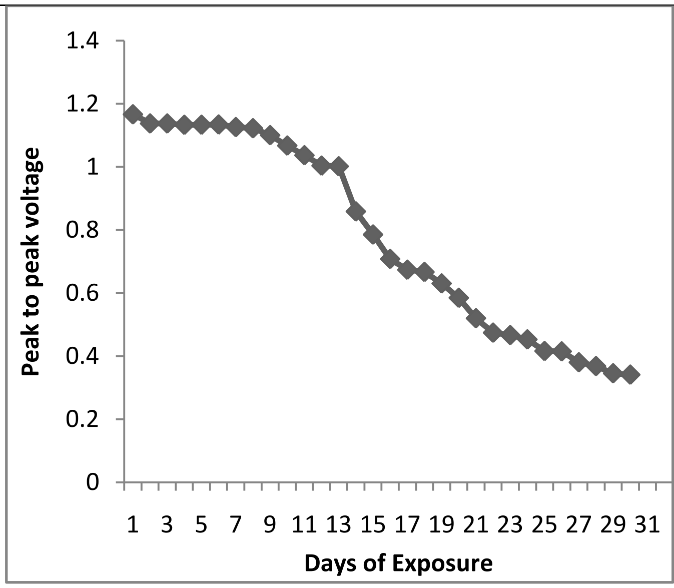
C-3 (0.1 MHz)	C-3 (1 MHz)
	
(a)	(b)

Fig.5.1: P-E trends for C-3 sample using (a) 0.1 MHz transducer, (b) 1 MHz transducer

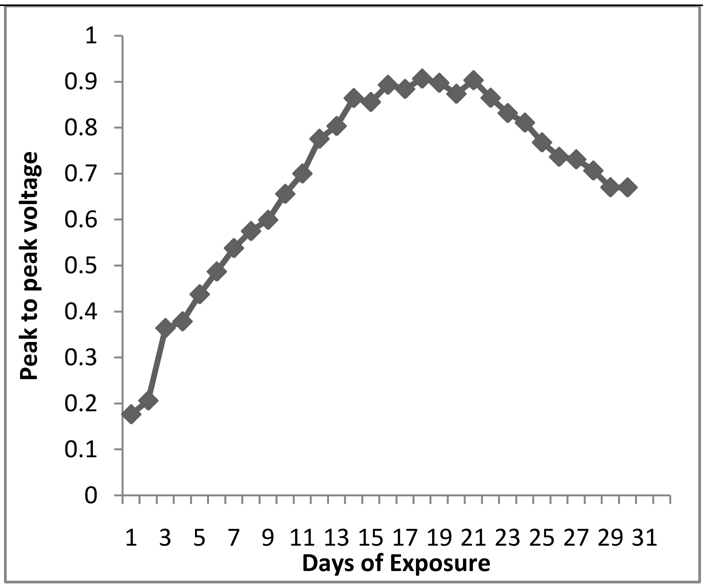
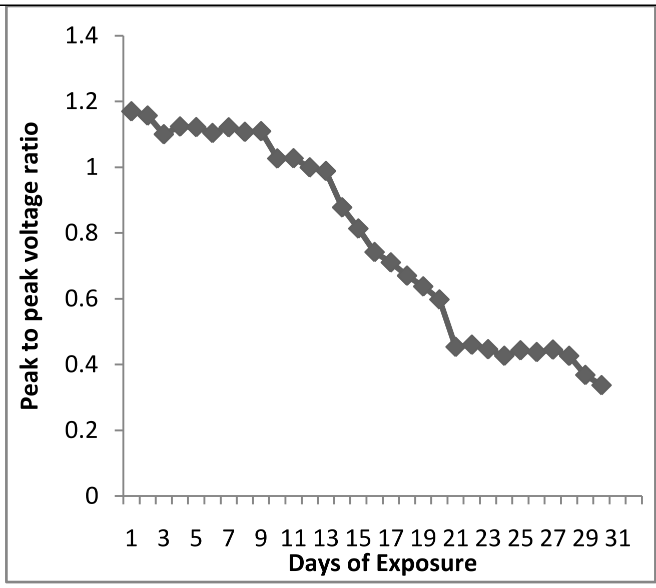
C-5 (0.1 MHz)	C-5 (1 MHz)
	
(a)	(b)

Fig.5.2: P-E trends for C-5 sample using (a) 0.1 MHz transducer, (b) 1 MHz transducer

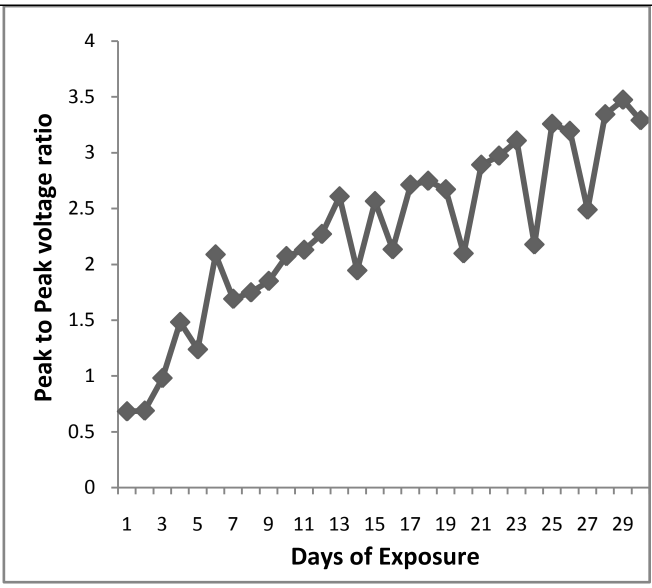
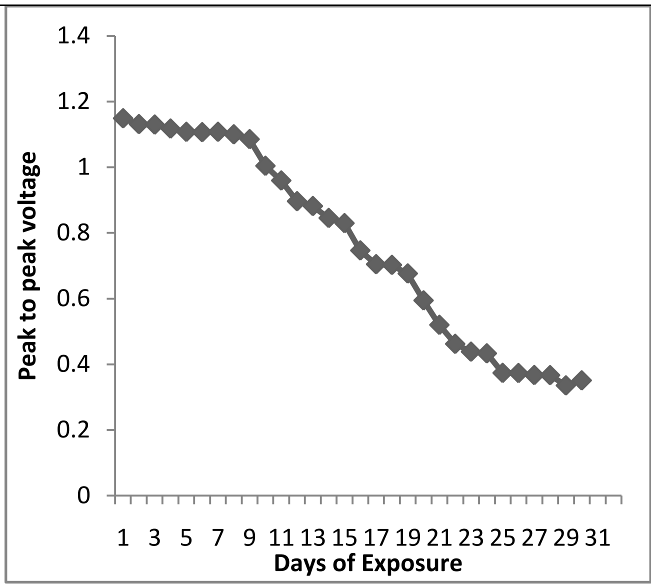
C-9 (0.1 MHz)	C-9 (1 MHz)
	
