

**ELECTROCHEMICAL AND ULTRASONIC INVESTIGATIONS FOR CHLORIDE
CORROSION MONITORING IN RC STRUCTURES**

A thesis report submitted in the partial fulfillment
of the requirement for the award of the degree
of

**MASTER OF ENGINEERING
IN
STRUCTURES**

Submitted by

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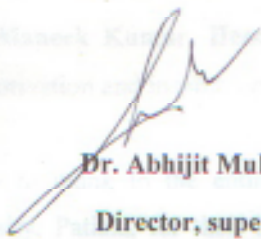


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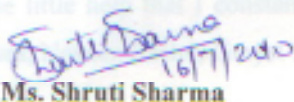
ACKNOWLEDGEMENT
CERTIFICATE

This to certify that the work which is presented in this thesis report entitled "Electrochemical and Ultrasonic Investigations for Chloride Corrosion Monitoring in RC Structures" being submitted by **Bhavneet Kaur** in partial fulfillment of requirements for the award of degree of Master of Engineering in Structural Engineering, at Civil Engineering Department, Thapar University, Patiala is an authenticated record of the initial work carried out by her under the supervision of **Dr. Abhijit Mukherjee, Director, Thapar University, Patiala** and **Ms. Shruti Sharma, Assistant Prof., CED, Thapar University, Patiala.**

The matter embodied in this report has not been submitted in parts or full to any other university or institute for the award of any 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 caused by corrosion. Thus, a rigorous inspection of the embedded reinforcements for corrosion related damages on a regular basis is imperative. There is a need for a complete health monitoring system for corrosion related damages in reinforcing bars embedded in concrete.

Electrochemical techniques are useful for evaluating the behavior of steel in concrete because it is non-destructive and can be used to monitor corrosion rate over a period of time. The two important parameters, corrosion potential (E_{corr}) and corrosion current (I_{corr}) are good indicators of corrosion initiation in reinforced concrete structures. Two techniques of electrochemical measurements and ultrasonic guided waves used in combination can reasonably predict the corrosion related damages in steel in concrete. Fall in corrosion potential (E_{corr}) and rise in corrosion current (I_{corr}) is a measure of corrosion initiation. Once initiation of corrosion is picked up, ultrasonic technique of pulse transmission can fairly measure corrosion progression in reinforcing bar in concrete. Surface and core seeking ultrasonic guided wave modes have been identified which were sensitive to delamination and pitting effects of corrosion respectively. These modes were used to ultrasonically monitor reinforced concrete beams undergoing accelerated impressed current corrosion in chloride environment.

Effect of different cover depth on ultrasonic voltages also has been studied. This thesis is an attempt to suggest a complete monitoring methodology for corrosion of steel in concrete using electrochemical and ultrasonic measurements.

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CHAPTER1

INTRODUCTION

1.1 GENERAL

The corrosion of steel reinforcing bar (rebar) in concrete represent a serious threat to the nation's infrastructural systems. In humid conditions, atmospheric pollutants percolate through the concrete cover and cause corrosion of steel reinforcements. The resulting corrosion products occupy volumes about 6 -10 times that of the steel. The increased volume induces tensile stresses in the concrete that result in cracking, delamination and spalling that further accelerates corrosion. In well made and good quality concrete the risk of corrosion is minimal as it normally provides good chemical and physical protection to the embedded steel reinforcement [1, 2]. The chemical protection is through the formation of a passive layer (thin protective oxide film) over the steel surface due to high alkalinity of concrete pore solution while the physical protection is through the retarding access of oxygen, moisture, and various aggressive species to the steel/concrete interface. However the breakdown of the passive film and consequently corrosion initiation takes place most frequently in the presence of chloride ions at the rebar level. The aggressive chloride ions can be originated either from the use of contaminated mix ingredients in the mix and/or from the surrounding environment in the hardened state [3]. Virtually all concrete structures exposed to nature experience deterioration over time. A particularly important problem is the in situ detection of corroding rebar before damage becomes evident as spalling of concrete from the rebar, or as rust weeps from the surface. Inspection personnel have difficulty determining the quality of *in-situ* concrete that has experienced decay without direct material sampling. The disadvantage to material sampling is that an inspector must remove a portion of the structure, usually by means of coring, and make repairs to the sample area. Removing cores from a concrete structure is an intrusive process that can weaken the structure and usually leads to long-term durability concerns [4]. Therefore nowadays the non-destructive techniques are widely used for the study of rebar corrosion in laboratories together with their application to real life structures [5].

Corrosion of reinforcing bar in concrete is generally considered as an electrochemical process [6–10]. Therefore, with the attention of researchers focusing towards the prediction of the residual life of reinforced concrete structures affected by the reinforcement corrosion, the use of electrochemical techniques for the determination of relevant parameters in this regard has become a major area of durability study. It is important to monitor the damages caused by corrosion in RC structures to avoid catastrophic failures. There is a need for non-intrusive, in-situ and real time corrosion monitoring system for RC structures. The type of corrosion can also be identified using ultrasoncis [45]. Ultrasonic wave propagation is beginning to gain popularity among researchers in the detection of corrosion related damage in reinforcing bars. The embedded reinforcements in concrete can be excited at one end. The bar acts as a waveguide that assists its propagation. The waves leak into concrete and thus attenuate before reaching the receiver at the other end of reinforcement.

1.2 OBJECTIVES OF PRESENT WORK

Corrosion monitoring can be a vital part of planned maintenance and life prediction by giving quantitative information about the development of corrosion as aggressive conditions develop in the concrete due to chloride ingress or carbonation. Corrosion monitoring techniques can help in several ways:

1. By providing an early warning that damaging process conditions exist which may result in a corrosion-induced failure.
2. By studying the correlation of changes in corrosion process parameters and their effect on structure.
3. By diagnosing a particular corrosion problem identifying its cause and the effect of cover depth of reinforcing steel bar in the real life structures.
4. By evaluating the effectiveness of a corrosion control /prevention techniques.

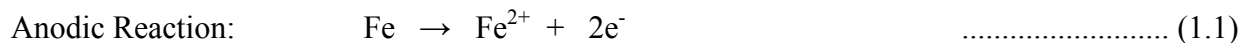
Hence the objective of the present work is to determine the corrosion initiation and corrosion progress by two different non-destructive techniques namely electrochemical LPR measurement and ultrasonic guided waves respectively. These techniques are particularly useful because they can be utilized to evaluate the probability of corrosion before damage is evident of real life structures [11]. Electrochemical techniques are useful for evaluating the behavior of steel in concrete because it is non-destructive and can be used to monitor corrosion over time. The two important parameters, corrosion potential and corrosion current are the easiest electrochemical technique for monitoring

corrosion in a structure [12]. Corrosion potential (E_{corr}) represents the ease with which steel gives up electrons and to go into solution as positive ions. The more negative the value of potential, the greater is the tendency of the metal to lose its electrons, i.e., to corrode. Also, current density (I_{corr}) measurement provides a useful quantitative parameter for studying corrosion in reinforced concrete. The second method uses ultrasonic guided wave propagation for monitoring progress of corrosion induced damages [13]. The applicability of ultrasonic waves to identify corrosion mechanism occurring in embedded reinforcements in concrete is investigated by measuring ultrasonic signals while the bar is subjected to corrosion in chloride environment at different cover depths. Another objective of the study is to monitor the corrosion of reinforcing steel bars in the two beam specimens at different depths to identify their critical levels after confirmation of the drop in the corrosion potential by ultrasonic investigation.

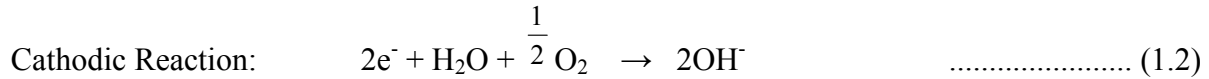
1.3 CORROSION OF REINFORCEMENT IN CONCRETE

1.3.1 THE CORROSION PROCESS

Corrosion is the destructive attack of a metal by chemical or electrochemical reaction with its environment. Concrete is alkaline. Alkalinity is the opposite of acidity. Metals corrode in acids; they can be protected from corrosion by alkalis. This is generally the case in concrete. The concrete contains microscopic pores which contain high concentrations of soluble calcium, sodium and potassium oxides. These form hydroxides, which are very alkaline, when water is present. This creates a very alkaline condition of pH 12-13 [15]. The alkaline condition leads to a 'passive' layer forming on the steel surface. The passive layer is a dense, impenetrable film, which, if fully established and maintained, prevents further corrosion of the steel. The layer formed on steel in concrete is probably part metal hydroxide and part mineral from the cement. A true passive layer is very dense, thin layer of oxide that leads to a very slow rate of oxidation (corrosion). Two conditions can break down the passivating environment in concrete without attacking the concrete first. One is carbonation and other is chloride attack. Once the passive layer breaks down then the areas of rust will start appearing on the steel surface. The chemical reactions are the same whether corrosion occurs by chloride attack or carbonation. When steel in concrete corrodes it dissolves in the pore water and gives up electrons.



The two electrons ($2e^-$) created in the anodic reaction must be consumed elsewhere on the steel surface to preserve electrical neutrality. There must be another chemical reaction to consume the electrons. This is a reaction that consumes water and oxygen:



We are generating hydroxyl ions in the cathodic reaction. These ions increase the local alkalinity and therefore will strengthen the passive layer, warding off the effects of carbonation and chloride ions at the cathode [16]. The hydroxyl ions combine with the ferrous ions to form ferrous hydroxide as shown in Fig 1.1:

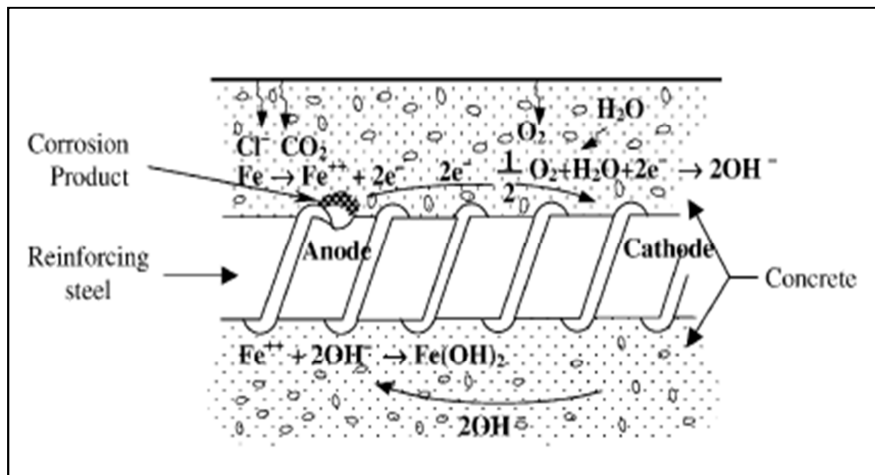
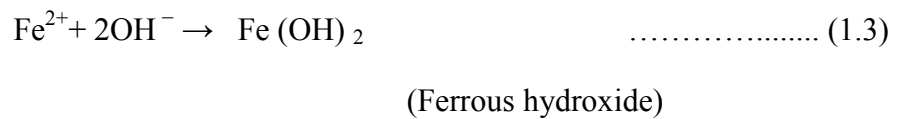
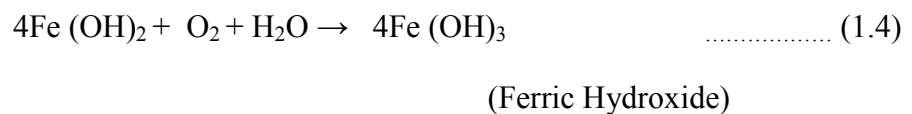


Fig1.1: Electrochemical Process of Corrosion of steel in concrete. [17]



Ferrous Hydroxide becomes ferric hydroxide in the presence of oxygen and water and further it becomes hydrated ferric oxide. Unhydrated ferric oxide Fe_2O_3 has a volume of about twice that of the steel it replaces when fully dense. When it becomes hydrated it swells even more and becomes more porous. This means that the volume increase at the steel /concrete interface is six to ten times. This leads to the cracking and spalling that we observe as the usual consequence of corrosion of steel in concrete and the red/brown brittle, flaky rust we see on the bar and the rust stains we see at cracks in the concrete.

1.3.2 SOURCES OF CORROSION

The two principal factors provoking corrosion are the ingress of chloride ions from deicing salts or sea water and the reaction of the alkaline pore solution with carbon dioxide from the atmosphere, a process known as carbonation.

1.3.2.1 CHLORIDE ATTACK

The diffusion of chlorides into concrete is the major problem. Chlorides can come from several sources. They can be cast into the concrete or they can diffuse in from the outside.

Chlorides cast into concrete can be due to

- i) Deliberate addition of chloride set accelerators (calcium chloride CaCl_2)
- ii) Use of sea water in the mix
- iii) Contaminated aggregates

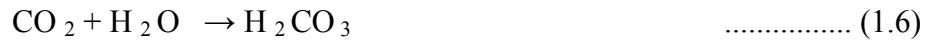
Chlorides can diffuse into concrete due to:

- i) Sea salt spray and direct seawater wetting
- ii) Deicing salts
- iii) Use of chemicals (structures used for salt storage, brine tanks, aquaria etc.)

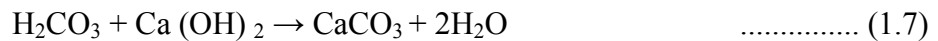
The chloride ion attacks the passive layer and the chlorides act as catalyst to corrosion. They are not consumed in the process but help to breakdown the passive layer of oxide on the steel and allow the corrosion process to proceed quickly.

1.3.2.2 CARBONATION ATTACK

Carbonation is the result of the interaction of carbon dioxide gas in the atmosphere with the alkaline hydroxides in the concrete. Like many other gases carbon dioxide dissolves in water to form an acid. Unlike most other acids the carbonic acid does not attack the cement paste, but just neutralizes the alkalies in the pore water , mainly forming calcium carbonate that lines the pores :



Gas Water Carbonic acid



Carbonic Pore
Acid solution

There is a lot more calcium hydroxide in the concrete pores that can dissolve in the pore water. This helps to maintain the pH at its usual level of 12-13 as the carbonation reaction occurs. However, as carbon dioxide proceeds to react with the calcium (and other)hydroxide, eventually all calcium hydroxides reacts, precipitating the calcium carbonate and allowing the pH to fall to a level where steel will corrode.

1.3.3 FACTORS AFFECTING CORROSION OF STEEL IN CONCRETE

The factors affecting corrosion of steel in concrete may be classified into two major categories, as follows:

- (a) External factors,
- (b) Internal factors.

1. External factors affecting corrosion of steel in concrete:

They include mostly the environmental parameters, as follows:

- i) Availability of oxygen and moisture at rebar level
- ii) Relative humidity and temperature
- iii) Carbonation and entry of acidic gaseous pollutants to rebar level

iv) Aggressive anions, mostly chloride ions, reaching to the rebar level, either through the concrete ingredients or from the external environment

2. Internal factors affecting reinforcement corrosion:

They include concrete and steel quality parameters, as discussed below:

i) Cement composition

ii) Impurities in aggregates

iii) Impurities in mixing and curing water

iv) Admixtures

v) w/c ratio

1.3.4 EFFECT OF CORROSION ON CONCRETE

The important factor in corrosion of steel in concrete compared to most other corrosion problems is the volume of oxide and where it is formed. A dense oxide formed at high temperatures usually has twice the volume of the steel consumed. In most aqueous environments the excess volume of oxide is transported away and deposits on open surfaces within the structure [17]. In the case of steel in concrete two factors predominate:

i) The main problem is that the pore water is static and there is no transport mechanism to move the oxide away from the steel surface. This means that all the oxide is deposited at the metal oxide interface.

ii) The second problem is that the oxide is not dense. It is very porous and takes up a very large volume, up to ten times that of steel consumed when the porosity of the corrosion products is taken into account.

Since reinforcing steel is doing its job in areas of tension in the structure, small cracks will occur in concrete as shown in Fig 1.2 as the tension load increase the tensile strength of the steel. Most of these are small cracks (< 0.5mm) at right angle to the reinforcing steel. They should not significantly affect the rate of corrosion of the steel as any local ingress of chlorides, moisture and carbonation is limited and contained by the local alkalinity. Obviously there is a limit to this 'self healing' ability. If there are large cracks (> 0.5mm) that stay open, or excessive shrinkage cracks along the bars then corrosion can be accelerated. Corrosion also causes horizontal

cracking along the plane of the rebar and the corner cracking around the end rebar. This leads to loss of concrete cover. Corners tend to crack first on corroding reinforced concrete structures. This is because the oxygen, water, chlorides and carbon dioxide have two faces as pathways to the steel. Delaminations occur as corrosion proceeds on the neighboring rebars and the horizontal cracks join up.

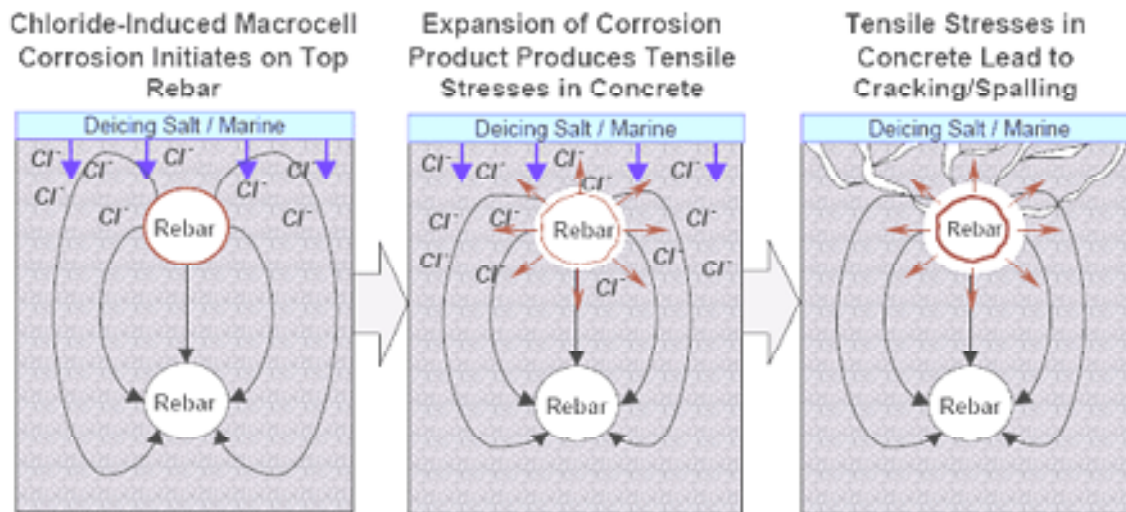


Fig 1.2: Diagrammatic representation of the cracking and spalling of corrosion effected concrete. [18]

1.3.5 EFFECT OF REINFORCEMENT CORROSION ON STRUCTURAL BEHAVIOR

The corrosion of reinforcing steel has the following major detrimental effects on the durability of RC structures:

- i) Since the rust produced as a result of corrosion has a volume 2 – 4 times than that of steel [19], it causes volume expansion developing tensile stresses in concrete, which ultimately results in cracking and spalling of the cover concrete as shown in Fig 1.3. Due to the loss of cover concrete there may be significant reduction in the load bearing capacity of the structure, and besides this steel may be more accessible to the aggressive agents leading towards further corrosion at an accelerated rate.
- ii) Corrosion reduces the cross-sections of the steel and thereby the load carrying capacity of the structure. Pitting (i.e., localized) corrosion of the rebar is more dangerous than uniform corrosion because it progressively reduces the cross-sectional area of rebar to a point where the rebar can no longer withstand the applied load leading to a catastrophic failure of the structure.

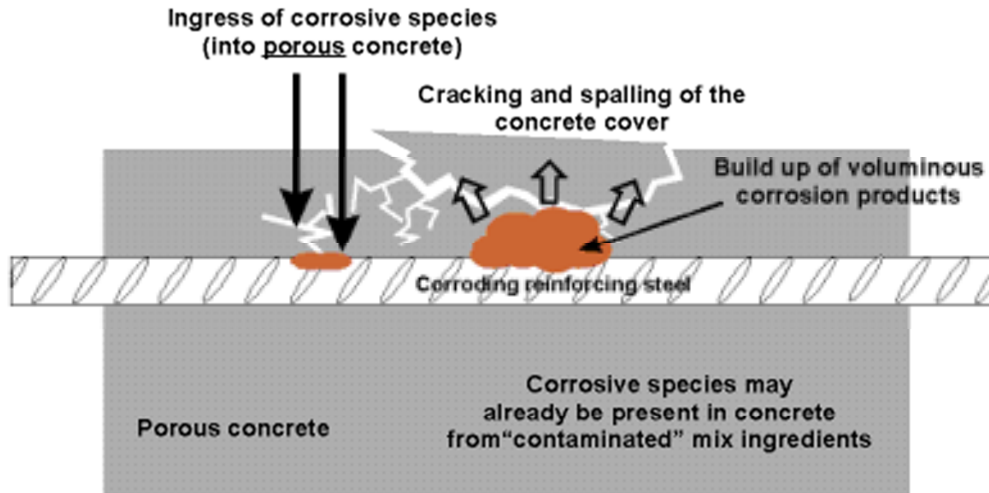


Fig 1.3: Effect of Reinforcement Corrosion on concrete structure. [18]

1.4 METHODS FOR CORROSION MONITORING

The service conditions of construction are estimated by taking into account the characteristics of the aggressive environment (indoor and outdoor), the technological process going on inside the structure and the function of the technological installations, including nonstructural elements. The investigation of the damage state (corrosion attack, etc.) of the members/structure in service is made by investigation methods that is electrochemical techniques and physical techniques and, without endangering the service safety of the members/structures.