(a)	(b)

Fig 5.3: P-E trends for C-9 sample using (a) 0.1 MHz transducer, (b) 1 MHz transducer

Pulse Echo investigations:

From P-E investigations of control samples, following observations are made using surface seeking and core seeking modes:

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

From **Fig. 5.1(a), 5.2(a)** and **5.3(a)**, it can be seen that the voltage amplitude of the reflected signal increases rapidly with the progression of corrosion 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 as shown in the graphs.

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

From **Fig 5.1(b), 5.2(b)** and **5.3(b)**, it can be seen that initially the reflected pulse strength is very high but as corrosion progresses, the reflected signal starts falling. The reflected signal keeps on falling till it vanishes. 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 reflected pulse. Hence pitting is marked by the core seeking mode.

Fig. 5.4(a), 5.5(a) and **5.6(a)** shows P-E Trends for passively protected cylindrical samples protected by CFRP monitored with 0.1 MHz transducer and **Fig. 5.4(b), 5.5(b)** and **5.6(b)** shows P-E Trends for passively protected cylindrical samples protected by GFRP and monitored with 0.1 MHz transducer.

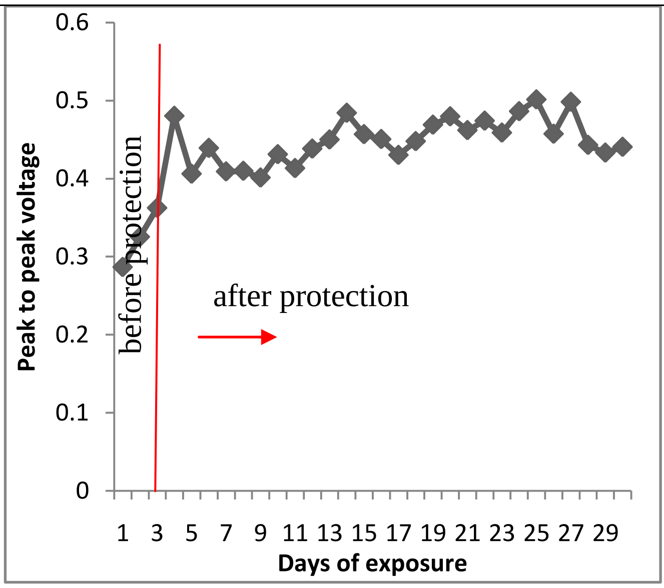
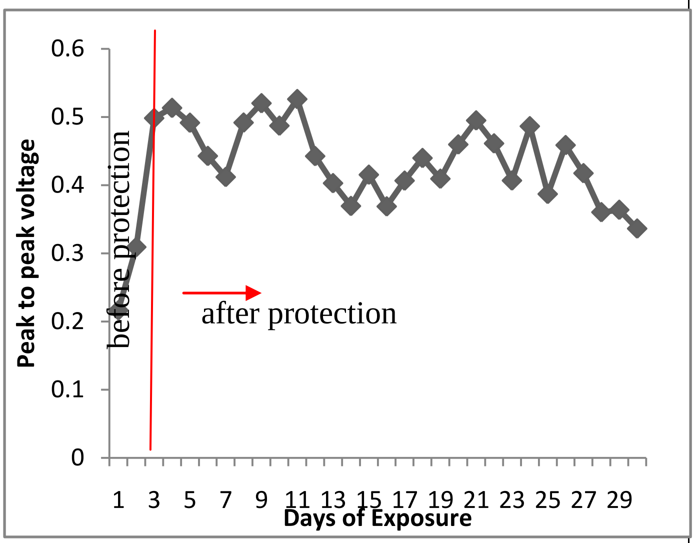
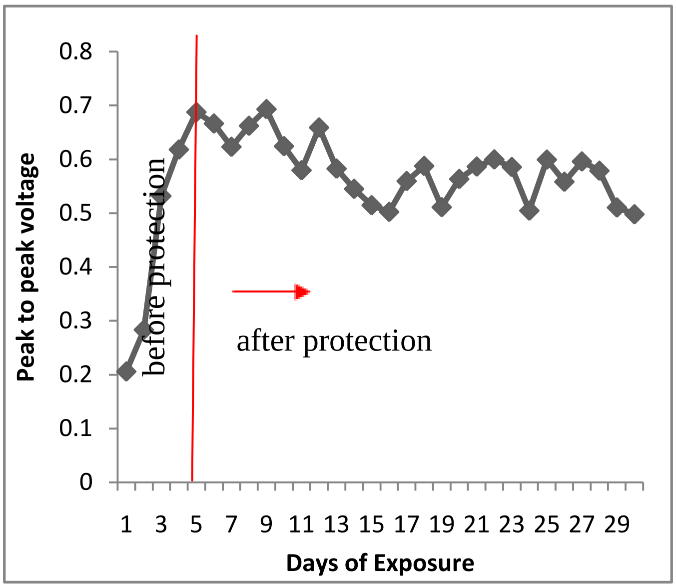
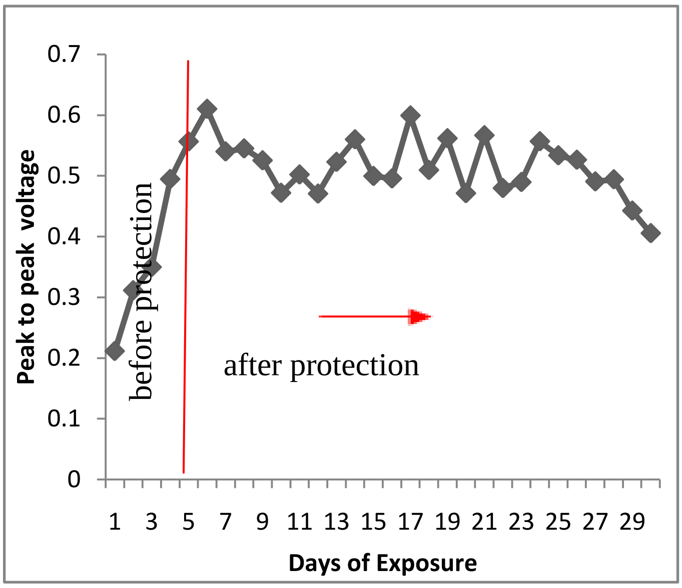
PAC-3 (0.1 MHz)	PAG-3 (0.1 MHz)
 (a)	 (b)

Fig. 5.4: P-E Trends with 0.1 MHz transducer for the specimens passively protected after 3 days of corrosion by (a) CFRP and (b) GFRP

PAC-5 (0.1 MHz)	PAG-5 (0.1 MHz)



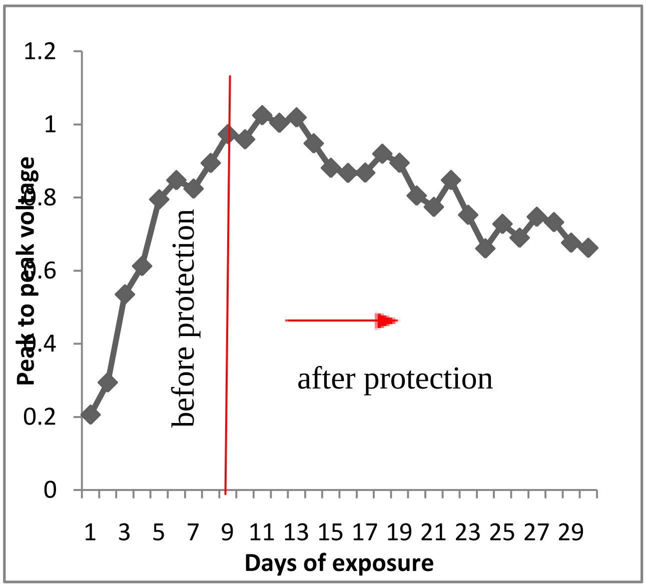
(a)



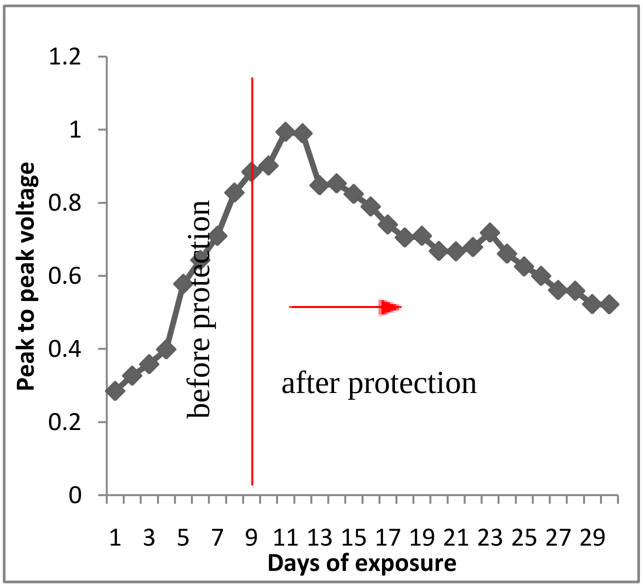
(b)

Fig. 5.5: P-E Trends with 0.1 MHz transducer for the specimens passively protected after 5 days of corrosion by (a) CFRP and (b) GFRP

PAC-9 (0.1 MHz)	PAG-9 (0.1 MHz)



(a)



(b)

Fig. 5.6: P-E Trends with 0.1 MHz transducer for the specimens passively protected after 9 days of corrosion by (a) CFRP and (b) GFRP

Fig. 5.7(a), 5.8(a) and **5.9(a)** shows P-E Trends for passively protected cylindrical samples protected with CFRP monitored with 1 MHz transducer and **Fig. 5.7(b), 5.8(b)** and **5.9(b)** shows P-E Trends for passively protected cylindrical samples protected with GFRP and monitored with 1 MHz transducer.

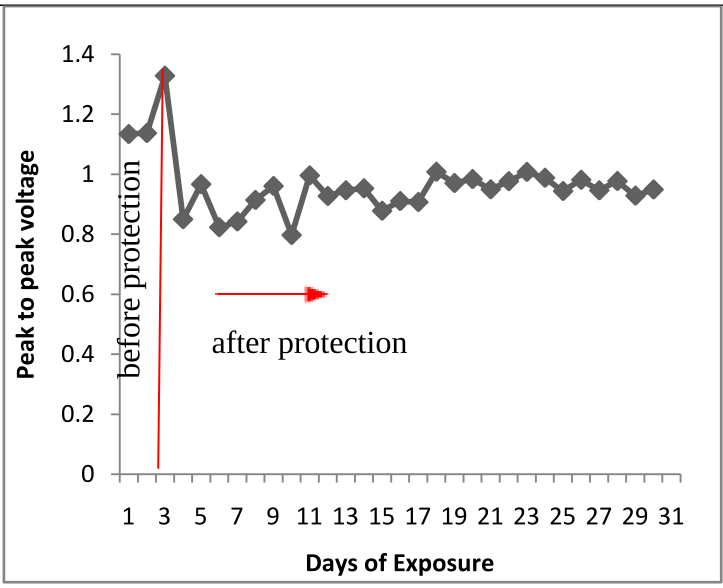
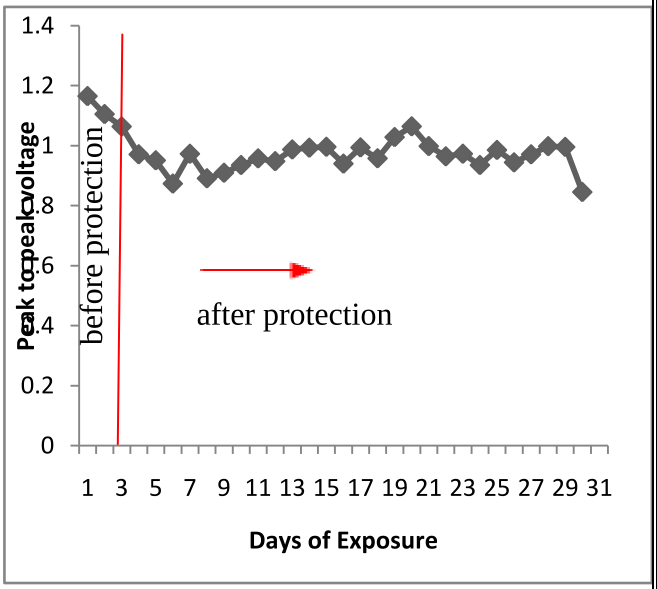
PAC-3 (1 MHz)	**PAG-3 (1 MHz)**
 **(a)**	 **(b)**