1.4.1 ELECTROCHEMICAL TECHNIQUES

- **HALF CELL POTENTIAL MAPPING:** The standard reference electrode or half-cell is a simple device having a piece of metal in a fixed concentration solution of its own ions. If we connect it to another metal in a solution of its own ions there will be a potential difference between the two 'half cells'. The cell will generate a voltage because of the different positions of the other two metals in the electrochemical series and due to the difference in the solutions. This is galvanic action in which a voltage is developed, corrosion occurs and current flows due to coupling of different metals.
- **MACROCELL CURRENT MEASUREMENTS:** An alternative approach, which reintroduces the theme of long-term corrosion monitoring is the embedding of macrocell devices. The advantage of this technique is that they are permanently set up and can be used to monitor the total charge passing with time. This is a clearer indication of the total

metal loss or total oxide produced than an instantaneous measure of the corrosion rate. Also the measurement equipment is fairly straight forward, being a voltage measurement across a resistor or a direct zero (or low) resistance ammeter measurement of the current.

- **CONCRETE RESISTANCE AND RESISTIVITY MEASUREMENTS:** Since corrosion is an electrochemical phenomenon, the resistivity of the concrete will have a bearing on the corrosion rate of the steel as an ionic current (electric current in the form of a flow of charged ions in the pore water) must pass from the anodes to the cathodes for corrosion to occur. Wenner probe or four probe resistivity meter with modifications are frequently used for measurement of concrete resistivity on the site. In this system the outer probes pass a current through the concrete while the inner probes detect the voltage difference [16].
- **ELECTROCHEMICAL IMPEDANCE SPECTROSCOPY (EIS):** Electrochemical Impedance measurements are made by imposing a small amplitude sinusoidal voltage or current at the monitoring point and measuring the response sinusoidal current and voltage respectively. The amplitude and the phase difference between the two signals are then analyzed to yield the impedance which is a measure of the resistance to the current flow in the system [20].
- **LINEAR POLARIZATION RESISTANCE MEASUREMENTS:** The linear polarisation technique (also known as polarization resistance) requires us to polarize the steel with an electric current and monitor its effect on the electrode potential. It is carried out with a sophisticated development of the reference electrode incorporating an auxiliary electrode and a variable low voltage DC power supply. The reference electrode potential is measured and then a small current is passed from the auxiliary electrode to the reinforcement. In some commercial device a guard ring system has been developed to confine the area of the impressed current.

The term linear polarization refers to the linear regions of the polarization curve, in which slight changes in current applied to corroding metal in an ionic solution cause corresponding changes in the potential of the metal. A working electrode connects to the rebar and auxiliary (or counter) and reference electrodes are placed on the concrete surface over the reinforcing steel. It uses a “guard ring,” i.e., a second, concentric counter electrode surrounding the first counter electrode. The same potential is applied at the

guard electrode to confine the current paths between the central counter electrode and the working electrode ensuring that they are essentially straight. Only the current passing through the center counter is recorded. Thus, the area of the working electrode polarized by the central counter electrode is, in theory, equal to the area of the central counter electrode. The reference electrodes should be in contact with the concrete, aligned over the rebar [42]. The linear polarization technique is the most successful nondestructive, relatively fast, cost-effective, and a quantitative approach in reinforced concrete corrosion assessment to date. It is a very useful technique in the field assessment of the remaining service life of the reinforced concrete structure.

1.4.2 PHYSICAL TECHNIQUES

- **VISUAL STRUCTURE INSPECTION:** The visual inspection is the first step in any investigation. It may start out as a casual ‘look over’ that spots a problem and end up as a rigorous logging of defect seen on the concrete surface. The aim of visual survey is to give a first indication of what is wrong and how extensive the damage is. If concrete is spalling off then that can be used as a measure of extent of damage.
- **X-RAY / GAMMA RADIOGRAPHY:** Radiography technique is one of the non-destructive methods of testing concrete for obtaining information about concrete quality, defects within the reinforced concrete structures. Use of radioactive isotopes for concrete testing has been employed in γ - radiography studies. Radiography technique is reported to be a reliable method of locating internal cracks, voids and variation in density of concrete. Radiographic methods are classified into two types. The first one is using X-rays and other using γ -rays. X-rays and γ -rays are invisible electromagnetic radiation, which can penetrate concrete and travel in straight line.
- **INFRARED THERMOGRAPHY:** All objects naturally emit infrared radiation in proportion to their surface temperature. Thermography measures the emitted radiation and displays the information as a visual image. Today’s state-of-art equipment measures radiation from 490,000 points every second and displays the information as a TV picture. This can then be recorded for subsequent analysis to provide a permanent record of heat loss and surface temperature. By combining infrared and computer technologies, it is possible to generate thermograms (heat pictures), that clearly shows thermal profiles and

temperature measurements [21]. A combination of thermography and natural heating /cooling cycle allows areas of delaminated concrete and debonded tendons to be detected.

- **IMPACT-ECHO METHOD:** The impact-echo is a method for non-destructive evaluation of concrete and masonry structures, based on the use of impact-generated stress (sound) waves that propagate through a structure and are reflected by internal flaws and external surfaces. It can determine the location and extent of flaws such as cracks, delaminations, voids, and debonding in plan, reinforced and post-tensioned concrete structures.
- **ACOUSTIC EMISSION MONITORING:** Corrosion of prestressing wire in prestressed structures including bridges, buildings, parking structures and concrete cylinder pipe is a widespread concern for owners and managers of these facilities. The general inaccessibility of the prestressing wire makes evaluation difficult, costly and often inconclusive. The operation of a continuous acoustic monitoring system to detect and locate corrosion-induced failures of prestressing wire has been considered as a favorable alternative in NDT. It can also be successfully applied in practice for unbonded tendons.
- **ULTRASONIC GUIDED WAVE:** Ultrasonic technique of NDT is basically mechanical phenomenon, they are particularly adopted for determining the structural integrity of materials. If one looks at the merits of this technique for inspection, it is seen that ultrasonic NDT has several such advantages to offer which are difficult to get with the help of any other technique. For the purpose of ultrasonic inspection a suitable source of ultrasonic waves of desired specification is a very important requirement. Ultrasonic waves can be generated and detected in a number of ways. The generation of ultrasonic waves for NDT, using the piezoelectric device is one of the most common methods. The transducer used in ultrasonic NDT applications is used to emit an ultrasonic beam. The ultrasonic wave, generated by the transducer is then transmitted into the material under inspection [22]. If there exist any interface inside the material due to even a slight difference in the media, the ultrasonic waves are reflected back to the transducer. The received ultrasonic waves are converted again into electrical signal by the transducers.

1.5 ULTRASONIC GIUDED WAVES

1.5.1 THEORY OF GUIDED WAVES

An ultrasonic approach is chosen because of the relative feasibility of using an embedded ultrasonic network for monitoring corrosion in real structures. Guided waves are chosen because they have the capability of testing over distances with a sensitivity often greater than conventional non-destructive testing (NDT) techniques, have the ability to test multilayered structures, and are relatively inexpensive due to simplicity and sensor cost. Furthermore, frequency and mode tuning can be utilized for evaluation of different types of deterioration or damage [11].

Guided waves refer to mechanical (or elastic) waves in ultrasonic and sonic frequencies that propagate in a bounded medium (such as pipe, plate, rod, etc.) parallel to the plane of its boundary. The wave is termed “guided” because it travels along the medium guided by the geometric boundaries of the medium. Since the wave is guided by the geometric boundaries of the medium, the geometry has a strong influence on the behavior of the wave [23, 24]. In contrast to ultrasonic waves used in conventional ultrasonic inspections that propagate with a constant velocity, the velocity of the guided waves varies significantly with the wave frequency and the geometry of the medium. In addition, at a given wave frequency, the guided waves can propagate in different wave modes and orders [25]. Guided waves travel either at boundaries (Surface Waves) or between the boundaries (Lamb Waves) as shown in **Fig1.4**. Guided waves are the result of the intersection occurring at the interface between the two different materials. This interaction produces reflection, refraction and mode conversion between longitudinal and shear waves which can be predicted using appropriate boundary conditions. Guided waves are highly dependent on wavelength and frequency, and propagating guided waves can only exist at specific combinations of frequency, wavenumber and attenuation.

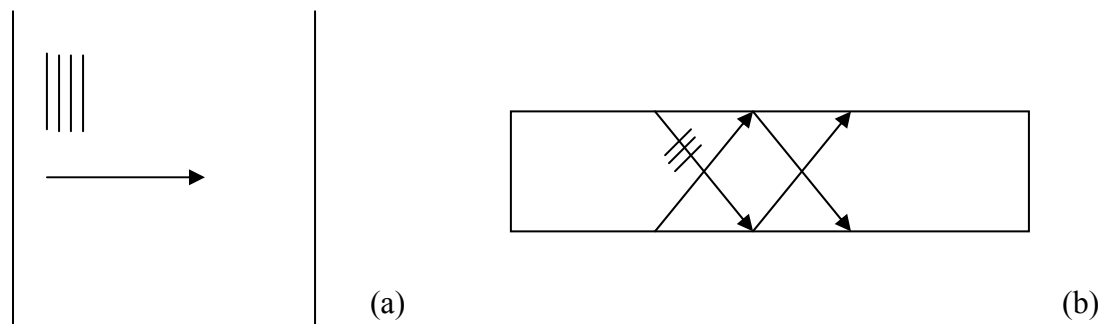


Fig 1.4: Schematic of bulk wave (a) and Guided wave (b) propagation [26]

In an infinite isotropic solid medium only two types of independent wave propagation exist, i.e., compressional and shear waves. Both waves propagate with constant velocities and are nondispersive. When geometry constraints are introduced and the dimensions are close to the wavelength, the wave becomes dispersive and is called a guided wave [33]. In an infinite bulk of a perfectly elastic material, ultrasonic waves travel as bulk waves, decaying in amplitude because of the spread of the wave front. However, in a finite perfectly elastic steel bar, the sound wave is reflected from the structure boundaries, and the energy is contained within the bar as a guided wave, which propagates with constant amplitude.

The complex effect of the boundaries results in dispersion of the wave and generates different modes that have predictable frequency-dependent properties. The velocity-frequency relationships of guided waves can be displayed as dispersion curves [38]. Every natural wave guided has associated with it a set of dispersion curves that presents to us the wave propagation possibilities in that structure. At each point of a dispersion curve there is a different wave structure. When studying the dispersion curve it is easy to understand that there is a corresponding frequency bandwidth associated with the abscissa value, but there is also a phase velocity bandwidth associated with the ordinate value on the phase velocity dispersion curve. This means that we are actually exciting a fairly large zone and multiple modes could propagate in a structure at the same time [28]. Adding further finite layers around the steel bar, such as in concrete further complicates the waveguide, as energy can now be passed between the layers. In this case, a guided wave will still propagate in the structure as a whole, but with properties that depend on the elastic and damping properties of all the layers. Stress and displacement boundary conditions must be satisfied at the boundaries between layers. Attenuation through leakage can occur if the outermost layer may be considered infinite in extent. Hence, steel bar in concrete is modeled as a solid cylinder embedded in an infinite concrete medium, considering both the materials as isotropic, homogenous and elastic [38]. A global matrix method is employed for solution of wave propagation equation using optimization techniques [43] which was then developed into a standard software Disperse [45]. For a layered system, the solution includes phase velocity, frequency and attenuation. Attenuation is due to material absorption and energy leakage into the surrounding concrete. The waves propagate in longitudinal, flexural and torsional modes due to complex effect of boundaries and they have frequency dependant properties. In such cases specific modes can be excited selectively by choosing a frequency bound. Longitudinal waveforms have axial and radial displacements, torsional waveforms have angular displacements

and flexural waveforms have all three displacements. They are represented by L (m, n); T (m, n) and F(m, n) respectively where 'm' and 'n' represent the circumferential displacements and sequential order of mode respectively.

1.5.2 EFFECT OF CORROSION ON GUIDED WAVE PROPAGATION

Corrosion in chloride environment is in the formation of the corrosion products on the surface of the rebar resulting in the alteration of steel-concrete interface. Due to higher volume of rust than the corresponding mass of steel, an outward pressure is generated. This might initially improve the interfacial bond. However, the pressure results in tensile stresses in concrete. As concrete is weak in tension, cracks are developed in it leading to debond. The resulting voluminous rust accompanying processes like cracking, spalling and delamination of concrete leads to debond. At the anode where iron is dissolved, pitting occurs where crevices are formed in the bar leading to local loss of area. Hence, in addition to debond, chloride corrosion manifests itself in local weakening of the bar. These two damage mechanisms of debond and pitting as a result of chloride corrosion affect the wave propagation in the rebar [38]. Therefore, once corrosion begins to occur the corrosion product accumulation will actually cause an increase in bond and subsequently lead to more energy leaking into the surrounding concrete. Irregularities in the bar profile surface from corrosion can cause more attenuation from reflections, scattering and mode conversions [11]. Pitting of the steel causes reflections of the wave form and mode conversions leading to the overall attenuation of the signal strength of the transmitted mode. Conversely, loss of bond between the steel and concrete interface allows for less leakage into the surrounding concrete, producing a stronger signal. Small non uniform changes to the diameter accompany most corrosion degradation. The effect of diameter change alters the group velocity of a guided wave. Depending on the rebar diameter size, the frequency of the propagated wave form, and the length of rebar affected by the change in diameter, the shift in group velocity may be difficult to detect. The two main corrosion effects are loss of bond and severe pitting, and they both have an effect upon signal energy. These two effects pitting and debonding of corrosion degradation counteract one another with respect to signal strength for through transmission testing as the percentage of corrosion increases [33].

1.5.3 BASIC PRINCIPLES OF ULTRASONIC TESTING

Ultrasonic nondestructive testing introduces high frequency sound waves into a test object to obtain information about the object without altering or damaging it in any way. A typical UT

inspection system consists of several functional units, such as the pulser/receiver, transducer, and display devices. A pulser/receiver is an electronic device that can produce high voltage electrical pulses. Driven by the pulser, the transducer generates high frequency ultrasonic energy. The sound energy is introduced and propagates through the materials in the form of waves. When there is a discontinuity (such as a crack) in the wave path, part of the energy will be reflected back from the flaw surface. The reflected wave signal is transformed into an electrical signal by the transducer and is displayed on a screen [32].

METHODS OF ULTRASONIC TESTING

1. Pulse echo method
2. Pulse transmission method

1. Pulse echo method:

In the pulse-echo method, a piezoelectric transducer with its longitudinal axis located perpendicular to and mounted on or near the surface of the test material is used to transmit and receive ultrasonic energy as shown in **Fig 1.5**. 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.

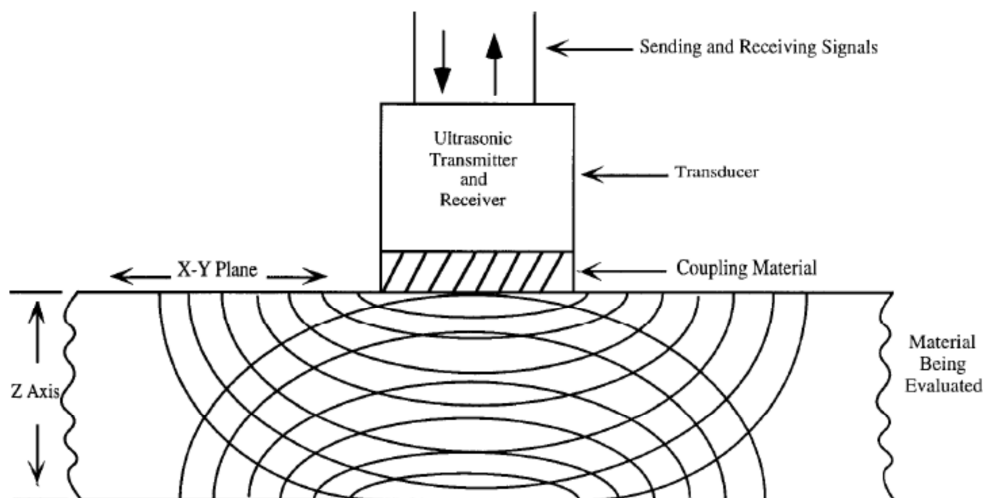


Fig 1.5: Principle of pulse echo method of inspection [32].

2. 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 as shown in **Fig 1.6**. Scanning of the material using this method will result in the location of defects, flaws, and inclusions in the X-Y plane.

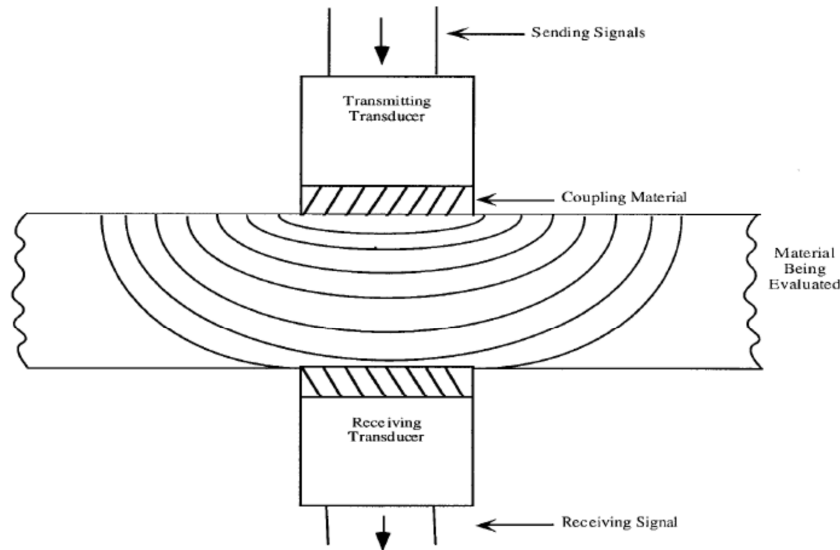


Fig 1.6: Principle of through transmission of ultrasonic testing [32].

1.6 CLOSING REMARKS

This chapter discusses the theory corrosion of reinforcing bars in RC beams. The various factors and effect of corrosion process are well discussed. The significance of electrochemical and ultrasonic technique as the corrosion monitoring technique is observed. In the next chapter literature review of electrochemical and ultrasonic investigations are studied.

CHAPTER 2

LITERATURE REVIEW

This chapter presents a review of literature on nondestructive monitoring technique for corrosion as well as propagation of elastic waves through solids. This gives an idea of study carried out in this area up to this stage. This work can be classified based on the electrochemical studies and ultrasonic studies.

2.1 LITERATURE REVIEW OF ELECTROCHEMICAL AND PHYSICAL TECHNIQUES

The following list presents a review of previous work done in the area of corrosion monitoring by both electrochemical and physical techniques.

Flis et al. [1993] studied data for the development of a methodology and standards for instruments to evaluate the corrosion rate of steel in concrete structures. Measurements of the polarization resistance of reinforcing steel were made with three devices, two of which operated on the principle of linear polarization with or without signal confinement. The third was based on superimposed current pulses of high and low frequency with signal confinement.

Macdonald, et al. [1994] examined the applicability of ultralow frequency ac impedance spectroscopy (ULFACIS) for characterizing corrosion of rebar in concrete. The study focuses on demonstrating that ULFACIS could be used to locate and characterize corrosion nondestructively in reinforced concrete structures.

Liu [1996] Significant factors on steel corrosion in chloride contaminated reinforced concrete and time-to-corrosion cracking were investigated in this study. Sixty specimens were designed with seven admixed chloride contents, three concrete cover depths, two reinforcing steel bar diameters, two exposure conditions, and a typical concrete with water to cement ratio of 0.45. Corrosion current density (corrosion rate), corrosion potential, ohmic resistance of concrete and temperature were measured monthly on these specimens using both the 3LP and Gecor devices. Metal loss measurements were performed in accordance with ASTM G1-90, method C3.5, after specimens cracked. The actual corrosion weight loss of the steel reinforcing bars was then compared to the result obtained from the corrosion rate measurement devices.

Ahmad et al. [1997] studied to assess the durability of Reinforced Concrete (RC) structures against the damage of cover concrete by chloride-induced rebar corrosion. The service lives of concrete

beam specimens with different chloride contents have been estimated by using the measured values of corrosion rate of rebar in various life prediction models currently available in the literature. The suitability and shortcomings of such life prediction models have been discussed. The purpose of this study is two fold: (i) to observe the effect of chloride on the service lives of RC structures, and (ii) to investigate the suitability of various models available for prediction of service lives of the RC structures.

Kepler et al. [2000] studied various research projects and field studies that have been conducted on different methods for protecting reinforced concrete bridges from corrosion damage. The methods included alternative reinforcement and slab design, barrier methods, electrochemical methods, and corrosion inhibitors.

Broomfield et al. [2002] Corrosion monitoring systems consisting of linear polarisation, concrete resistivity and other probes have been installed in new structures to monitor durability and in existing structures to evaluate rehabilitation strategies such as corrosion inhibitor application and patch repairs.

Elsener [2002] The consequences for corrosion monitoring by half-cell potential mapping and by polarisation resistance measurements on locally corroding rebars are discussed.

Andrade et al. [2002] studied the results of corrosion rate of steel in chloride containing concretes exposed to natural weathering. The data on corrosion rate values measured on-site in real size concrete structures are scarce, while the data bank of values in laboratory specimens was relatively larger.

Ahmad [2003] reviewed was presented on the mechanism of reinforcement corrosion, techniques utilized to monitor reinforcement corrosion and methodologies that are utilized for the prediction of remaining service life of structures.

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

Yang [2004] In order to develop a better understanding of the relationship between 90-day salt ponding test and accelerated chloride migration test (ACMT; the electrochemical technique is applied to accelerate chloride ion migration), the transport properties for concrete obtained from

ACMT are compared to the diffusion coefficient from ponding test. The plain cement concrete, fly ash concrete, and slag concrete with different w/b ratios (0.35, 0.45, 0.55, and 0.65) were used. In this study, the total chloride content and penetration depth of concretes were measured after the ponding test, and the Fick's second law of diffusion was fitted to the data from experiment to determine the diffusion coefficient.

Montemor et al. [2006] The multiprobe sensor presented in this work was tested in mortar and concrete specimens, revealing good stability. The results reveal that the Ag/AgCl sensor presents good sensitivity in a wide range of chloride concentrations. The present work aims at developing and testing a sensor based on Ag/AgCl electrodes for in situ monitoring of chloride ions in reinforced concrete structures.

Song et al. [2007] reviewed all the electrochemical and nondestructive techniques from the point of view of corrosion assessment and their applications to bridges, buildings and other civil engineering structures.

Pradhan et al. [2009] studied that half-cell potential is a stable indicator of rebar corrosion initiation. Through this work it was reconfirmed that the critical chloride level leading to corrosion initiation was not a unique value and varies with steel type, cement type, and w/c ratio.

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

Trejo et al. [2009] The existing test method to assess the corrosion performance of reinforcing steel embedded in concrete, mainly ASTM G109, is labor intensive, time consuming, slow to provide comparative results, and often expensive. This study evaluated four accelerated test procedures: the mini-macrocell (MM) test, the concrete chloride ion assessment (CCIA) test (also referred to as the concrete corrosion inhibitor association test), the accelerated chloride threshold (ACT) test, and the modified G109 test.

Martínez, et al. [2009] presented several examples of recorded data for corrosion potential, electrical resistance and corrosion rates, along with a methodology to obtain a representative corrosion rate, averaged per year. The representative value can be used in corrosion predictive models to calculate the remaining service life.

2.2 LITERATURE REVIEW OF ULTRASONIC TECHNIQUES

A brief account on recent developments for damage detection is done through ultrasonic techniques. A wide range of techniques have been reported in the literature that may be suitably employed for the monitoring of steel in concrete structures for the purpose of diagnosing the cause and extent of damage in the form of fractures and corrosion.

Pavlakovic et al. (2001) studied the dispersion relationships of a system comprising a circular bar imbedded in a solid medium having a lower acoustic impedance than the bar have been predicted. A generic study of such systems has been undertaken, motivated by a particular interest in the case of a circular steel bar imbedded in cement grout which has application to the inspection of tendons in post-tensioned concrete bridges; measurements to confirm the predictions have been carried out for this case.

Shah et al. (2001) studied the mutual effects between mechanical loading and corrosion of reinforcing steel, as well as their combined effect on serviceability (flexural deflection and residual loading capacity) of reinforced concrete beams. NaCl solution ponding was employed to accelerate the corrosion process. Half-cell potential and galvanized current measurements were taken to monitor time for corrosion initiation. After corrosion initiated an external current was applied to some of the specimens to expedite corrosion propagation. Beam deflections were recorded throughout all of the tests. Residual flexural loading capacity of the beams was evaluated at the end of the experiment.

Kim et al. [2001] studied that long-range guided wave inspection is a new emerging technology for rapidly and globally inspecting a large area of a structure from a single test location. Also, a general overview of the guided wave properties and its application for long-range inspection of structures, the principle and instrument system for a guided wave inspection technology called “magnetostrictive sensor (MsS)” that generates and detects guided waves electromagnetically in the material under testing, and examples of long-range guided wave inspection of structures that can be accomplished using the MsS.

Iyer et al. [2002] This study deals with the investigation of an NDE method called C-scan imaging to detect corrosion and voids in post-tensioned specimens. The acoustics of ultrasound wave propagation were verified in the samples in this preliminary study.

Na et al. [2002] conducted an inspection of the interface between a steel bar and concrete using the combination of a piezoelectric zirconate-titanate transducer (PZT) and an electromagnetic

acoustic transducer (EMAT). The PZT is used for generating elastic waves by mechanical vibration and then the EMAT is used for receiving the transmitted ultrasonic guided waves. This arrangement is made in order to overcome the major shortcomings of the PZT, i.e., the requirement of a couplant, and of the EMAT, i.e., relatively low transmitted ultrasonic energy. To investigate the applicability of this technique in the field, outside the laboratory environment, the experiments are conducted on different types of steel **bars**: corrosion-free, naturally corroded, and zinc-coated as well as corroded bars.

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

Demma [2003] The thesis investigates the effect of geometrical discontinuities in many type of structures on propagation of guided waves. The discontinuities studied are both defects in structure and features of the structure. A symmetric numerical analysis (finite element) of the pipe size, defect size, guided wave mode and frequency on the reflection from notches is presented.

Beard et al. [2003] A method of inspection using guided ultrasonic waves has been proposed, which uses a pulse-echo technique carried out from the free end of the structure. The maximum inspection range is determined by the amount of attenuation that the wave experiences as a result of leakage into the embedding material and material losses.

Kundu et al. [2003] studied the feasibility of detecting interface degradation and separation of steel bars in concrete beams using lamb waves. This investigation showed that the lamb wave inspection technique is an efficient and effective tool for health monitoring of reinforced concrete structures.

Rose [2004] studied that a principal advantage of guided waves is inspection over long distances with excellent sensitivity from a single probe position. There is also an ability to inspect hidden structures and structures under water, coatings, insulations, and concrete. Basic theoretical aspects of dispersion curve analysis, wave structure, source influence, sensor types and instrumentation possibilities and commercialization ventures will be discussed along with a variety of practical applications on ship hull, containment structures, aircraft, ice detection,

pipelines, rail, overlap joints, and crystal manufacture. Phased array focusing in pipes and across elbows will be highlighted. Computational aspects of FEM and BEM analysis for defect classification and sizing analysis will be outlined. Future directions of leave in place sensors and wireless activity will also be presented.

Lowe et al. [2004] Constant, long-time monitoring of large plate-like structures, e.g., oil storage tanks, can be performed using permanently attached remote sensors. A guided ultrasonic waves array, consisting of piezoelectric transducer elements for the excitation and reception of the first antisymmetric Lamb wave mode A_0 , was designed and built. Laboratory measurements for a steel plate containing various defects have been performed. The results were compared to theoretical predictions and the sensitivity of the array device for defect detection was ascertained.

Reis et al. [2005] Waveform energy (indicative of attenuation) was presented and discussed in terms of corrosion damage. Current results indicated that the loss of bond strength between the reinforcing steel and the surrounding concrete can be detected and evaluated using guided waves

Kermani et al. [2005] studied the numerical method that was investigated for drawing the dispersion and displacement curves of ultrasonic lamb wave, propagated in Aluminum thin plate. Two ultrasonic lamb wave techniques, pulse-echo (a_1 mode emitter) and emission (s_1 mode emitter), were used for interpretation of notch defects with depths of 10%, 30% and 60% of plate thickness. Thickness of plate was 2 mm and the nominal center frequency of transducers was 2 MHz. It was observed that these techniques are sensitive to evaluate defects, especially in short probe to defect distances. Also, it was found that amplitude analysis can give some qualitative information about defects depth by using Distance-Amplitude-Correction curves, but it was not sometime repeatable. In this respect, pulse echo method showed better sensitivity of amplitude to defects depth variation.

Cawley [2007] The application of ultrasonic guided waves for the long range inspection of large structures is reviewed. The technique is in routine commercial use on pipes and this technology is described. However, the method is much more difficult to apply on complex structures where the reflections from multiple features are not resolved in time. Here it is necessary to look for changes relative to a baseline condition as part of a structural health monitoring strategy; this requires a method to compensate for benign changes such as temperature variations, and possible methods for achieving this are discussed.

Reis et al. [2008] Guided longitudinal modes in both low (<200 kHz) and high (2–8 MHz) frequency ranges were invoked to monitor damage in reinforced mortar specimens undergoing accelerated uniform corrosion.

Lowe [2008] A self-contained, permanently attached guided ultrasonic waves array for the constant, long-term monitoring of the structural integrity is being designed and built. The array consists of a ring of piezoelectric transducer elements for excitation and reception of the guided wave. The properties and coupling of the transducers is studied and optimized

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

Ervin et al. [2009] studied the creation of an embeddable ultrasonic sensing network for assessment of reinforcement deterioration. Towards this effort, guided ultrasonic waves were used to monitor reinforced mortar specimens undergoing accelerated uniform and localized corrosion. Longitudinal waves were invoked at higher frequencies (2- 9MHz), where the attenuation is a local minimum. Using a through transmission configuration, waveforms were sensitive to both forms of corrosion damage. Scattering, mode conversions and reflections from irregularities at the bar surface from uniform corrosion and the severely tapered cross-section from localized corrosion are thought to cause the increase in attenuation. Because localized corrosion did not yield a discontinuity that was nearly perpendicular to the bar axis, incident waves were severely scattered, mode converted and rapidly attenuated. As evidence, this was the inability of pulse-echo testing to detect reflected waveforms for the localized corrosion.

Sharma et al. [2010] In the present work, high frequency ultrasonic guided waves have been utilized to develop a damage detection methodology for steel bars embedded in concrete with simulated notch and debond defects. Both pulse transmission and pulse echo techniques have been adopted and the time of flight and signal attenuation have been observed to locate and quantify damages accurately. The method is then successfully applied to reinforced concrete beam specimens undergoing

accelerated chloride corrosion. The simulated and actual corrosion results are compared. The ultrasonic signals effectively relate to the state of reinforcing bar undergoing actual corrosion.

Sharma et al. [2010] utilized ultrasonic guided waves for monitoring progression of corrosion in oxide and chloride environments in RC beams.

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

CHAPTER 3

EXPERIMENTAL STUDIES: ELECTROCHEMICAL INVESTIGATIONS

3.1 GENERAL

The experimental programme for corrosion monitoring is divided into two phases. In the initial phase, corrosion initiation is investigated. It is done by using LPR Method with electrochemical measurements of embedded reinforcement in reinforced concrete beams. Once the initiation is captured, propagation of corrosion is monitored by ultrasonic guided waves. The monitoring of progression of corrosion in chloride environment is done by utilizing different guided wave modes. The specimens are exposed to 5% NaCl solution ponding at room temperature. Effect of different cover depths on ultrasonic voltages is studied in detail.

3.2 EXPERIMENTAL DETAILS

The corrosion process is divided into two primary stages: corrosion initiation (**Stage I**) and corrosion propagation (**Stage II**). Corrosion initiation described is the process by which chloride ions permeate into the cover concrete and accumulate around the reinforcing steel, thereby breaking down passivity of the reinforcing steel and allowing corrosion to initiate. Corrosion propagation is described as the process by which the rate of corrosion is accelerated by the electric current at a constant voltage. Half – cell potential and galvanic current measurements were taken to monitor corrosion initiation (**Stage I**). After corrosion initiation is detected, an external direct current is applied to the selected beams through a direct current to accelerate corrosion propagation (**Stage II**). Propagation of corrosion is monitored using ultrasonic guided waves. Guided wave modes are selected to pick up delamination and pitting effects caused by chloride corrosion.

Four RC beams specimens, having dimensions 150 mm x 150 mm x 700 mm, are reinforced with steel of 25mm diameter and of 1.1m length. The RC beam specimens are made with a glass pond on the top surface. They are subjected to continuous ponding with 5.0% NaCl solutions to a depth of 25 mm. NaCl solution ponding is employed to accelerate the corrosion process. The pond is built of glass and water proofing is done on all the four sides of the beams with ARELDITE as shown in **Fig 3.1**. The concrete mix used for casting of beams is M20. It is designed according to IS code method. The weight proportions of the concrete mix are taken as 1

(cement): 1.5(coarse aggregate): 2.83 (fine aggregate): 0.5 (water). The 7-day and 28-day compressive strength of the concrete is found to be 16 N/mm^2 and 25 N/mm^2 respectively. Two types of beam specimens are made with different number of reinforcing steel bars and at different cover depths. One set of specimens is made with two reinforcing bars at two different cover depths. Another set of beam specimens with three reinforcing bars at three different cover depths are casted. The basic aim of providing different cover depths is to monitor the effect on corrosion initiation and progression in the reinforcing bars at different depths. It is done using Electrochemical measurement of corrosion potential (E_{corr}) and corrosion current (I_{corr}) and ultrasonic voltages using conventional ultrasonic testing arrangement.

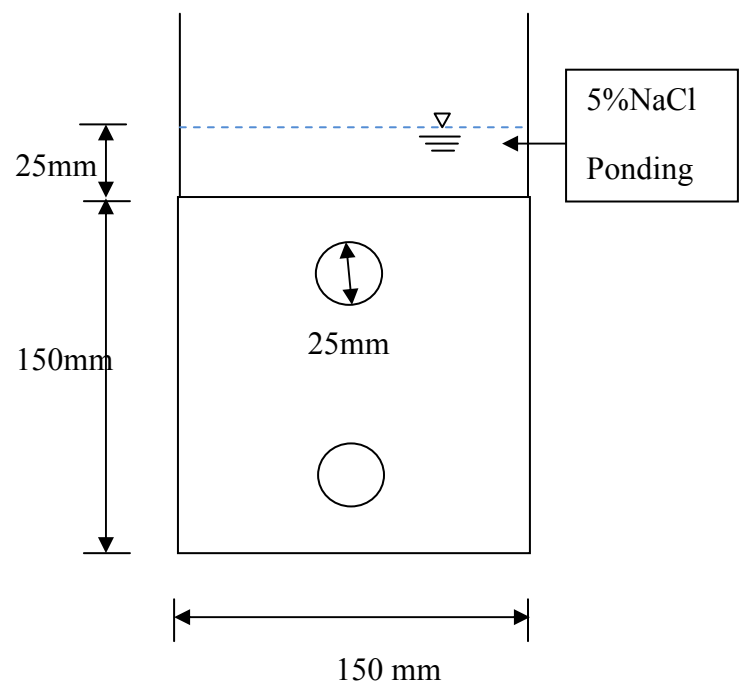


Fig 3.1: Beam specimen with a glass pond (5%NaCl)

3.2.1 MATERIALS USED

The materials used for the casting of RC beams are cement, fine aggregates, coarse aggregates and reinforcing steel. Properties of the ingredients used for making concrete for RC Beams are as discussed below.

CEMENT

Ultratech (43 grade), PPC is used for the casting of all the samples. **Table 3.2.1** gives the properties of cement used for casting.

Table 3.2.1: The various properties of cement used for casting

Properties of Cement	
Fineness	0.02%
Standard consistency and Setting time	32
Compressive Strength: 3days	16.38N/mm ²
7days	22.5N/mm ²
Specific gravity	2.38

FINE AGGREGATES

Sand is used as fine aggregates in the concrete specimen. The various properties of fine aggregates are mentioned in the **Table 3.2.2**.

Table 3.2.2: Properties of Fine aggregates used for casting

Properties of Fine aggregates	
Fineness Modulus	3.31
Maximum size	4.75mm
Specific gravity	2.57

COARSE AGGREGATES

The following **Table 3.2.3** gives all the details of the properties of the coarse aggregates used.

Table 3.2.3: Properties of Coarse aggregates used for casting

Properties of Coarse aggregates	
Fineness Modulus	6.31
Specific Gravity	2.54
Maximum size	20mm

REINFORCING STEEL

The reinforcing steel used was 25mm in diameter and 1.1m (approx.) in length. Plain bars were used to study the effect of corrosion. The following **Table 3.2.4** gives the specific details of the properties of the reinforcing steel used.

Table 3.2.4: Properties of reinforcing bars used for casting of RC beams

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

3.2.2 SPECIMEN DETAILS

Two types of RC beam specimens are casted which are named as 2-Bar Beam specimen and 3-Bar Beam specimen (**Fig 3.2**). In 2-Bar beam specimen two reinforcing steel bars are used at 25mm and 100mm cover depths. In 3-Bar beam specimen, three reinforcing steel bars at different cover depths of 25mm, 62.5mm and 100mm are used. Different cover depths are selected in the RC beam specimens as presented in **Fig 3.3**. **Fig 3.2** shows the top (Rod1) and the bottom (Rod2) reinforcing steel in two bar beam specimen, and top (Rod1), middle (Rod2) and bottom (Rod3) reinforcing bars in three bar beam specimen. The smaller clear cover depth of 25mm was adopted so that corrosion initiation can be observed in a reasonably short period of time. Other cover depths of 62.5mm and 100mm are used to investigate the effect of cover depth on the corrosion initiation and progression structures.

Further two categories of beam specimens are investigated. In one set of 2-Bar and 3-Bar specimens, after corrosion initiation, the process is accelerated by impressing corrosion current. These are called Accelerated Beam specimen. In another set of 2-Bar and 3-Bar specimens corrosion is not accelerated by impressing current. These are called Non-accelerated Beam specimen. In all four specimens are investigated. Two specimens (one accelerated and other non-accelerated) of 2-Bar and two specimens of 3-Bar specimens are casted for testing. In natural environments, corrosion process takes several years to occur. Hence, in the present study on one set of 2-Bar beam specimen and 3-Bar beam specimen after corrosion initiation corrosion is accelerated with an external current of constant voltage of 30V by means of a constant power supply device. Positive terminal of the power supply is attached to the bars in the beam specimens acting as anode. The negative terminal is connected to the copper wires which are

submerged in the pond and they act as cathode. These equal length wires were kept parallel to each other and at an equal distance. Each steel bar (anode) in the beam specimens, with two bars and three bars, were provided individually with the copper wires (cathode). This type of corrosion cell, composed of two dissimilar metals (copper and carbon steel) in contact and sharing a common electrolyte (concrete pore solution), is called a galvanic cell. Each cell was connected across the power supply of 30V.

In another set of samples of the beam specimens, in which corrosion is not accelerated by impressed current. The monitoring of all these beams accelerated and non-accelerated is done by Electrochemical measurements by means of corrosion analyser (**Fig 3.4**) as well as by ultrasonic investigation.