Fig. 5.7: P-E Trends with 1 MHz transducer for the specimens passively protected after 3 days of corrosion by (a) CFRP and (b) GFRP

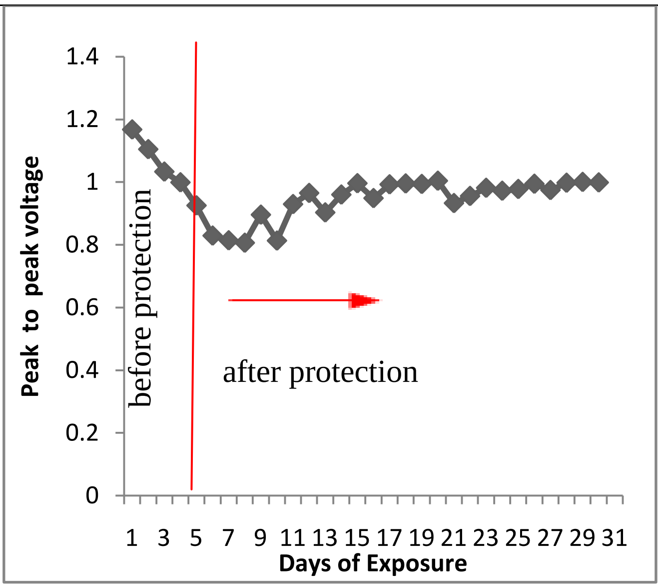
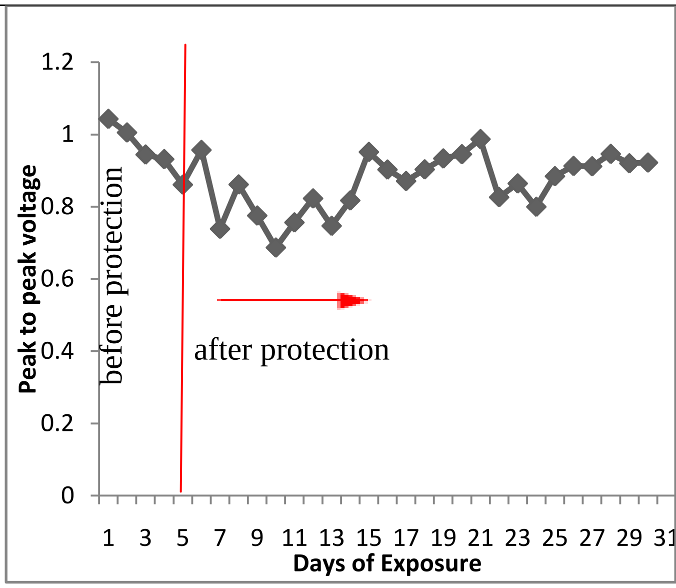
PAC-5 (1 MHz)	**PAG-5 (1 MHz)**
 **(a)**	 **(b)**

Fig. 5.8: P-E Trends with 1 MHz transducer for the specimens passively protected after 5 days of corrosion by (a) CFRP and (b) GFRP

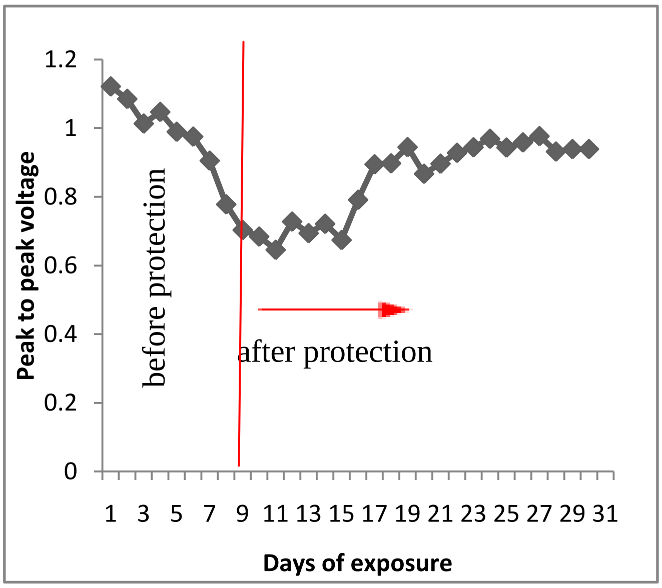
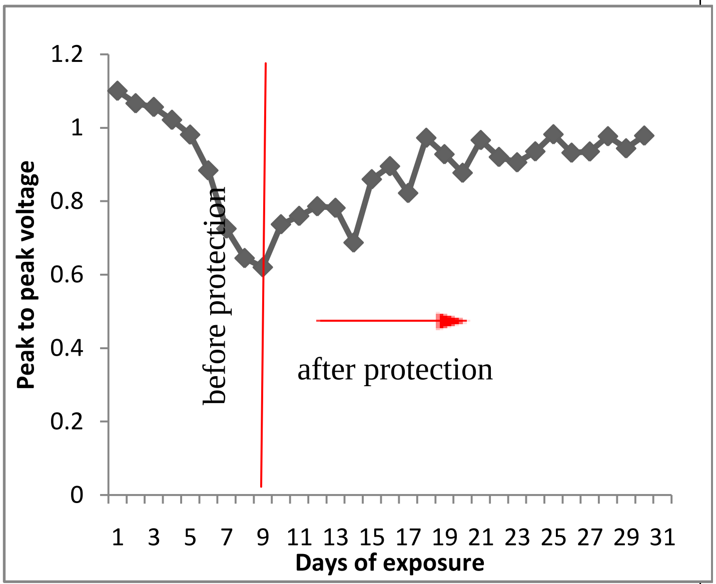
PAC-9 (1 MHz)	PAG-9 (1 MHz)
 (a)	 (b)