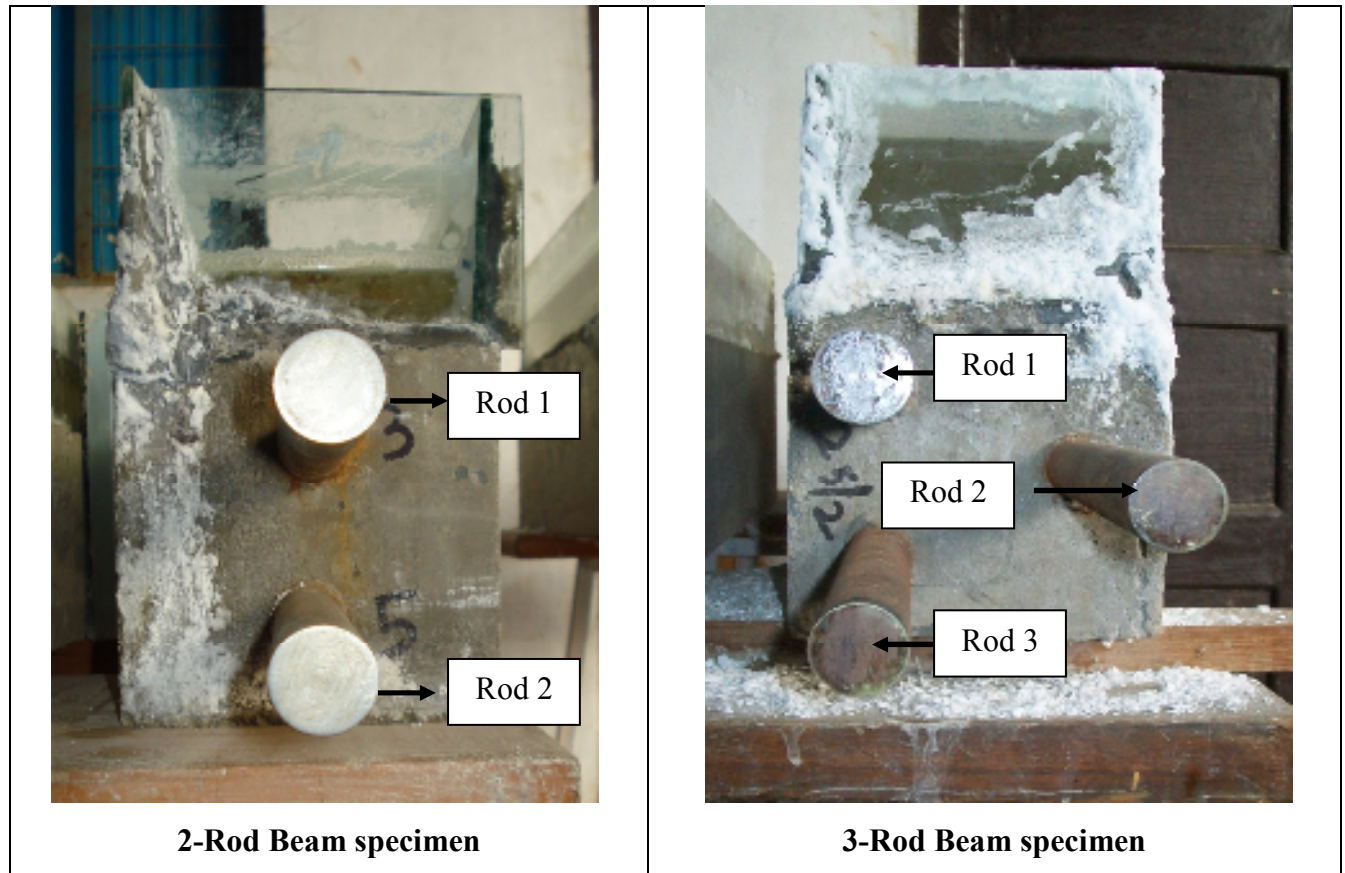


Fig3.2: Different beam specimens

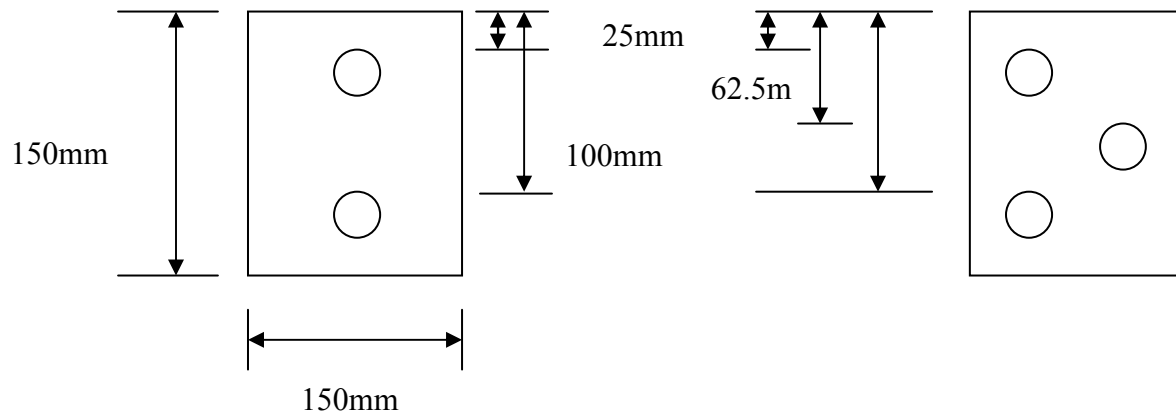


Fig3.3: Details of the cover depths used for two beam specimens

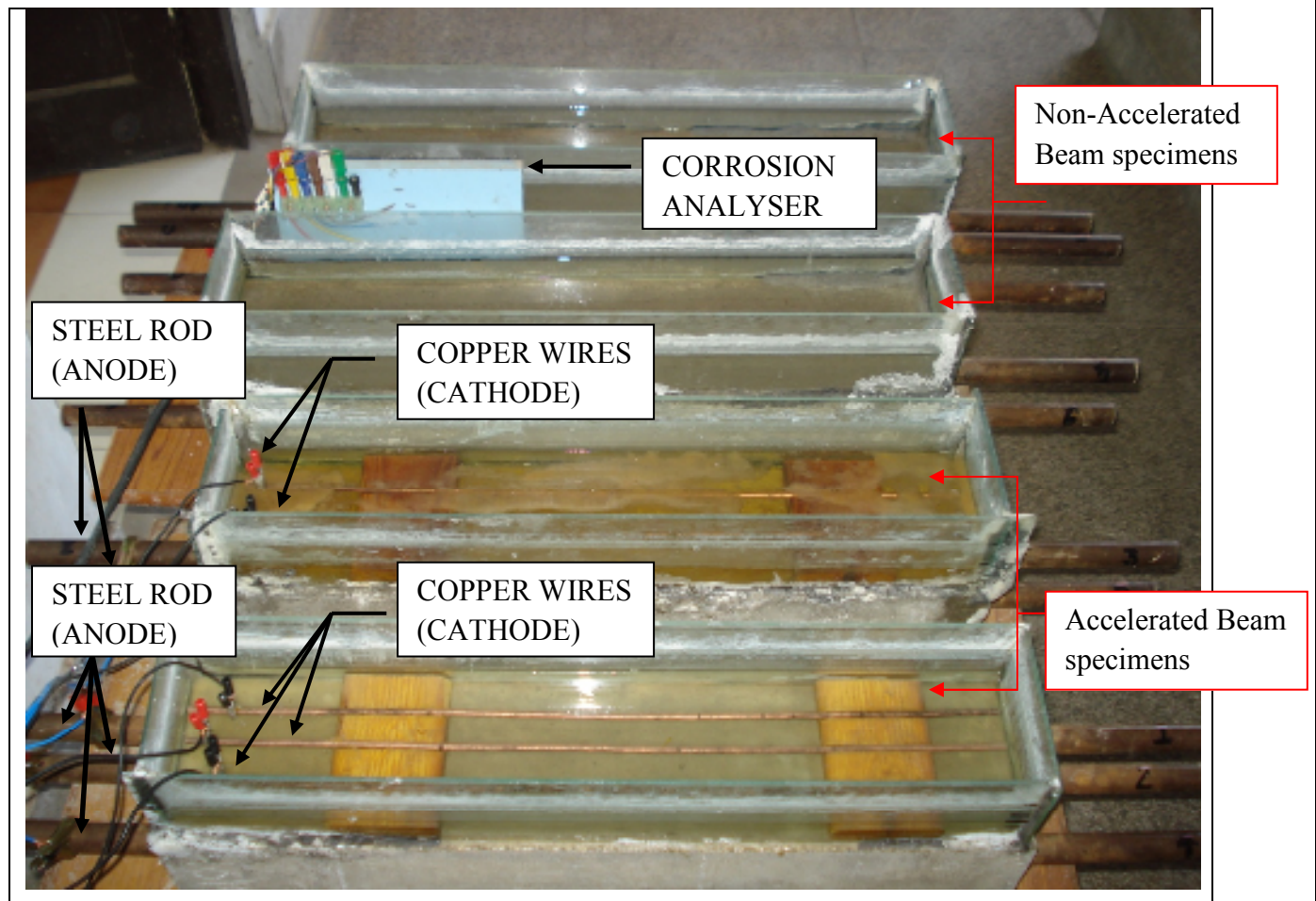


Fig3.4: Setup showing the Accelerated beam and Non-accelerated beam specimens undergoing electrochemical monitoring

3.3 ELECTROCHEMICAL INVESTIGATIONS

Corrosion of steel embedded in concrete is not visually evident until the damage reaches to the external signs of deterioration as rust spots, cracks or spalling. In order to predict the corrosion service life of reinforced concrete structures and to determine the need of repair or rehabilitation, it is necessary to use non-destructive techniques for assessing the corrosion activity and measuring the corrosion rate of the reinforcements. In the present study, Corrosion rate of steel reinforcement is determined by linear polarization resistance test for detecting the corrosion initiation. The instrument used for this purpose is CORROSION ANALYSER (ACM INSTRUMENTS, U.K).

3.3.1 CORROSION INITIATION (STAGE 1) – BY CORROSION ANALYSER

Corrosion initiation is very important for the study of monitoring of structures as it helps to overcome the damage that is not evident at an early stage. Two important parameters that are used for the studying the initiation are corrosion potential (E_{corr}) and corrosion current /current density (I_{corr}). These determining parameters indicate the corrosion initiation which account for steel surface condition and the chloride ion concentration in concrete.

Corrosion potential (E_{corr}) is the potential at which anodic and Cathodic reactions are in balance (currents for the reactions are equal). Also, current density (I_{corr}) is the net electrode current per unit surface area of the electrode i.e current at E_{corr} , is called corrosion current (I_{corr}). Intersection of the two curves is passive zone. At this point the chlorides in concrete cause pitting to be initiated and corrosion occurs at lower potentials [11]. Hence, E_{corr} and I_{corr} were taken as the two important parameters for the further study indicating the initiation of corrosion. In the present study, the corrosion is monitored daily for each beam by corrosion potential (E_{corr}) and current (I_{corr}) measurements. Corrosion potentials (E_{corr}) for the top and the bottom bars were measured as an indicator for the onset of corrosion [36]. Galvanic current (I_{corr}) was also used to monitor the corrosion process of reinforcing steel in the present study the amount of which can indicate the degree of corrosion activity in the cell [37]. In the present study, the potential and galvanic current was monitored daily for each beam through Corrosion Analyser (Stage 1) at the same position of the beam.

ACM Instruments designs, manufactures, markets and supports a wide range of electrochemical instrumentation. This instrument can perform tests such as AC Impedance (EIS), LPR, current and voltage. The Galvo Guard is a complete kit that enables this Field Machine to perform

galvanostatic pulses on concrete surfaces using the supplied guard ring for precise location of reinforcing steel bar areas. The Guard Ring simply connects to the front panel via the supplied cables. Incorporated into the Guard Ring are a Cu/CuSO₄ reference electrode. The front of the Guard Ring is covered with conductive foam for electrical connection to the concrete surface. An excellent addition for concrete mapping, the Galvo Guard focuses the current field to the reinforcement for precise location as shown in **Fig 3.5**. Before performing the test, conducting sponge is wetted with NaCl solution and placed on the surface of the slab specimen to have proper electrical contact with the guard ring. Guard ring assembly is then placed above the wetted sponge. Based on the detection and analysis of spikes in current and voltage across a cell the Electrochemical LPR technique is especially good at measuring the localized corrosion. If the corrosion potential reading is more positive than -200mV probability is that no reinforcing steel corrosion is occurring in the area at the time of measurement and if the potential reading is more negative than -350mV probability is that the reinforcing steel corrosion is occurring [16]. When spots of rust form during localized corrosion they are accompanied by cascades of current, rather than the continuous presence of *I_{corr}* that is the signature of more uniform corrosion.

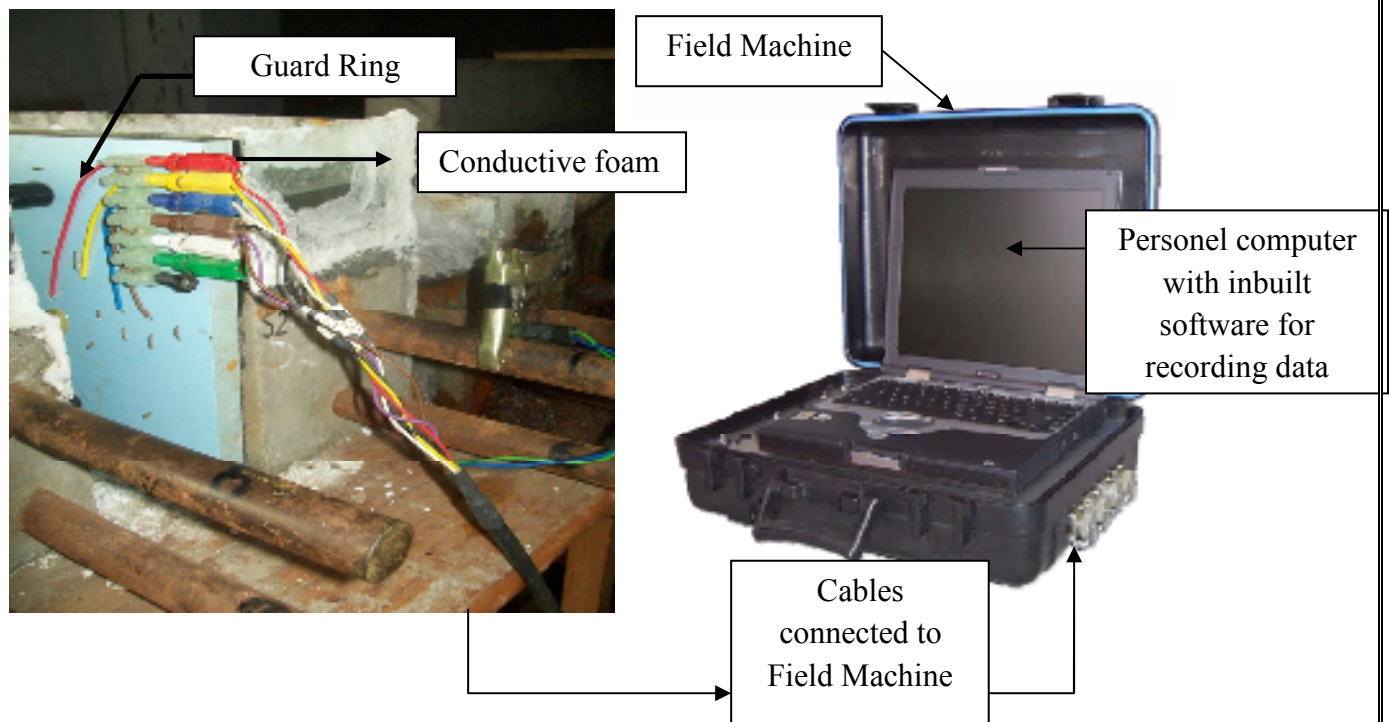


Fig 3.5: ACM setup used for electrochemical monitoring

For ease of use the software is divided into three stages. **Stage one** is the sequencer, where tests are setup. The **second stage** is core running which collects the data while performing the tests,

real time plotting can be followed at this point. In the **final stage** the analysis software allows easy to use yet sophisticated handling of collected data [40].

SEQUENCER

The sequencer is the part of the software which allows you to set up the timing and parameters of your tests within an easy to use interface. Simply drag the desired test such as AC Impedance into the sequence list, choose from a set of parameters, and away you go by pressing 'run now'. It could not be easier to set up multiple tests over multiple channels!

- Clear easy to use interface,
- ASTM standard database notebook,
- Create metal factors from a periodic table,
- Save common test set-ups for quick retrieval,
- Customised techniques easily created

Core Running

Once tests have been set up and started. Core Running reliably handles data collection. Watch as valuable data is collected in real time by viewing graphs develop reading by reading. It is also a reassuring tool to check instruments are set up correctly by seeing real results instantly.

- Watch graphs draw in real-time
- Log data collection process
- Diagnose errors with data collection
- Control tests whilst in progress

ANALYSIS

Analysis is perhaps the most important part of the process, when you get to see the results obtained, manipulate them and have the opportunity to interpret them with your knowledge and expertise.

- Fast data exporting to Excel and compatible
- Label, resize save and print graphs
- Tafel and LPR Rulers

3.4 OBSERVATIONS AND CONCLUSIONS

The beam specimens are monitored by Corrosion Analyser each for corrosion potential (E_{corr}) and corrosion current (I_{corr}) values for both the accelerated and non-accelerated beams. The basic aim is to study the initiation of corrosion for Electrochemical measurement. To develop a complete corrosion methodology, the process of corrosion is then accelerated for ultrasonic measurement in one set of specimens. In another set of non-accelerated specimens, the ultrasonic investigations are carried out without impressing current.

3.4.1 ACCELERATED BEAMS

In beam specimens corrosion will be accelerated after initiation. Electrochemical investigations show that with the increase in the period of exposure (days) a sudden fall in the value of corrosion potential (E_{corr}) and rise in the value of corrosion current (I_{corr}) is observed after 30 days of 5% NaCl ponding in top bar. Drop in corrosion potential (E_{corr}) and rise in corrosion current (I_{corr}) indicates the initiation of corrosion in the beams for the topmost bar in the 2- bar and 3-bar beam specimens. As the corrosion progresses in the beams the corrosion potential (E_{corr}) becomes more negative and the value of corrosion current (I_{corr}) rises.

- **For 2-Rod Beam specimen:** After 30 days, in this beam specimen the value of corrosion potential (E_{corr}) for Rod 1 falls to -480mV and after the application of impressed current the value falls further to -690mV in next 20 days as shown in **Fig 3.7(a)**. The value of corrosion current (I_{corr}) for Rod 1 suddenly rises to 13 mAmp/cm² after 30 days of ponding. Further after the external current application the value rises to 30mAmp/cm² as shown in **Fig 3.7(b)**.

In case of Rod 2, the value of corrosion potential (E_{corr}) suddenly falls to -450mV after 30 days of ponding and after the external current application the value further falls to -670mV in next 20 days as shown in **Fig 3.8(a)**. The value of corrosion current (I_{corr}) after 30 days of ponding rises to 10 mAmp/cm² and in next 20 days it rises to 32 mAmp/cm² as shown in **Fig 3.8(b)**.

- **For 3-Rod Beam specimen:** After 30 days, in this beam specimen the value of corrosion potential (E_{corr}) for Rod 1 goes negative upto -570 mV for initial 30 days and after the application of external current falls to -520mV as shown in **Fig 3.9(a)**. The value of

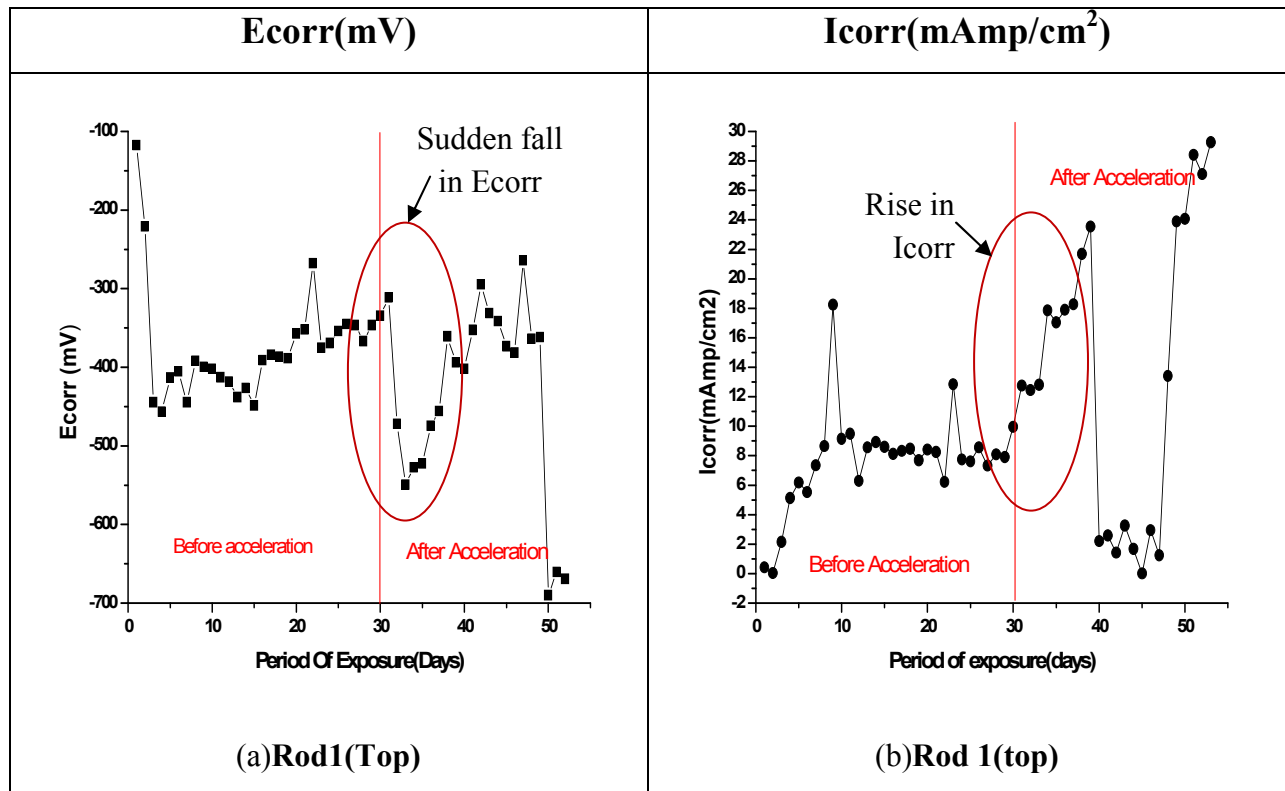


Fig 3.7: 2-Bar beam specimen showing Ecorr and Icorr for the Top Bar (Rod 1)

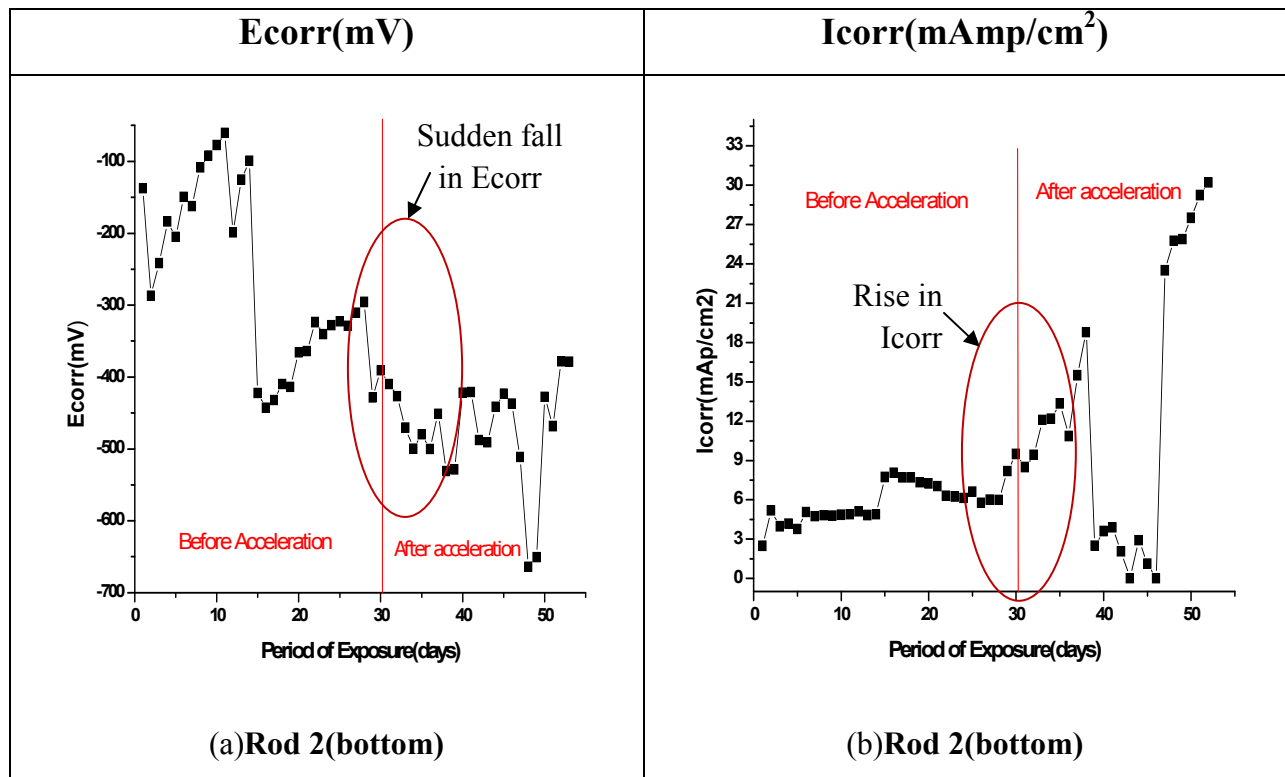


Fig 3.8: 2-Bar beam specimen showing Ecorr and Icorr for Bottom Bar (Rod 2)

corrosion current (I_{corr}) rises from 11mAmp/cm^2 after 30 days of ponding and after the impressed current application the value rises to 55mAmp/cm^2 as shown in **Fig 3.9(b)**.

In case of Rod 2(middle), after 30 days of ponding the value of corrosion potential (E_{corr}) falls suddenly to -590mV and after impressed current is applied the value falls to -660mV as shown in **Fig 3.10(a)**. The value of corrosion current for initial 30 days suddenly rises to 11mAmp/cm^2 and after external current application the value rises to 50mAmp/cm^2 as shown in **Fig 3.10(b)**.

In case of Rod 3(Bottom), after 30 days of ponding the value of corrosion potential (E_{corr}) falls to -550mV and after the application of external current the value becomes more negative to -600mV as shown in **Fig 3.11(a)**. The value of corrosion current rises to 15mAmp/cm^2 in first 30 days of ponding and after the application of current the value rises to 50mAmp/cm^2 as shown in **Fig 3.11(b)**.

Therefore, these values indicate the initiation of corrosion in the RC beams after 30 days exposure to the NaCl ponding. Drop in corrosion potential (E_{corr}) and rise in corrosion current (I_{corr}) in the top bar indicates corrosion initiation. Hence, in accelerated beam specimen after 30 days external current was applied to the two specimens for further study of corrosion progression through ultrasonic monitoring as well as electrochemical investigation.

After the application of external current, the values of corrosion potential (E_{corr}) becomes more negative and the corrosion current (I_{corr}) rise which indicates the increases the rate of corrosion.

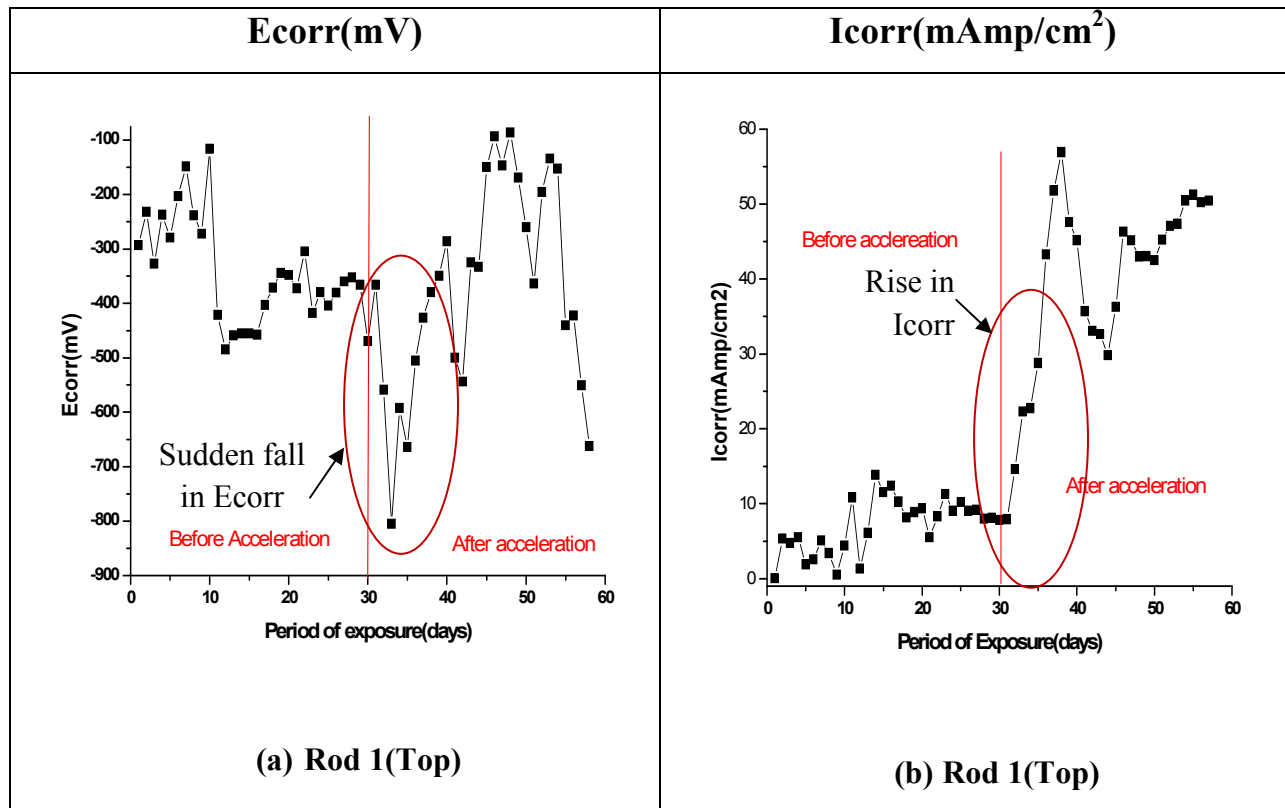


Fig 3.9: 3-Bar Beam specimen showing values of E_{corr} and I_{corr} for Top bar (Rod1)

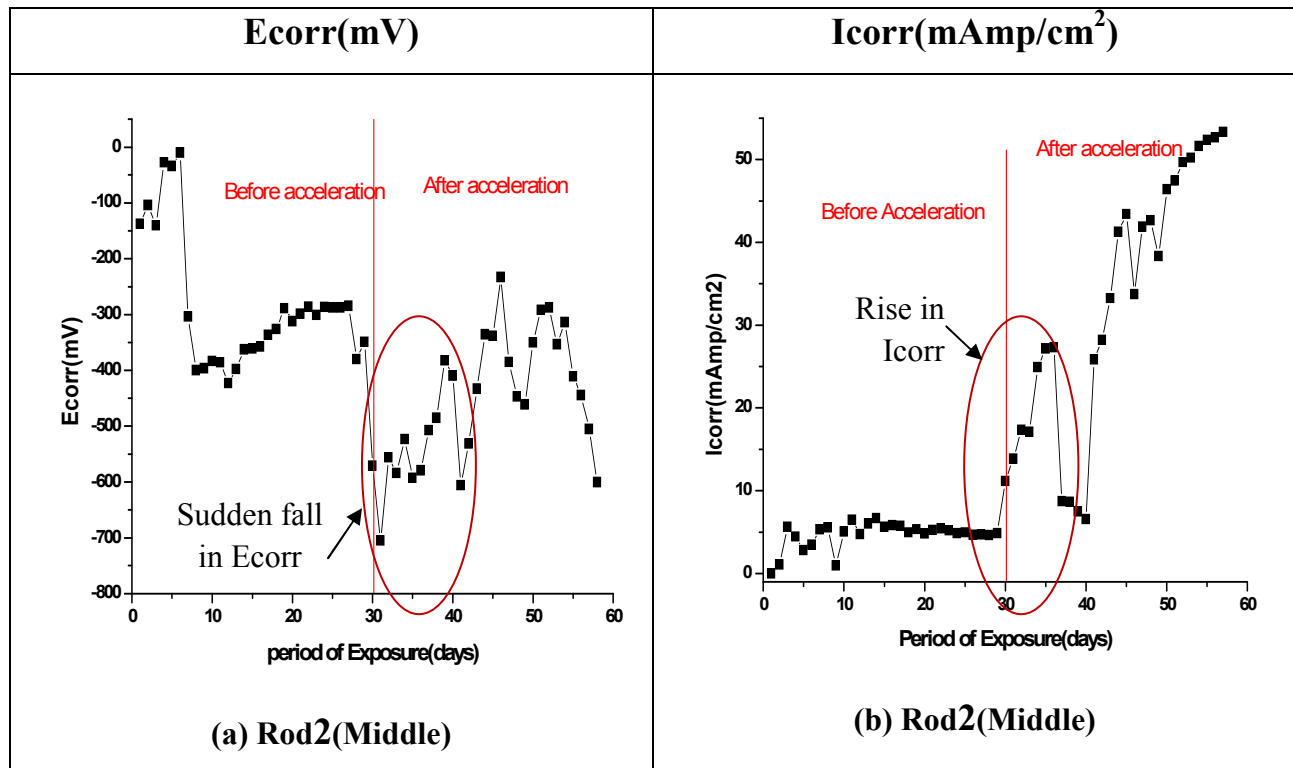


Fig 3.10: 3-Bar Beam specimen showing values of E_{corr} and I_{corr} for Middle bar (Rod 2)

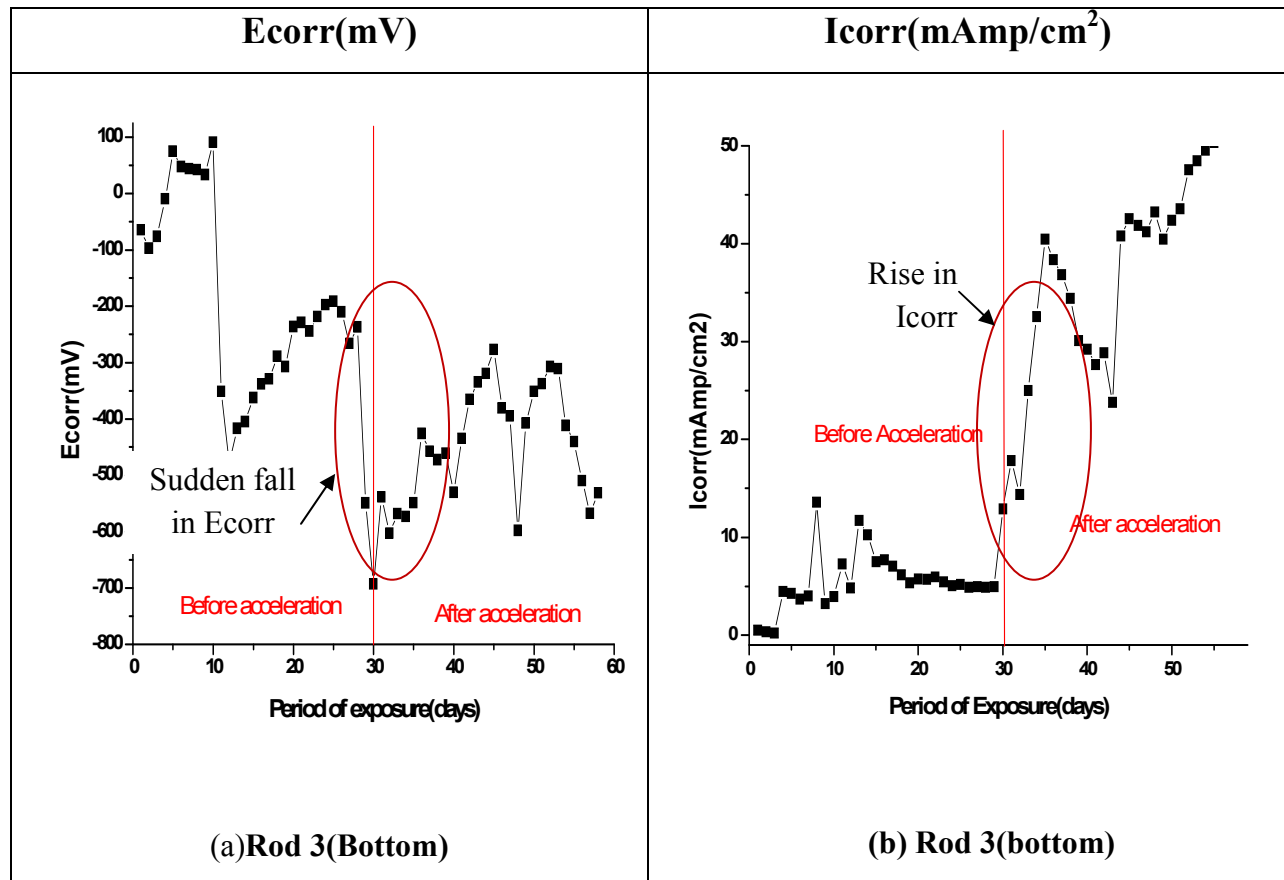


Fig 3.11: 3-Bar Beam specimen showing values of E_{corr} and I_{corr} for Bottom bar (Rod 3)

Hence, corrosion initiation is considered after 30 days exposure to ponding to NaCl solution. It is considered to initiate when the I_{corr} suddenly rises and E_{corr} falls in the bar at the smallest cover i.e Rod 1, in both the specimens.

3.5.2 NON-ACCELERATED BEAMS

In other set, 2-Rod and 3-rod beam specimens, in which corrosion will not be accelerated is observed by electrochemical investigation. The basic aim is to monitor the behavior of values of corrosion potential (E_{corr}) and corrosion current (I_{corr}) in case of natural corrosion process by ponding method.

- 2-Rod Beam specimen:** For Rod1 value of corrosion potential (E_{corr}) reaches -450mV after first 30 days of ponding and after that the value remains constant for next 20 days as shown in **Fig 3.12(a)**. For first 30 days of ponding the value of corrosion current (I_{corr}) rises and in next 20 days the value goes constant as shown in **Fig 3.12(b)**.

In case of Rod2 the fall in corrosion potential (E_{corr}) is upto -150mV in first 30 days of ponding and in next 20 days the value goes constant as shown in **Fig 3.13(a)**. Value of corrosion current (I_{corr}) is 6mAmp/cm^2 for first 30 days of ponding and in next 20 days the value goes remains constant as shown in **Fig 3.13(b)**.

- **3-Rod Beam specimen:** For Rod1 the value of corrosion potential (E_{corr}) falls to -330mV for first 30 days of ponding and after that the value is steady as shown in **Fig 3.14(a)**. The value of corrosion current (I_{corr}) is 10mAmp/cm^2 for first 30 days and after that the value becomes steady as shown in **Fig 3.14(b)**.

For Rod2 the fall in corrosion potential is -300mV in fits 30 days of ponding and for next 20 days the value becomes constant as shown in **Fig 3.15(a)**. The value of corrosion current (I_{corr}) is 6mAmp/cm^2 for first 30 days of ponding and in next 20 days the value becomes constant as shown in **Fig 3.15(b)**.

In case of Rod 3, the value of corrosion potential (E_{corr}) is even less -150mV for first 30 days of ponding and in next 20 days the value becomes steady as shown in **Fig 3.16(a)**. The value of corrosion current (I_{corr}) in Rod 3 is even less 5mAmp/cm^2 . After, 30 days, the corrosion potential (E_{corr}) and corrosion current (I_{corr}) values remain steady as shown in **Fig 3.16(b)**.

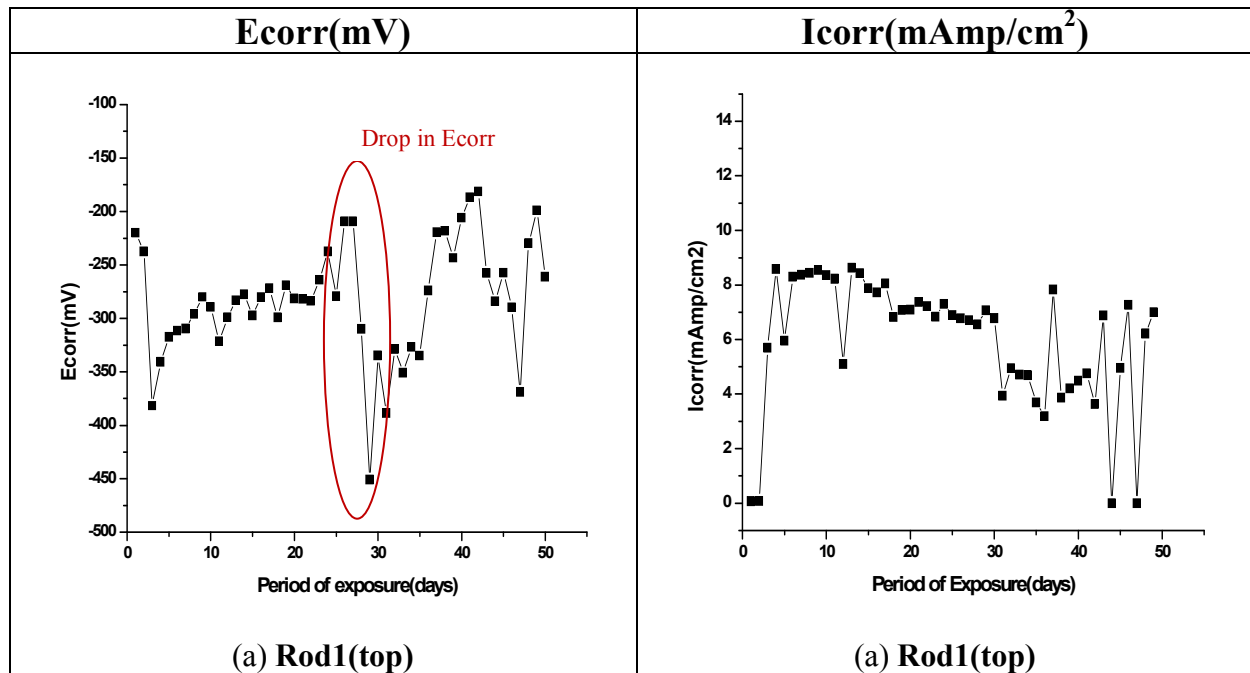


Fig 3.12: 2-Bar beam specimen showing E_{corr} and I_{corr} for Top Bar (Rod 1)

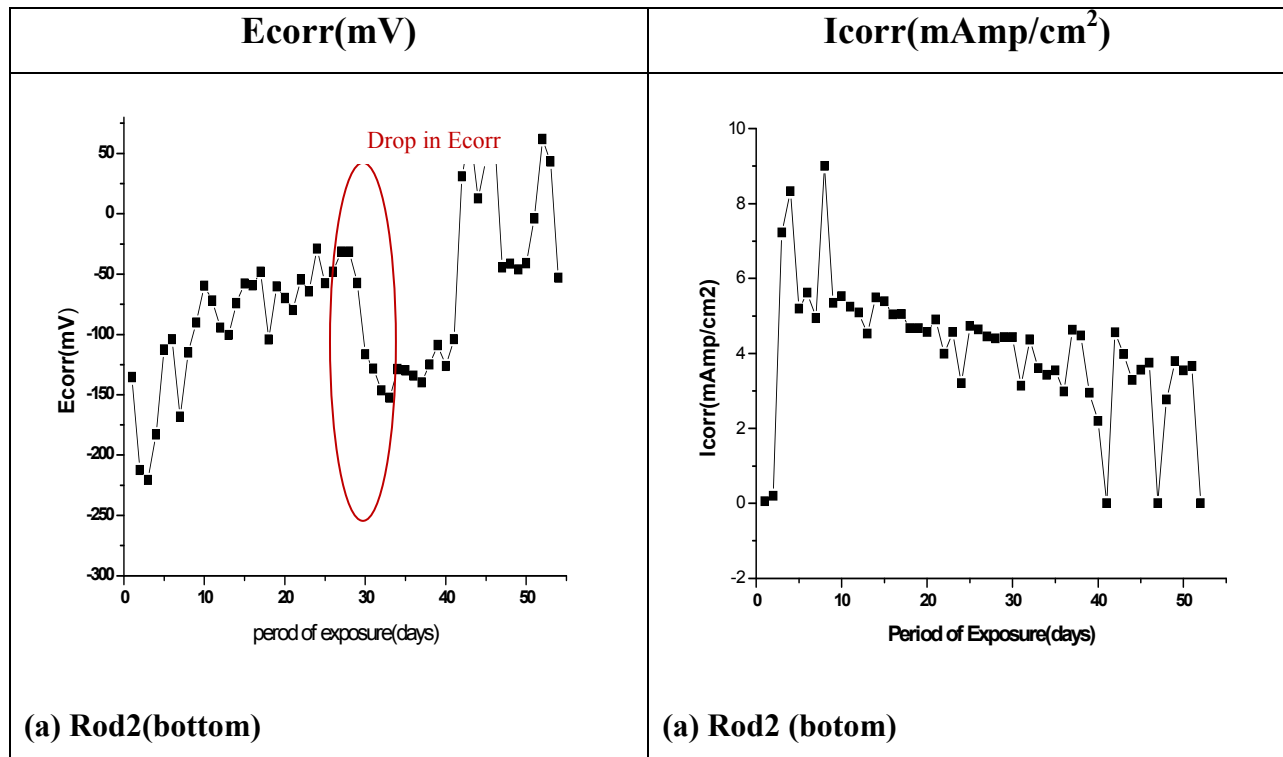


Fig 3.13: 2-Bar beam specimen showing Ecorr and Icorr for Bottom Bar (Rod 2)

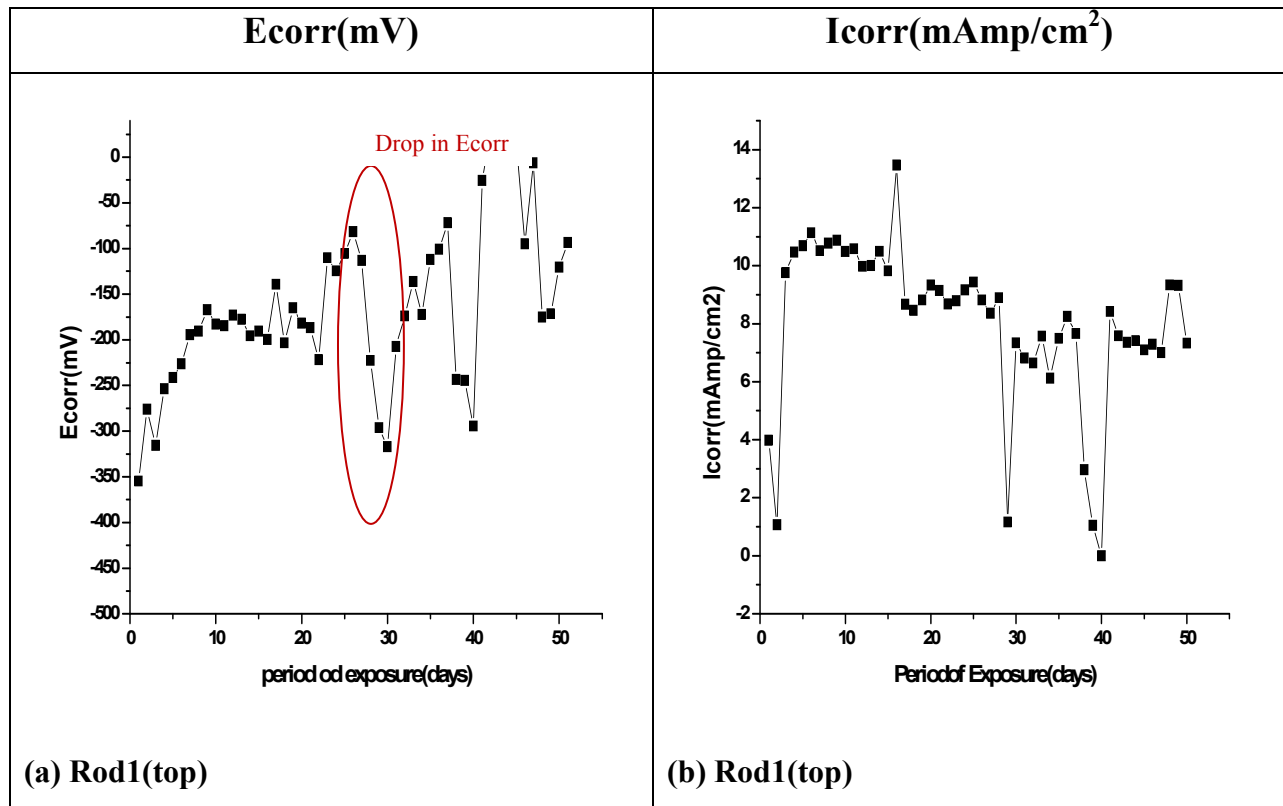


Fig 3.14: 3-Bar Beam specimen showing values of Ecorr and Icorr for Top bar (Rod1)