Fig. 5.9: P-E Trends with 1 MHz transducer for the specimens passively protected after 9 days of corrosion by (a) CFRP and (b) GFRP

Pulse Echo Investigations:

From P-E investigation of CFRP and GFRP protected specimens providing passive protection using surface seeking and core seeking modes, following observations are made:

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

From the graphs shown in **Fig. 5.4(a), 5.5(a) and 5.6(a) and Fig. 5.4(b), 5.5(b) and 5.6(b**), following observations are made:

1. The peak to peak voltage amplitude starts rising with the progression of corrosion till the days upto which the corrosion is carried out i.e., 3 days, 5 days and 9 days, pointing towards the delamination due to corrosion with increased exposure. This causes less leakage into concrete and signal strength rises. It is similar to the trends observed with the control samples
2. After providing passive protection with GFRP in PAG-3, PAG-5 and PAG-9 samples, the signal instead of rising starts becoming constant first and then

starts falling. It points towards confining effect of wrapping on concrete, hence impeding corrosion which is shown by fall in signal strength. Hence, the guided waves are not only effective in picking up corrosion but are also able to detect effect of corrosion protection by fall in signal using surface seeking modes.

3. After providing passive protection with CFRP in PAC-3, PAC-5 and PAC-9 samples, using the surface seeking mode, same behaviour of signal as it was in case of GFRP is seen. The signal becomes constant for a while and then starts falling after protection. But in this case, the fall in the signal is not as good as in case of GFRP protected samples. This shows that GFRP gives better passive protection than the CFRP.

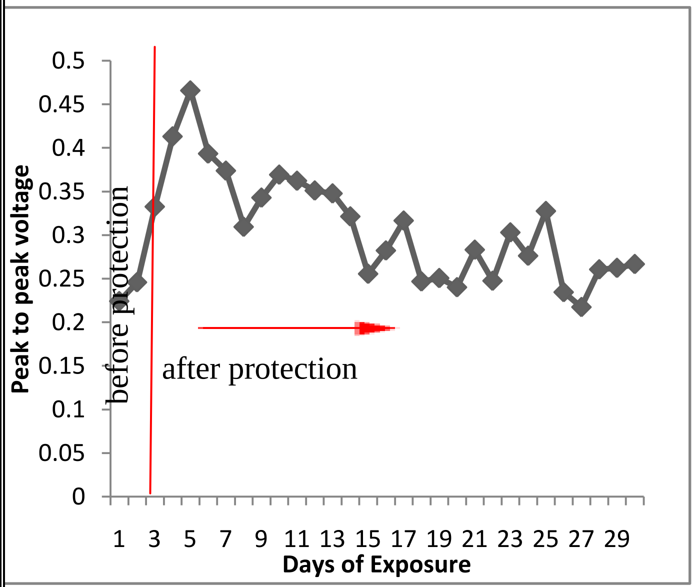
- **Core seeking mode L(0,7) at 1 MHz**

From the graphs shown in **Fig. 5.7(a), 5.8(a) and 5.9(a)** and **Fig. 5.7(b), 5.8(b) and 5.9(b**), following observations are made:

1. As in case of control samples, upto corrosion in 3, 5 and 9 days in PAC and PAG samples, the signal starts falling upto the respective exposure period due to pitting effect of chloride corrosion causing the attenuation of signal.
2. But after protection using both GFRP and CFRP, the signal stops falling and almost becomes constant pointing towards the confinement of concrete with FRP wraps, slowing down the progression of corrosion in protected samples.
3. Both passive protection systems using GFRP and CFRP showed similar trends.
4. Moreover, the signal starts rising instead of falling in case of PAC and PAG samples after 5 and 9 days. This is a very remarkable observation showing the effectiveness of ultrasonic guided waves.

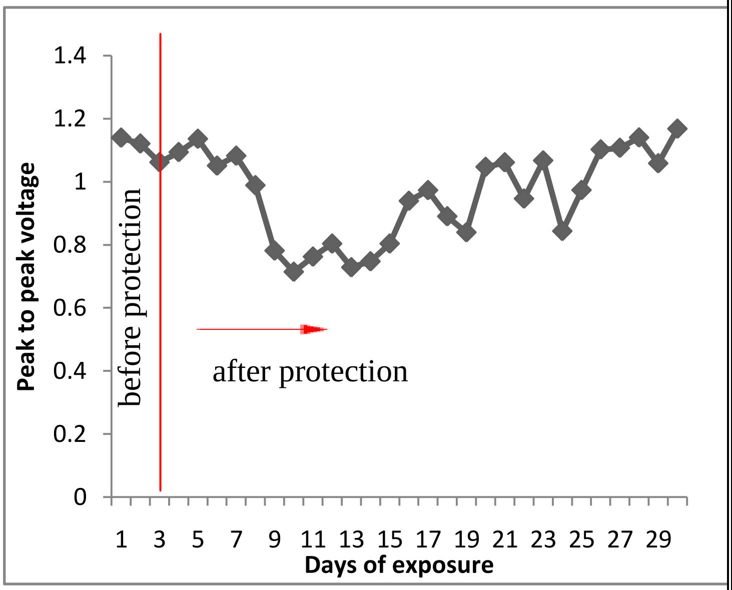
Fig. 5.10(a), 5.11(a) and **5.12(a)** shows P-E Trends for actively protected cylindrical samples protected with CFRP monitored with 0.1 MHz transducer and **Fig. 5.10(b), 5.11(b)** and **5.12(b)** shows P-E Trends for actively protected cylindrical samples protected with CFRP and monitored with 1 MHz transducer.