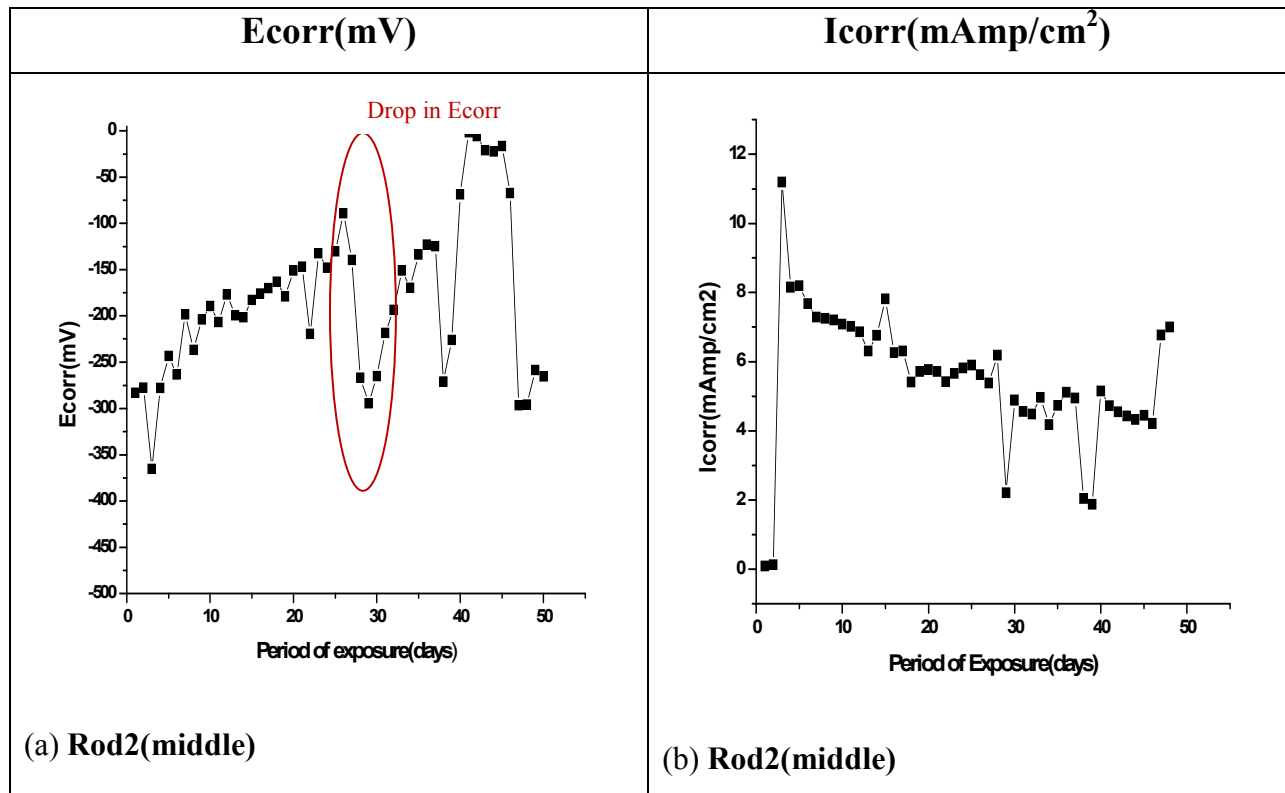


Fig 3.15: 3-Rod Beam specimen showing values of Ecorr and Icorr for Middle bar (Rod 2)

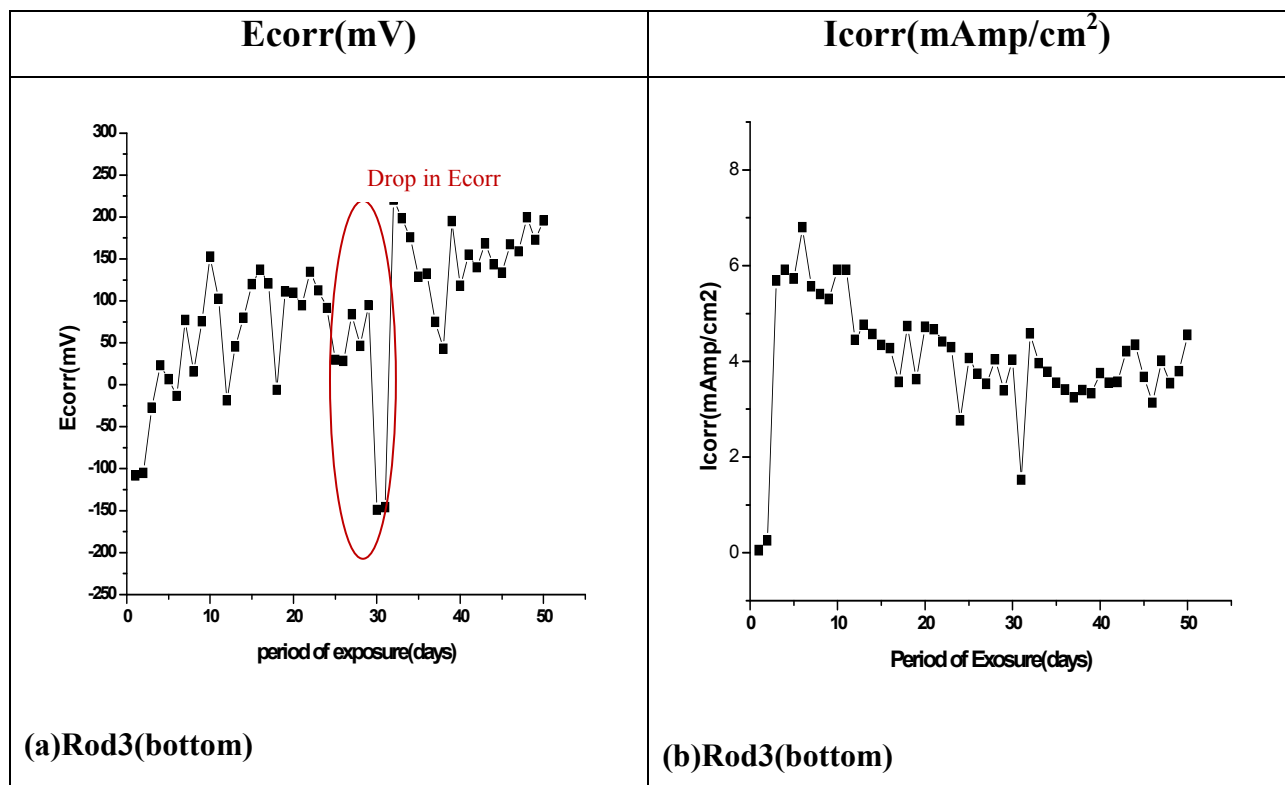


Fig 3.16: 3-Bar Beam specimen showing values of Ecorr and Icorr for Bottom bar (Rod 3)

As in case of accelerated beam specimen, as the period of exposure of RC beams increases a sudden fall in the value of corrosion potential (E_{corr}) is noticed after 30 days. This represents the initiation of corrosion in the beams as observed in topmost reinforcing steel bars. But the value of current density (I_{corr}) remains steady for longer duration of time. Hence, the values indicated that for the initial 30 days, there is corrosion initiation indicated by the fall in corrosion potential (E_{corr}). Moreover, the values of corrosion potential (E_{corr}) and corrosion current (I_{corr}) remain steady after 30 days for the rest of the duration.

3.6 CLOSING REMARKS

Corrosion initiation is well picked up by Electrochemical measurements after 30 days of 5% NaCl ponding). For further monitoring of progression of corrosion, since no significant drop in voltages or currents is observed, electrochemical monitoring is not a very good method to monitor the progression. It is suggested to use ultrasonic measurements for monitoring progression after initial corrosion initiation is well picked up by Electrochemical measurements.

CHAPTER 4

EXPERIMENTAL STUDIES: ULTRASONIC INVESTIGATIONS

4.1 GENERAL

The chloride ingress into the reinforced concrete takes many years. Once the corrosion initiation is picked up by corrosion potential (E_{corr}) and corrosion current (I_{corr}), it is decided to accelerate the corrosion process by an external current in one set of specimen. The progression will be monitored by means of ultrasonic investigations. Ultrasonic guided waves have been identified as an effective technique for monitoring reinforcing bar corrosion in concrete. Surface and core seeking ultrasonic guided wave modes have been identified which were sensitive to delamination and pitting corrosions respectively [44]. These modes are used to ultrasonically monitor reinforced concrete beams undergoing accelerated impressed current corrosion in chloride environment [38]. Also ultrasonic investigation is also carried out on another set of 2-bar and 3-bar specimens with only ponding of 5%NaCl and not impressed current corrosion.

4.2 CORROSION PROPAGATION (STAGE II) – ULTRASONIC INVESTIGATION

4.2.1 EXPERIMENTAL SET-UP

After corrosion initiation, an external direct current of 30V is applied to one set of specimens through a power supply to accelerate the corrosion propagation process. Both accelerated and non-accelerated beams are monitored by ultrasonic guided wave modes in Pulse Transmission (P/T) mode. The concept of using guided waves for the inspection of individual bars has been in existence for some years. To produce guided waves in the bars of concrete beam two transducers (Karl Deutsch contact type) are attached at the two ends of the bar in projected beam. One transducer acting as a transmitter and the other acting as a receiver are attached parallel to the axis of bars in pulse transmission mode of testing [38]. The excitation wave mode from the transmitter T travels through the material to its opposite surface where the receiving transducer R is placed. **Fig 4.1** shows the set up used for ultrasonic investigations. DPR 300 pulse/receiver is used to generate the ultrasonic pulse, by means of through transmission method, which propagates through the embedded bar in the form of longitudinal waves. The excitation signal consisted of a compressive spike pulse. Both RC beam specimens, 2-Bar and 3-Bar beam specimens, for accelerated as well as non-accelerated beams are monitored by this pulse transmission method.

For monitoring two different phenomena of pitting and delamination occurring as a result of corrosion, two different frequencies and modes have been identified [38]. The beams are monitored till the ultrasonic signature completely vanishes for all the specimens. Ultrasonic testing results are reported as Voltage-Time (V-t) values. The ratio of the peaks of the applied and transmitted pulses is determined and reported as peak-peak voltage ratios.

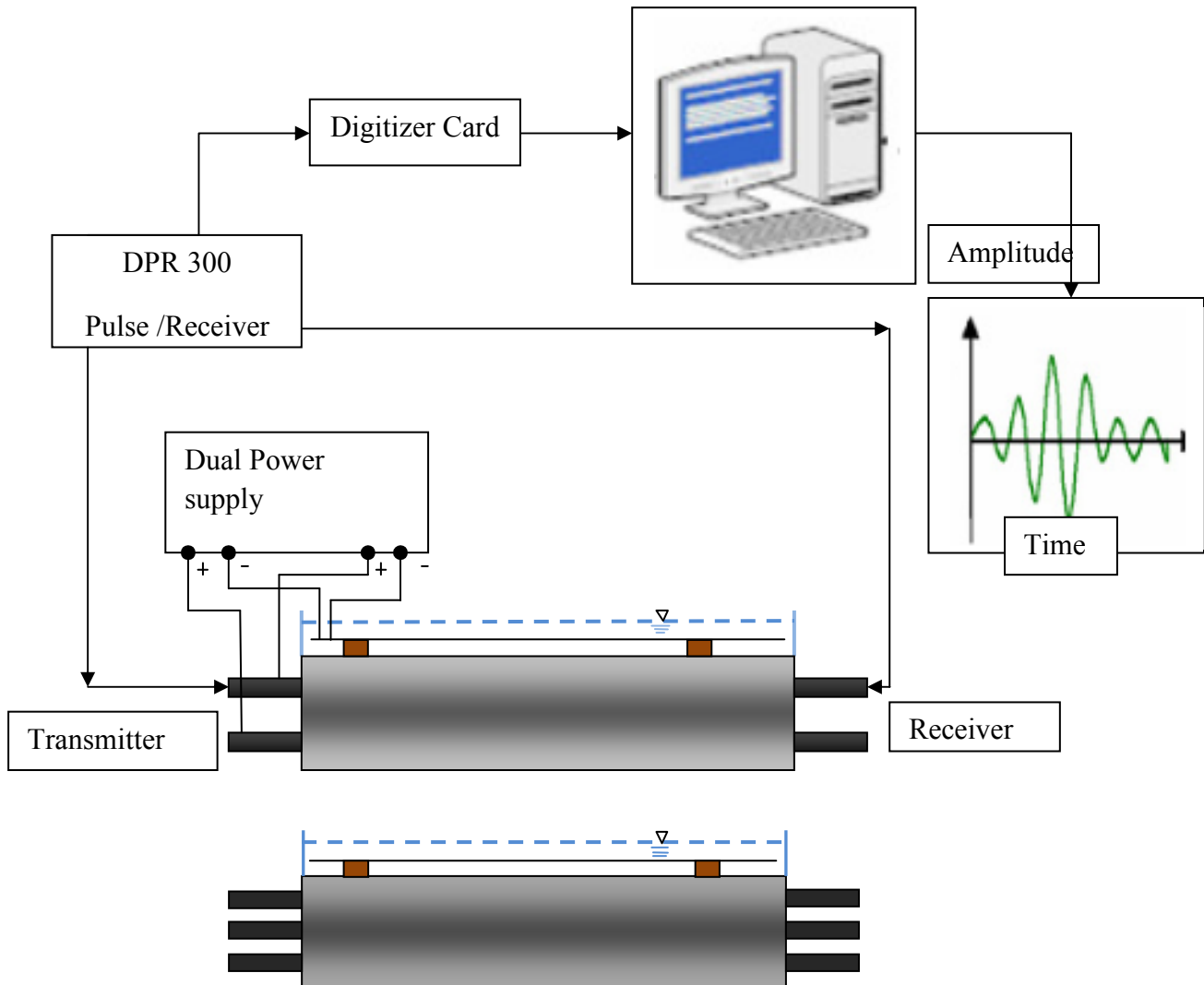
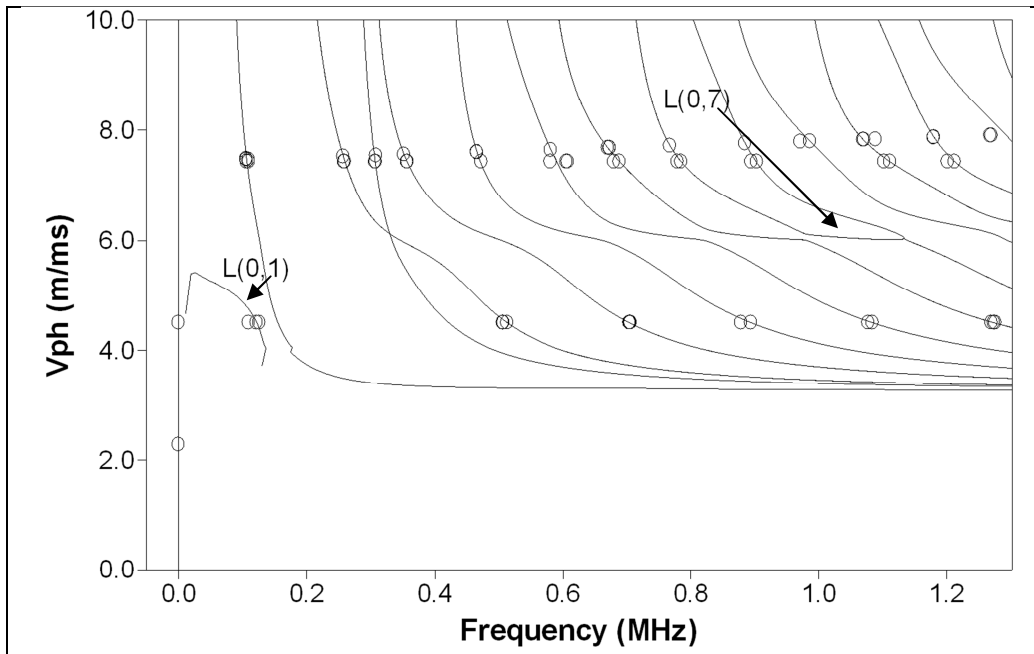


Fig 4.1: The experimental set-up for the ultrasonic investigations

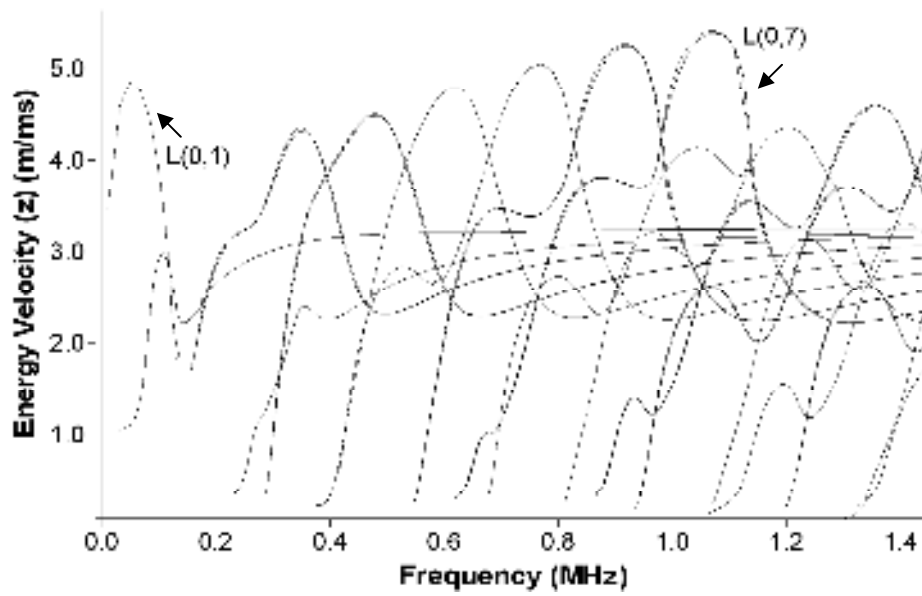
4.2.2 SELECTION OF EXCITATION MODE AND FREQUENCY

The selection of frequencies for testing is done using the software Disperse [45]. The selection of a suitable test mode and frequency can be made by close examination of the dispersion curves. The modes that are easily distinguishable and have lowest signal attenuation are selected [38]. It is desirable to use a mode at a point of low attenuation, to maximize the inspection range, and to use a mode at a point of maximum energy velocity, to limit the effects of dispersion, and to reduce the risk of other modes complicating the received signal [39]. Dispersion curves for a 25mm bar embedded in concrete are plotted as shown in **Fig 4.2**. Only longitudinal modes have been considered in the study as the flexural and torsional modes experience high theoretical attenuation. Guided longitudinal waves are produced in the embedded bars by keeping compressional transducers parallel to the guiding configuration at the two ends of the bars embedded in concrete. The different longitudinal modes are excited by varying the excitation frequencies. The selection of frequencies for testing is done based on the phase velocity dispersion curves **Fig 4.2(a)**. They are validated by experimentally confirming the signal fidelity.

For bars embedded in concrete, which is a layered waveguide system, leakage plays an important role. High frequency low attenuating modes with displacement profiles centered in the middle of bar to minimize leakage [19] are found to be the best for layered systems. Phase velocity dispersion curves show the fundamental L (0, 1) mode starting at zero frequency with each higher order mode starting from a higher cut off frequency. Each of the higher modes shows a plateau region around the steel longitudinal bulk velocity line. But L (0, 7) mode shows a different pattern. Instead of each plateau region belonging to a single mode, L (0, 7) breaks from this pattern and links the subsequent plateau regions together to form a single mode that propagates close to the longitudinal bulk velocity of steel. The plateau regions correspond to the points of maximum energy velocity as shown in **Fig 4.2(b)** and minimum attenuation as shown in **Fig 4.2(c)**. This L (0, 7) mode is chosen for study. At a frequency of 1 MHz, the mode exhibits global attenuation minima of 22dB/m and is the fastest propagating mode. The phase velocity as obtained from dispersion curve at this frequency is 6 km/s. Also, L (0, 1) being a low attenuative mode and low frequency mode can also be used for testing.



(a) Phase velocity Vs Frequency



(b) Energy Velocity Vs Frequency

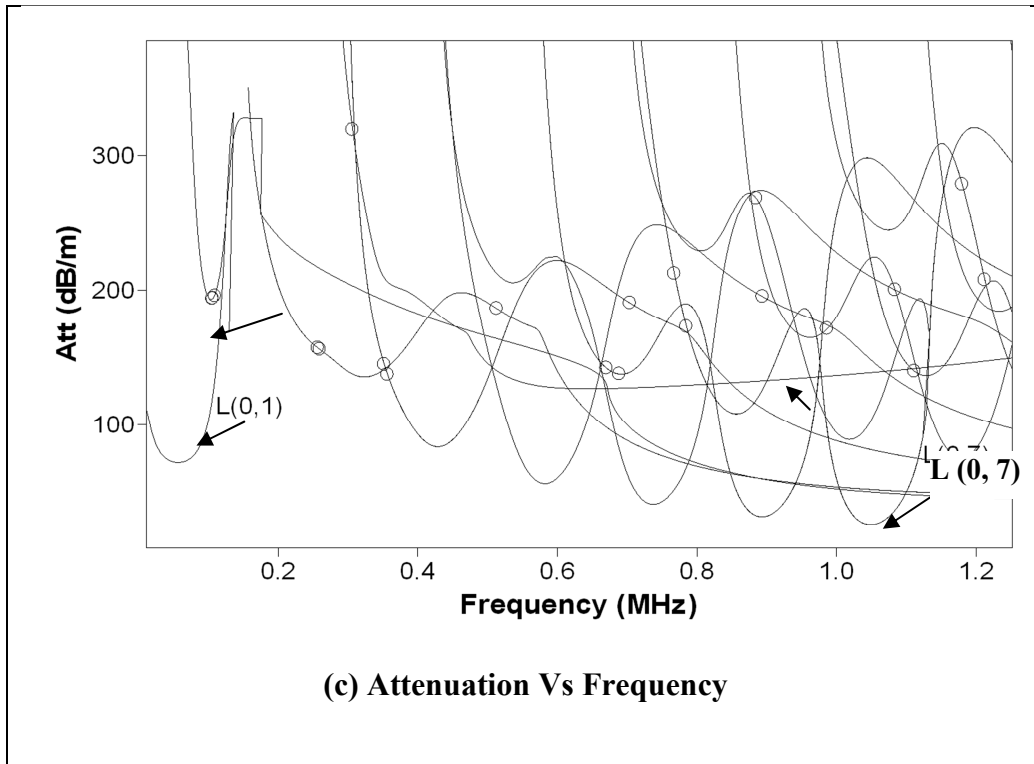


Fig 4.2: Dispersion curves for 25mm diameter bar [38]

Another contributing factor to the selection of mode is the relative sensitivity of ultrasonic waves to different aspects of corrosion. For monitoring two different phenomena of pitting and delamination occurring as a result of corrosion, two different frequencies and modes have been identified. **Fig 4.3(b)** shows the displacement mode shape and radial strain energy density distribution for L (0, 7) mode selected in the present investigation. The energy is concentrated in the central core portion of the bar and has relatively less surface component. Hence, it should be more sensitive to local bar topography or loss of material changes and not the surface profile changes. ***It is a core seeking mode.*** Thus, this mode may not be sensitive to delamination that is more of a surface phenomenon [38]. A mode that has significant surface component would be sensitive to delamination effect of corrosion of the bar. Such mode is L (0, 1) mode at a low frequency of 100 kHz having negligible amount of signal loss due to material absorption. This mode shows significant axial displacement at the interface and is ***a surface seeking mode*** as shown in **Fig 4.3(a)** and hence, is chosen to assess the interfacial changes at 100 kHz. Thus, these two modes have been considered in an attempt to distinguish between the debond and area loss effect of chloride corrosion through ultrasonics. Also the two modes are the lowest attenuating modes as shown in **Fig 4.2(c)**.

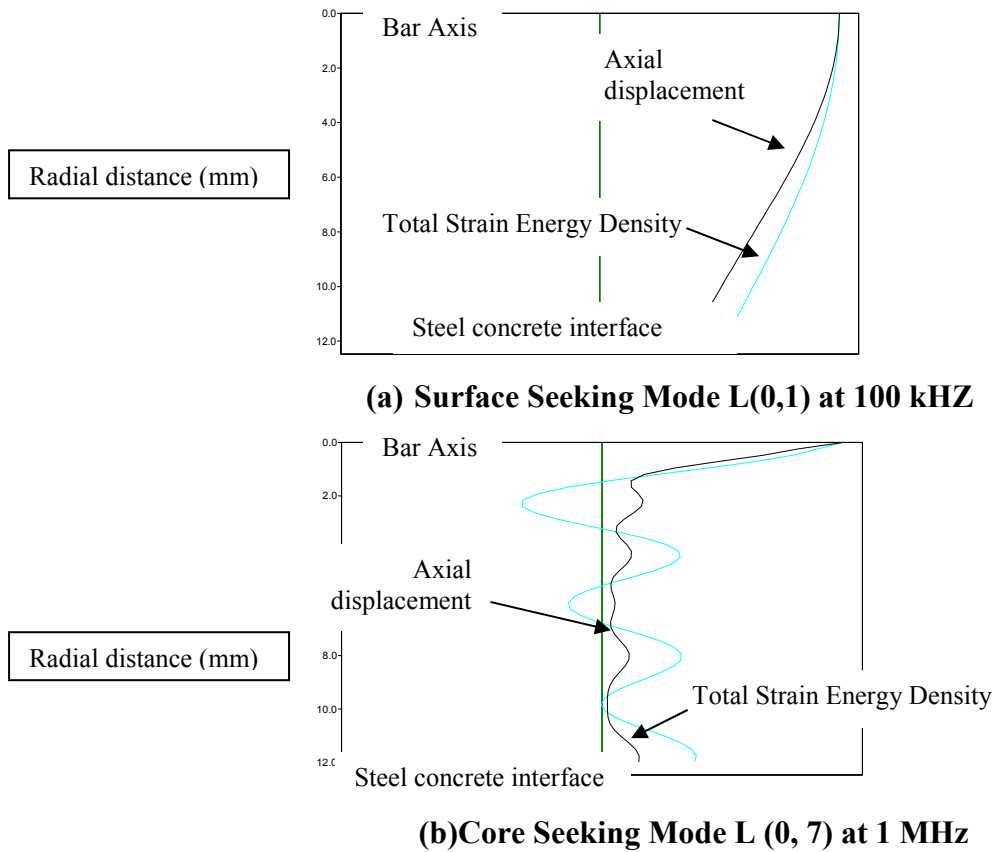
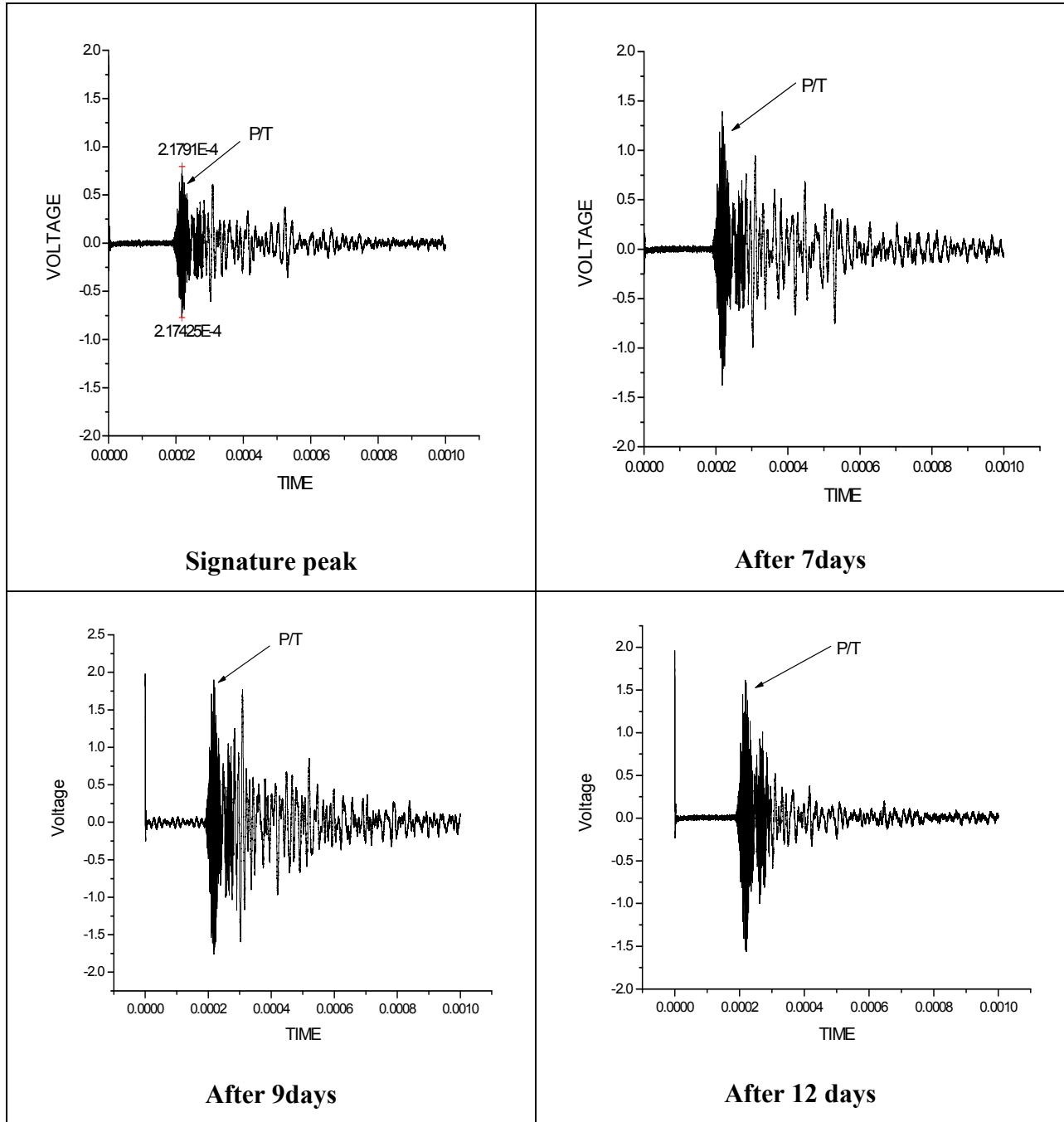
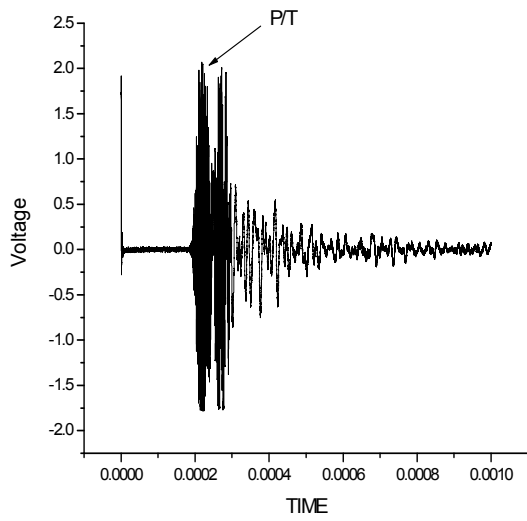


Fig 4.3: Mode Shapes [38]

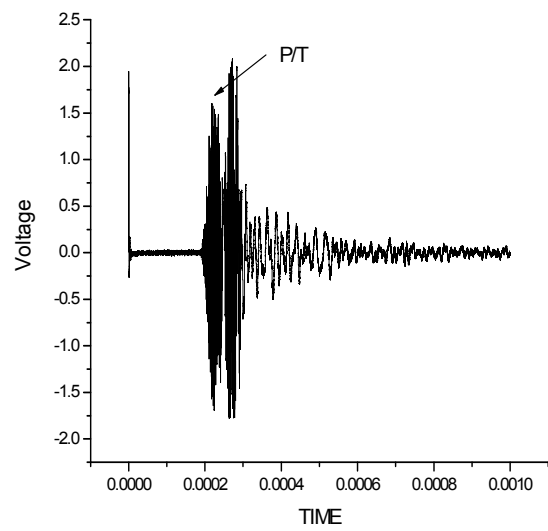
Ultrasonic voltage trends of the received signal using surface seeking mode L (0, 1) at 100 kHz for the topmost bar in a 2-Bar Beam specimen is shown in **Fig 4.4**. The core seeking mode L (0, 7) at 1MHz follows the trends as shown in **Fig 4.5** for ultrasonic signal recieved for topmost bar in 2-Bar Beam specimen.

Fig 4.4: Signature peaks of the Topmost Bar (Rod1) of 2-bar beam specimen in pulse transmission for L (0, 1) at 0.1MHz.

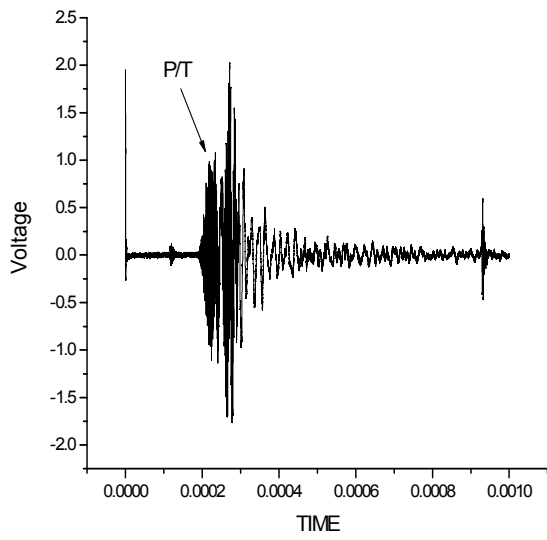




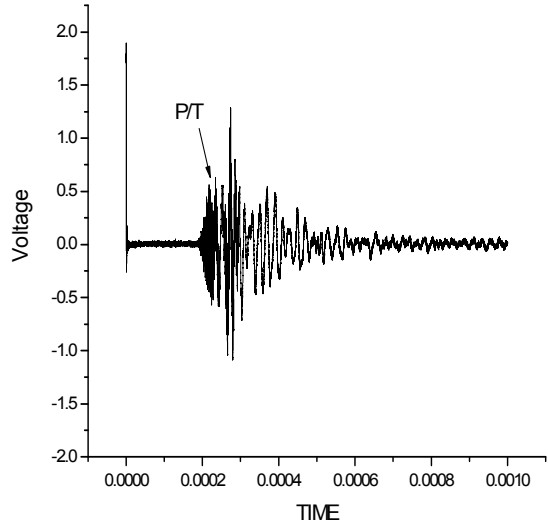
After 14days



After 17days



After 21 days



After 23 days

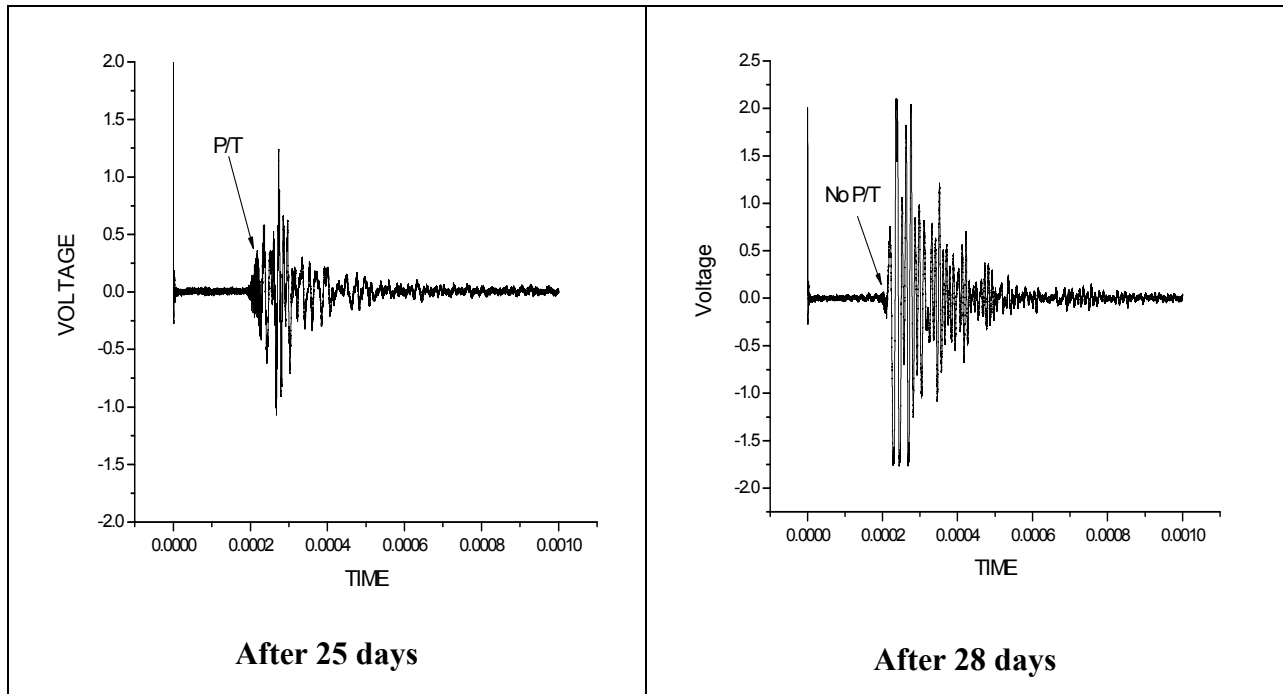
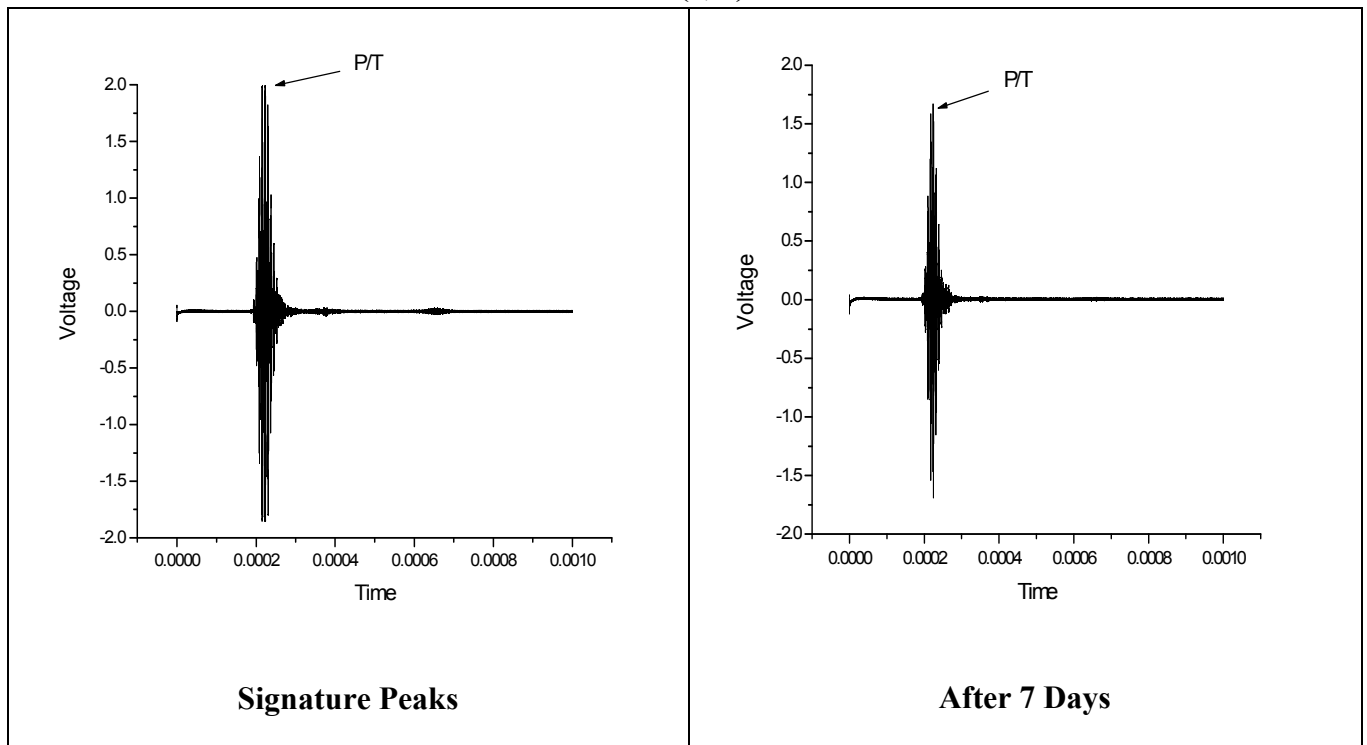
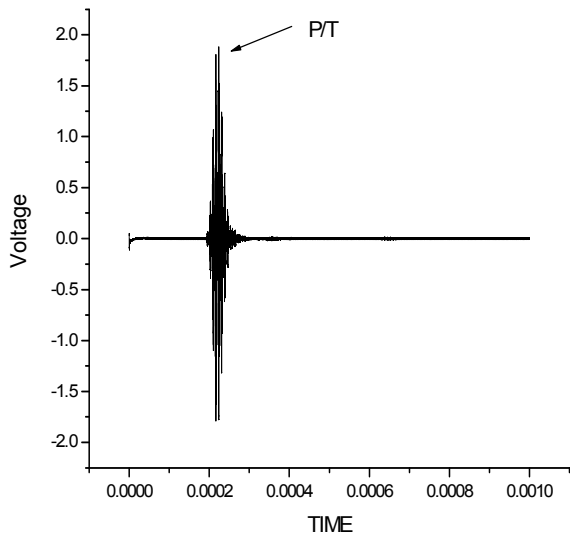
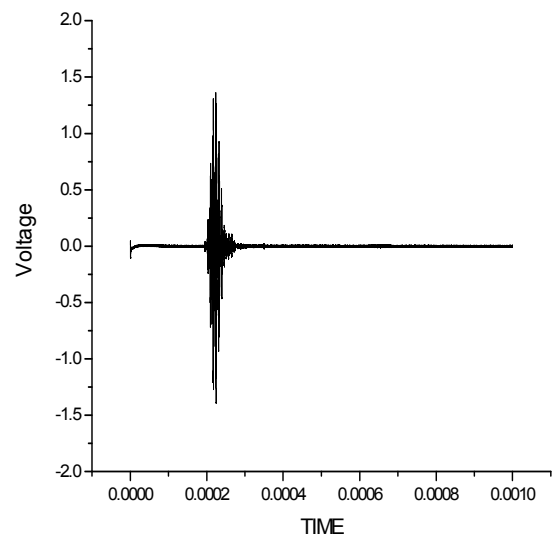


Fig 4.5: Signature peaks of the Topmost Bar (Rod1) of 2-bar beam specimen in pulse transmission for L (0, 7) at 1MHz