APC-3 (0.1 MHz)



(a)

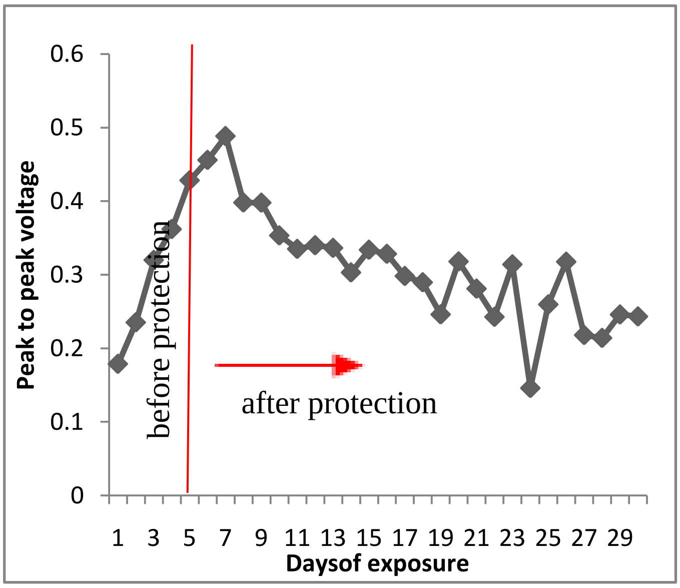
APC-3 (1 MHz)



(b)

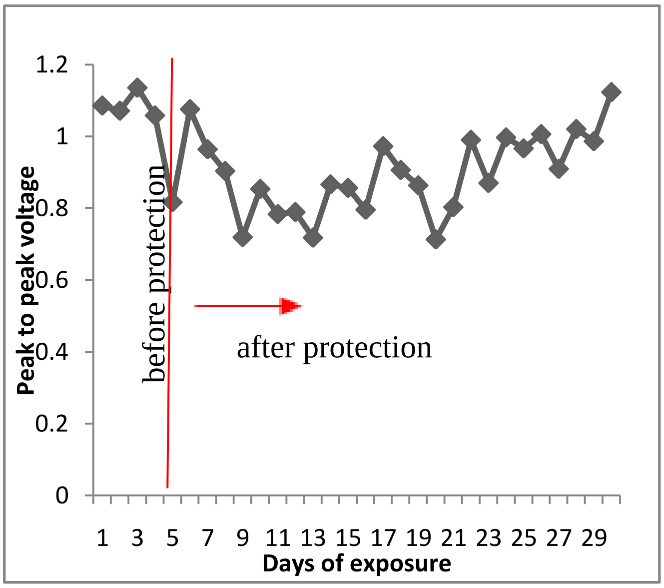
Fig. 5.10: P-E Trends for the specimens actively protected by CFRP after 3 days of corrosion using (a) 0.1 MHz transducer, (b) 1 MHz transducer

APC-5 (0.1 MHz)



(a)

APC-5 (1 MHz)



(b)

Fig. 5.11: P-E Trends for the specimens actively protected by CFRP after 5 days of corrosion using (a) 0.1 MHz transducer, (b) 1 MHz transducer

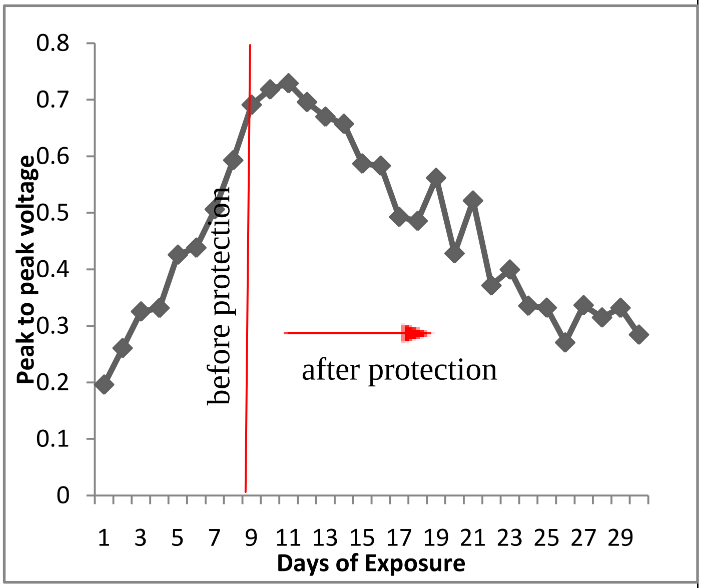
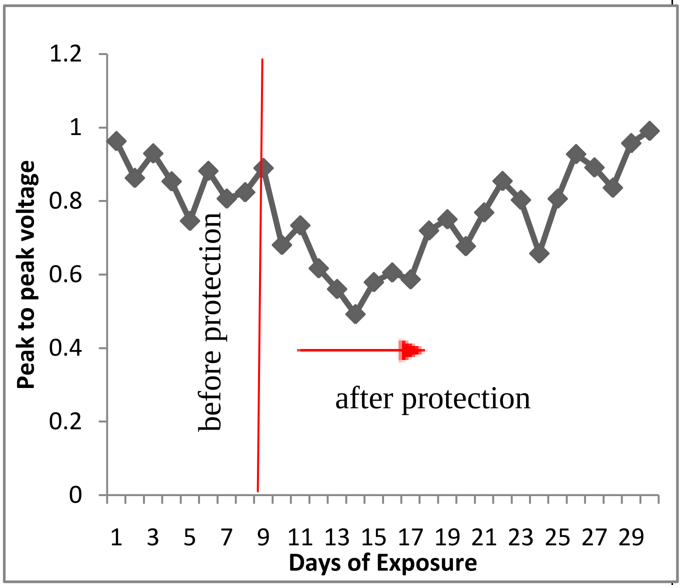
APC-9 (0.1 MHz)	APC-9 (1 MHz)
 (a)	 (b)

Fig. 5.12: P-E Trends for the specimens actively protected by CFRP after 9 days of corrosion using (a) 0.1 MHz transducer, (b) 1 MHz transducer

Pulse Echo investigations

From P-E investigation of actively protected samples using CFRP, following observations are made:

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

From the graphs shown in **Fig. 5.10(a), 5.11(a)** and **5.12(a)**, 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.
2. After the protection, there is steep fall in the peak of the signal. Surface seeking waves could pick up wonderfully the active protection provided by CFRP.
3. The fall of signal with protection is large and huge in actively protected structures than in case of passively protected structures. This implies that the active protection is more effective than the passive protection.

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

From the graphs shown in **Fig. 5.10(b), 5.11(b)** and **5.12(b)**, following observations are made:

1. The peak of signal starts falling with the progression of corrosion upto respective days of corrosion.
2. After active protection is applied, it shows a steep rise in the reflected signal.
3. Better protection offered by CFRP actively to RC specimens which implies Active protection is more effective than the Passive protection.

5.3 DESTRUCTIVE TEST MEASUREMENTS

5.3.1 ***Pull-out test:*** Destructive pull-out test is performed when the specimen has been subjected to exposure of corrosion for respective days and protected both passively and actively. This was done by securing the cylinder in a Universal Testing Machine (UTM) and attaching the grip to the protruding portion of the reinforcing bar as shown in **Fig. 5.13**.

Fig. 5.13: Pull-out test set-up

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

Specimen	Pull-out Strength (MPa)
C -3	7.56
C-5	6.72
C-9	5.9
PAG-3	9.8
PAG-5	10.3
PAG-9	9.4
PAC-3	10.81
PAC-5	8.9
PAC-9	9.3
APC-3	5.9
APC-5	5.71
APC-9	6.1

From **Table 5.1**, it can be said that as the number of days of corrosion exposure increases, pull out strength decreases. This is due to the formation of rust products that delaminate or debond the bar from surrounding concrete. Hence, the bars are pulled out from the concrete very easily.

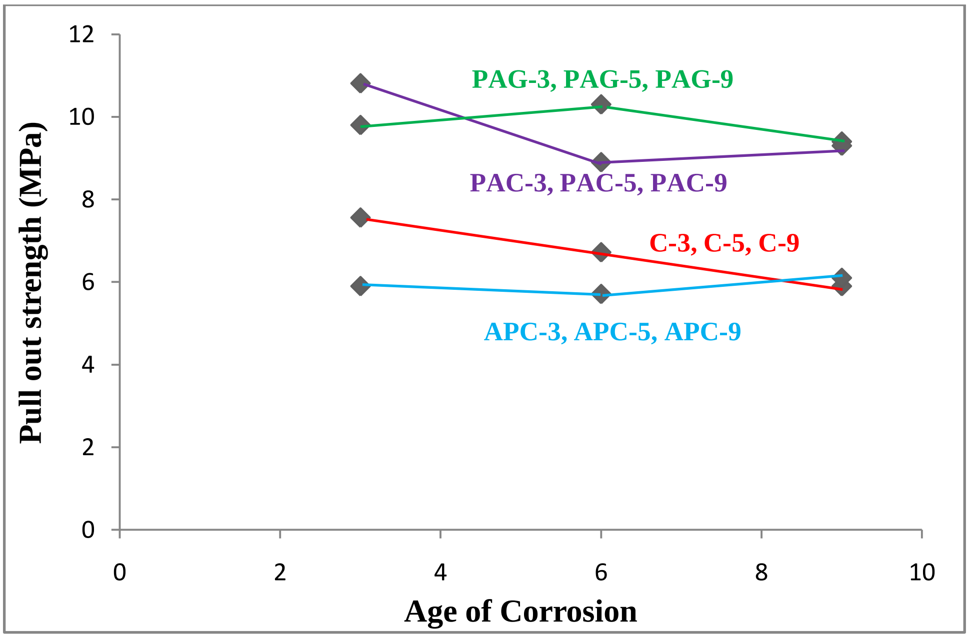


Fig. 5.14: Variation of pull-out strength with corrosion for all specimens

From the graph shown in **Fig. 5.14**, following conclusions can be drawn:

- The pull out strength of the controlled samples is decreasing with the increase in the time of corrosion. This is basically due to the development of tensile stresses which further leads to cracks and spalling. Eventually, concrete goes in compression and this result in less bond strength.
- The pull-out strength of the specimens protected passively with GFRP and CFRP has increased in comparison with the controlled samples. Thus, it can be drawn that FRP protection prevents the phenomenon of Bond degradation, cracking and spalling due to corrosion to a larger extent. Thus, the protection with FRP reduces the rate of propagation of corrosion in RC Structures and also offer better confinement.
- Now, in case of actively protected RC specimens, the Pull out strength has decreased to a great extent when compared with the controlled specimens. This is basically by the continuous flow of current 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.

5.3.2 ***Mass Loss:*** After carrying out the pull-out test, the corroded bars were cleaned of all corrosion products and weighed to determine their mass loss. **Table 5.2** shows the variation in mass loss for different samples.

Table 5.2: Mass loss measurements for all the specimens

Specimens	% Mass loss
C-3	5.9
C-5	6.5
C-9	7.2
PAG-3	2.34
PAG-5	1.86
PAG-9	5.4
PAC-3	5.1
PAC-5	5.5
PAC-9	5.87

APC-3	1.11
APC-5	1.9
APC-9	2.35

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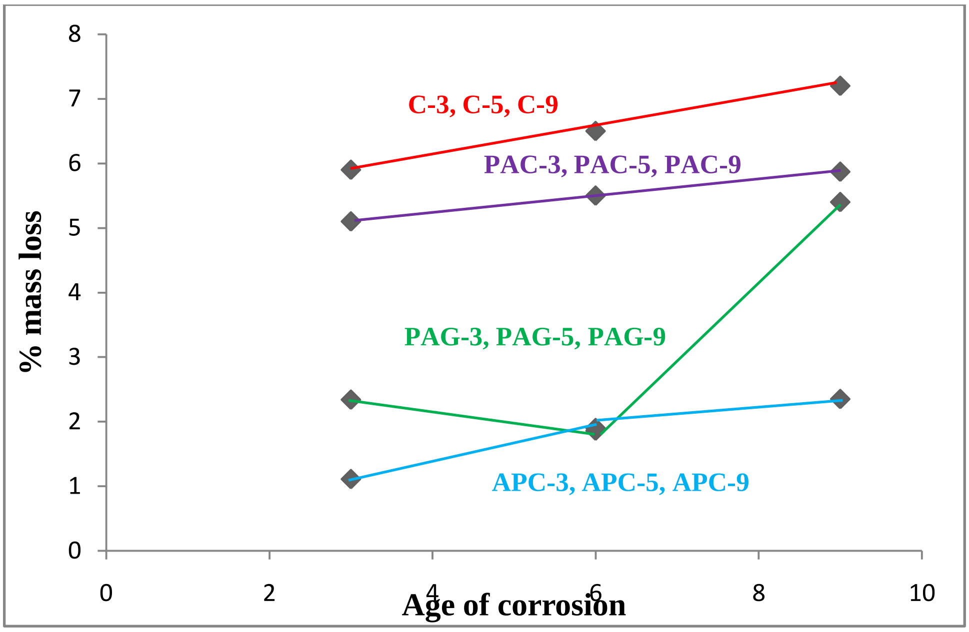

Fig. 5.15: Variation of mass loss with corrosion for all specimens

Analysis:

From **Table 5.2** and graph shown in **Fig. 5.15**, following conclusions can be drawn:

- For controlled samples, mass loss is highest which is simply because of easy ingress of chloride ions and carbon dioxide due the absence of any physical barrier.
- For passively protected samples, the mass loss in case of CFRP protected specimens is less than the controlled samples and more than the GFRP protected samples. This implies that CFRP has been able to decrease the corrosion rate to an extent by decreasing the diffusion rate of moisture and oxygen because of CFRP wrapping in comparison with controlled samples. But when compared with mass loss in case of GFRP, GFRP has shown more effective results as the mass loss in this case is very low. This may be due to

higher electrical resistance of GFRP and also, the thickness of GFRP is higher than that of CFRP in case of filed applications.

- For actively protected samples, the mass loss has been the least in comparison with the passively protected and controlled samples. This implies that the active protection has been able to decrease the rate of corrosion to the maximum, i.e., active protection is the most effective.

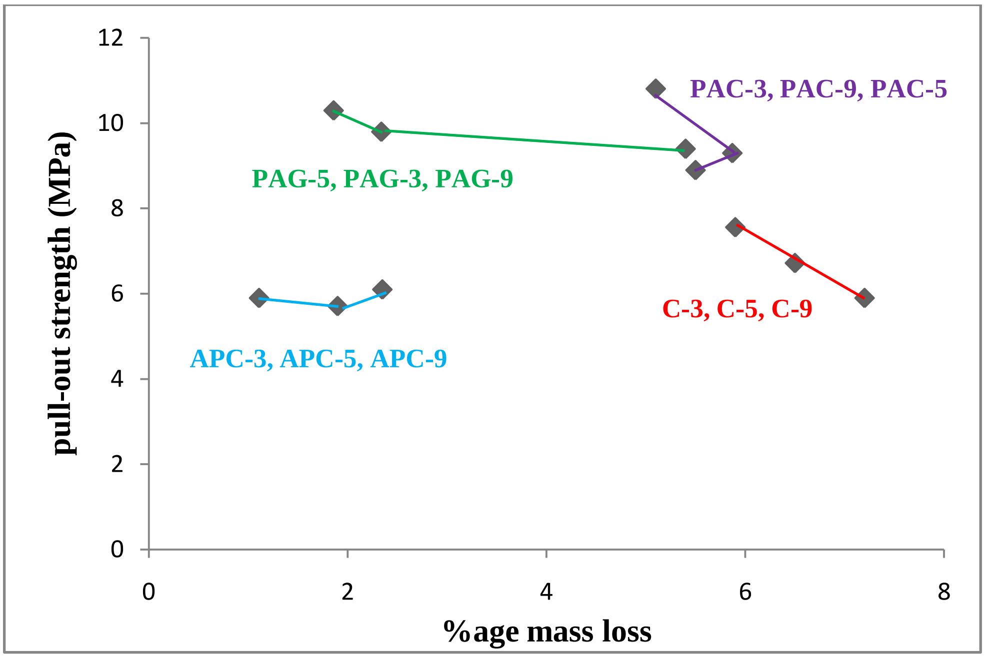

Fig. 5.16: Variation of pull-out strength with mass loss for all specimens

Fig. 5.16 shows variations of mass loss with pull out strength for all specimens. From the graph, we can say that pull out strength varies inversely with the mass loss i.e. corrosion reduces bond strength. The rate of loss of pull-out strength in GPP and CPP specimens is lowest. This implies that even with the same level of corrosion, the passively protected specimens exhibit a better bond with concrete. As a result of corrosion, the bars exert a bursting pressure on the concrete. In the absence of FRP wrap, tensile stresses develop in the concrete that result in its cracking and spalling. Eventually, concrete goes in compression. This result in loss of bond strength .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.

5.4 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 electrochemical methods both actively and passively.

CHAPTER 6

CONCLUSIONS

From the results obtained from various tests performed in this research work for evaluating the efficacy of ultrasonic guided waves to monitor protection offered by FRP's both actively and passively to RC specimens can be summarised as:

- Ultrasonic guided waves technique has proven to be very effective in monitoring the corrosion in RC structures and also been able to pick up the behaviour when protected with FRP.
- By monitoring with ultrasonic guided waves, it can be established that Active protection proves to be a very effective method of protection. The electrical conductivity of CFRP is utilized in creating an anode around the steel. This eliminates the need of any other anode and therefore, is very much economical.
- Ultrasonic guided waves have been very much able to pick up the behaviour of RC specimens when subjected to Passive Protection. It also provides wonderful results that can be used to compare the passive protection provided by different FRP (Carbon and Glass). In this experiment, GFRP proves to give better protection than CFRP passively.
- The surface seeking modes and the core seeking modes are very much able to explain the behaviour of RC specimens subjected to corrosion and also when subjected to protection. This further helps in examining the extent of delamination and pitting as a result of corrosion.
- It is also observed that the surface bonded FRP wrapping protects the steel in concrete and reduces the corrosion to a great extent. The protected samples exhibited lower mass loss than the controlled samples.
- 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.

Therefore, Ultrasonic Guided Waves has proved to be very effective in picking up the behaviour of corrosion of the RC specimens.

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