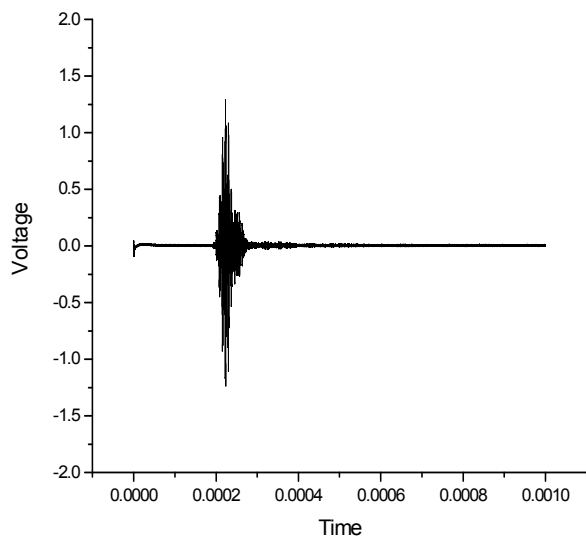




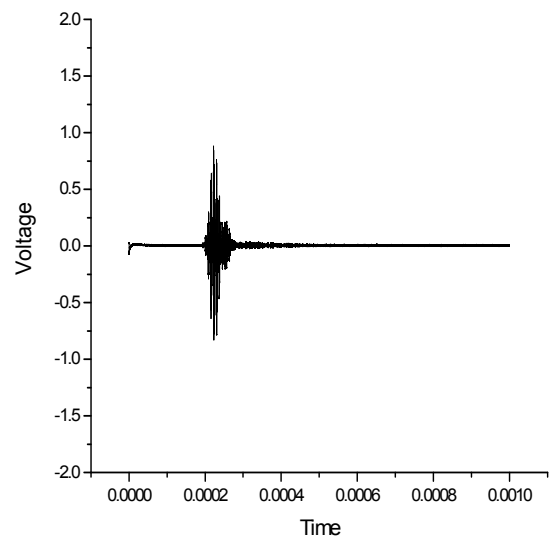
After 9 Days



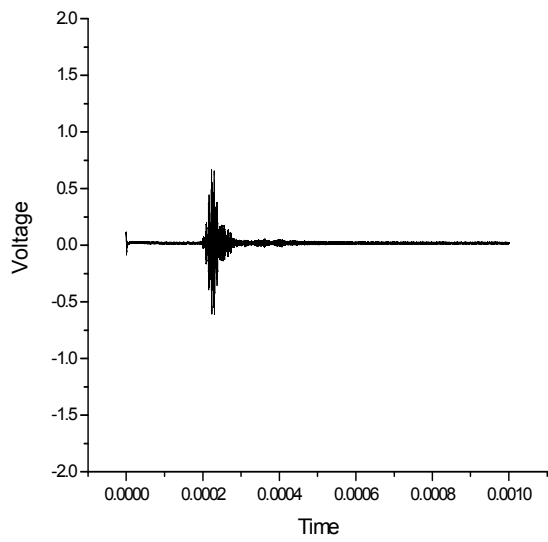
After 12 Days



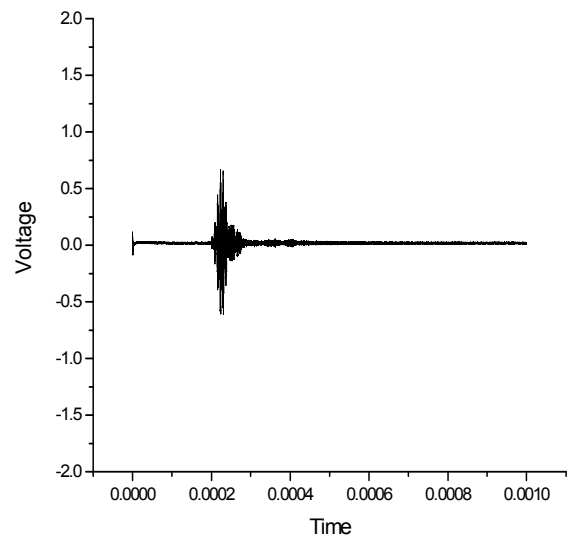
After 14 Days



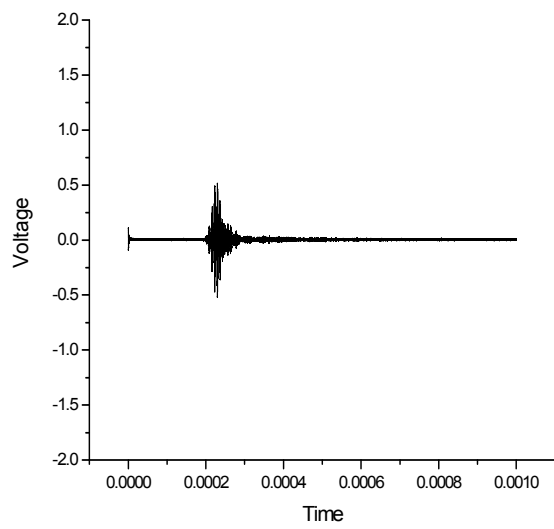
After 17 Days



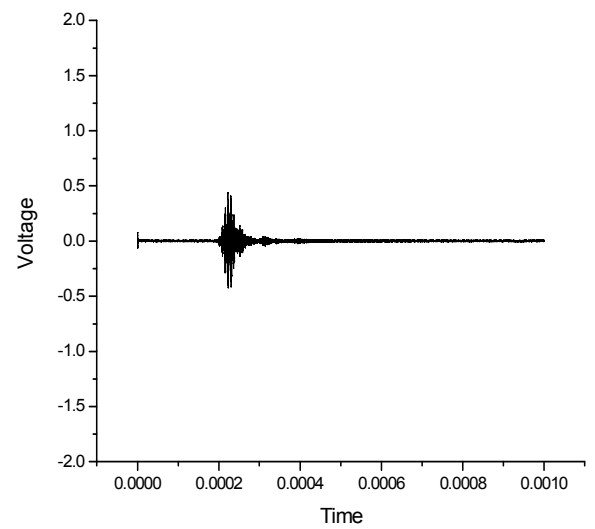
After 21 Days



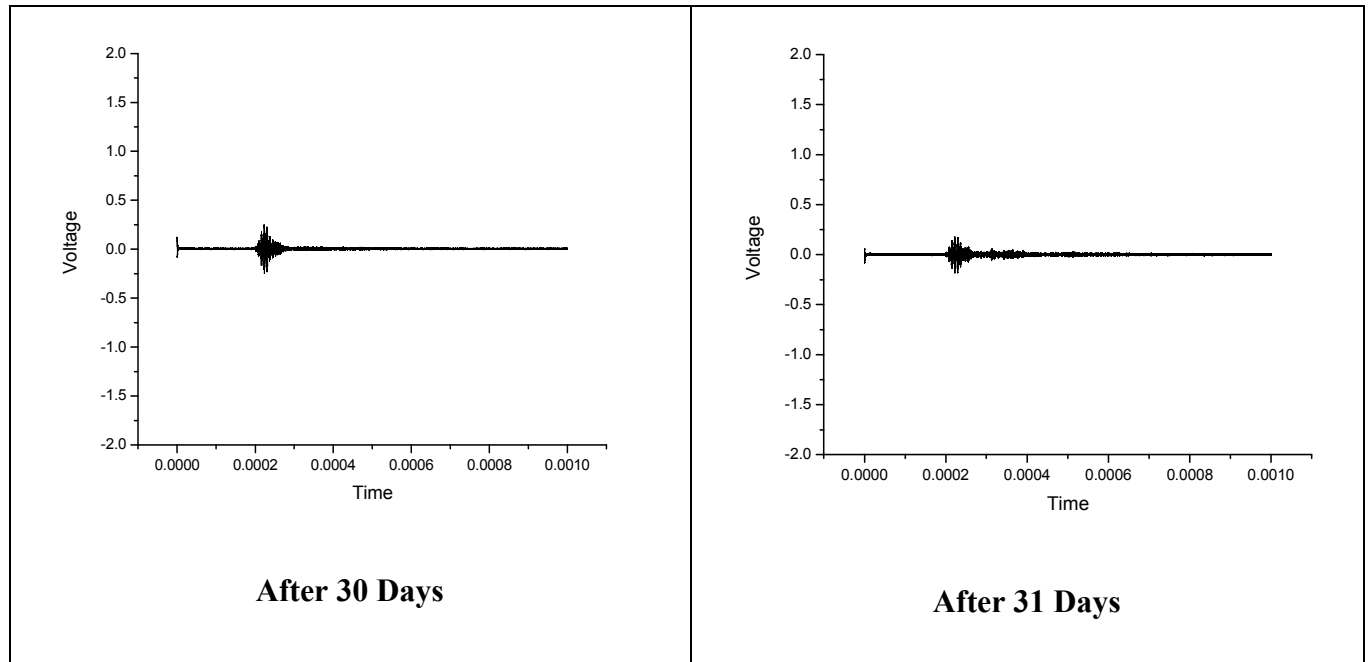
After 23 Days



After 25 Days



After 28 Days



4.3 OBSERVATIONS AND CONCLUSIONS

The ultrasonic waves passing through the bar are measured everyday for accelerated beams and for non-accelerated beams as well. Two modes L (0, 1) surface seeking mode and L (0, 7) core seeking mode have been used in this investigation. The ratio of the peaks of applied and transmitted pulses is determined.

4.3.1 VISUAL OBSERVATIONS

Beams undergoing chloride corrosion by ponding did not show any change for first 30 days. After 30 days, when the external current is applied to two beam specimens one with 2-bar and 3-bar specimen, both the beams showed reddish brown patches of corrosion products as shown in **Fig 4.6(a)&(b)**. Gradually, with the increase in the exposure of the beams, corrosion products also increased. A reddish brown ooze out of the cracks and at the end of the beams. The cracks enlarge that divide the whole beam into two parts. In 2-Rod beam specimen, a longitudinal crack is also produced on the upper surface as shown in **Fig 4.7(a)**. The crack progressed along the direction of the reinforcement. For 3-Rod beam specimen two longitudinal cracks along the direction of reinforcement is observed as shown in the **Fig 4.7(b)**.

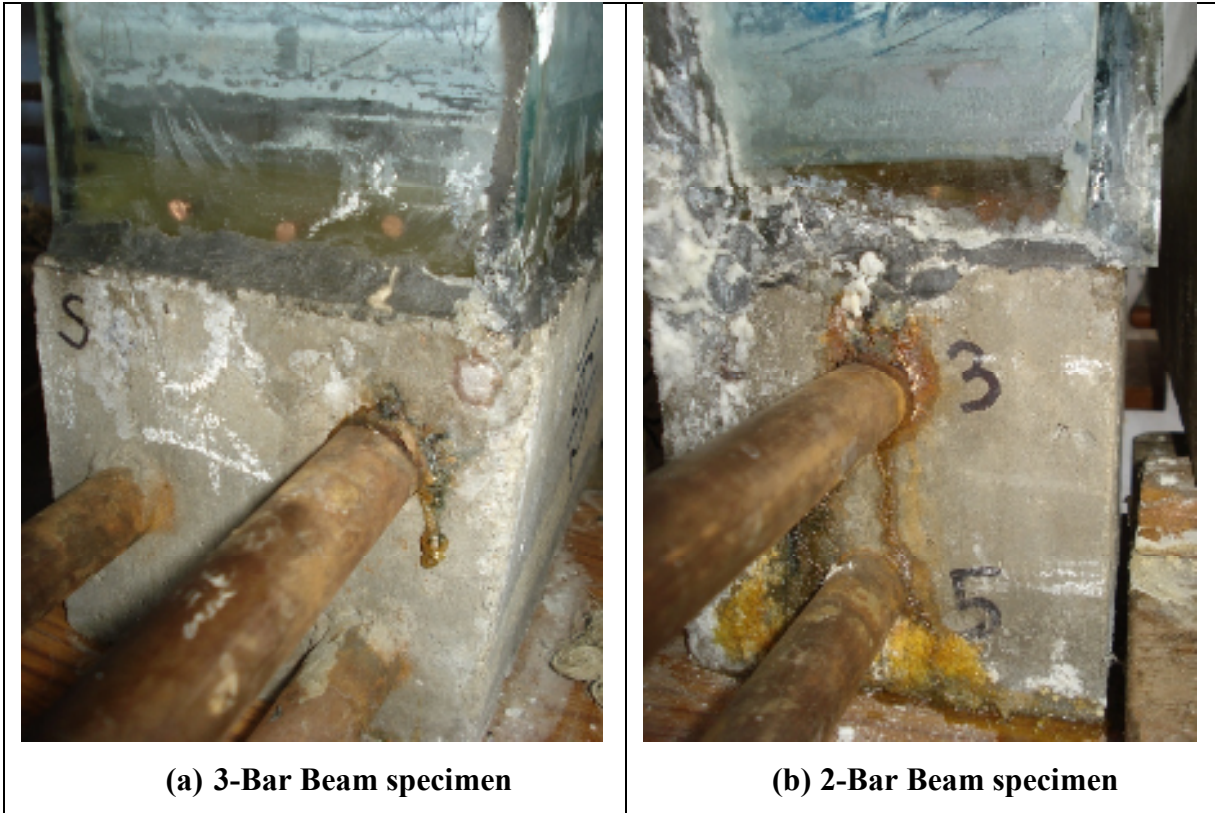


Fig 4.6: Corrosion products seen at the ends of the beam

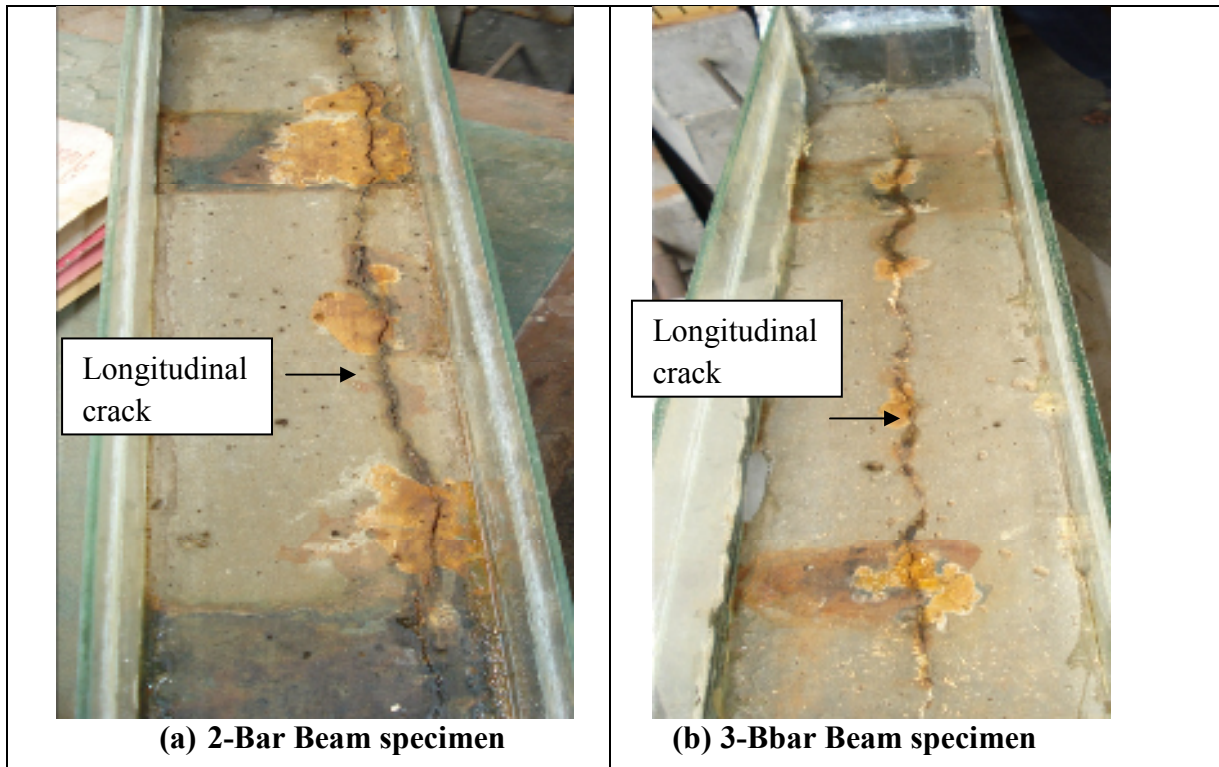


Fig 4.7: Effect of corrosion on RC beams

4.3.2 ACCELERATED BEAMS

Ultrasonic Monitoring with L (0, 1) mode shows rise in the peak right from day 1. It indicates the loss of bond between steel and concrete. Corrosion is accelerated after 30 days of ponding (equivalent to 10 days here) and the monitoring is continued till the peak vanishes. Testing is done with both modes and frequencies of testing.

- First 7 days had a rising L (0, 1) signal but steady L (0, 7) signal indicating predominant surface changes but inappreciable core changes. This zone is referred as '**Delamination Zone**'.
- From 7 to 14 Days, the L (0, 1) signal slightly shows steady state but L (0, 7) signal started showing fall. This indicates that the corrosion makes inroads deeper in the bar and it is not restricted to the surface only. Thus, both modes of corrosion are present. This zone is referred as '**Transition zone**'.
- Beyond the 14th day, both L (0, 1) and L (0, 7) signals fell continuously exhibiting the same trend. At this stage, pitting of the reinforcing bars is predominant and this zone is referred as '**Pitting Zone**'.
 - **2-Rod Beam specimen:** From the ultrasonic plots for Top Bar (Rod 1), in L (0, 1) mode the peak rises for 7 days of exposure period which indicates the Delamination Zone. Then the peak continues to be in a steady state indicating the Transition Zone for next 7 days. After 14 days there is an abrupt fall in the peak representing the pitting zone. This trend is followed till the peak completely vanishes as shown in **Fig 4.8(a)**. In L (0, 7) mode for the same rod peak remain steady for 14 days of exposure period. After 14 days the peak falls drastically and the observation is continued till the peak vanishes completely as shown in **Fig 4.8(b)**.

In case of Bottom Bar (Rod 2), the ultrasonic investigations show that the peak in L (0, 1) mode slowly rises in 17 days of exposure period. The rise indicates the Delamination Zone. A gradual fall is observed for next 20 days of corrosion propagation as shown in **Fig 4.9(a)**. In L (0, 7) mode the peak for Rod 2 remains steady for 20 days of period of exposure. After that a drastic fall is observed indicating pitting zone which continues till the peak vanishes as shown in **Fig 4.9(b)**.

- **3-Rod Beam specimen:** From the ultrasonic plots of Topmost Bar (Rod 1), in L (0, 1) mode peak rises in 7 days of exposure period. This rise indicates the Delamination Zone. For next 7 days the peak remains in a steady state showing the transition zone. As the peak falls drastically after 14 days it represents the pitting of bar. The same trend is followed till the peak disappears as shown in **Fig 4.10(a)**. The trend is very similar to the topmost bar in a 2-Bar beam specimen. In L (0, 7) modes for top bar the peak remain steady for first 14 days of exposure period. The peak falls after 19 days and the trend continues till the peak vanishes as shown in **Fig 4.10(b)**.

In case of Middle Rod (Rod 2), in surface seeking L (0, 1) mode peak rises for 11 days of exposure to ponding. This indicates the delamination zone. After 11 days the peak remains steady. The fall in the peak is observed after 21 days. This represents the pitting zone. The same trend is then followed as the days of exposure increases as shown in **Fig 4.11(a)**. In other core seeking mode L (0, 7) the peak remains steady for 11 days and then falls suddenly after 21 days. The rise indicates the delamination zone and the fall represents pitting zone. This trend is continued and the peak is observed till it completely disappears as shown in **Fig 4.11(b)**.

In case of Bottom bar (Rod 3), in the surface seeking mode L (0, 1) peak rises in 11 days of exposure period. This represents the Delamination zone. A slight fall in the peak is observed in next 10 days representing the Transition zone. The fall in the peak is observed after 21 days. This represents the pitting zone as shown in **Fig 4.12(a)**. In the core seeking mode L (0, 7) the peak remains steady for 11 days and then a fall is observed after 21 days. The peak is further observed till it completely disappears as shown in **Fig 4.12(b)**.

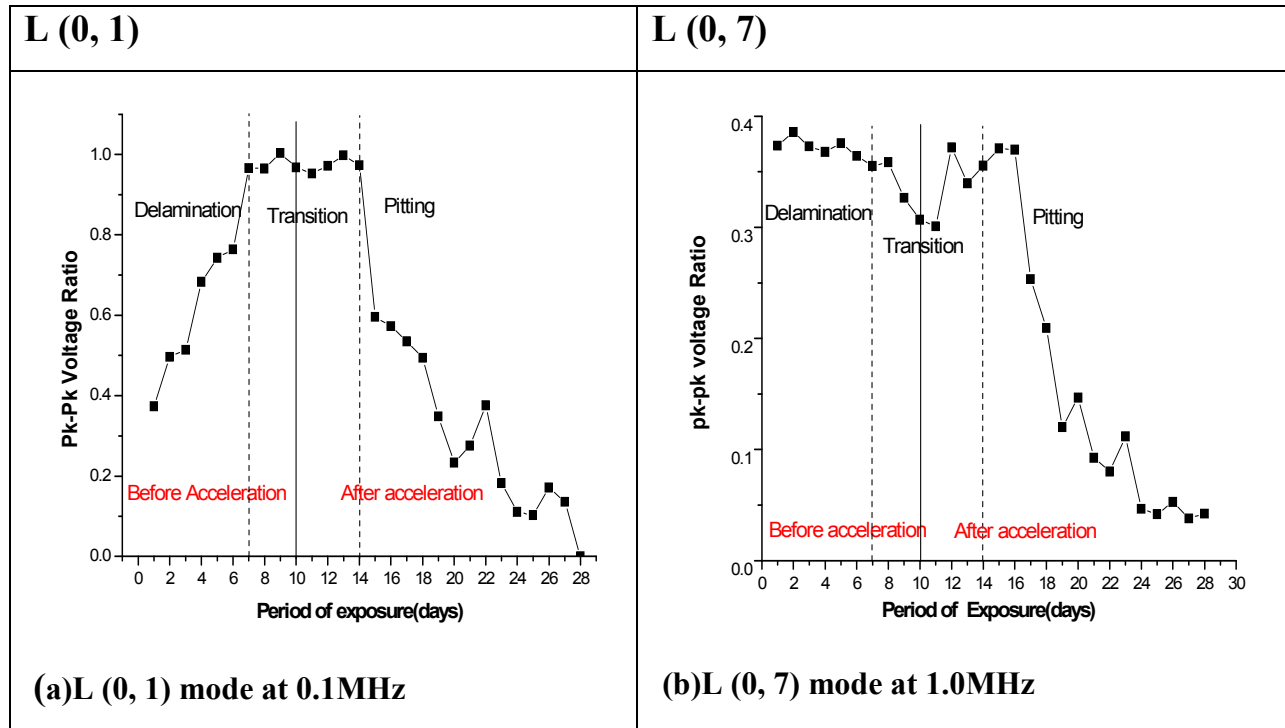


Fig 4.8: Peak to Peak Voltage ratio trends of transmitted pulse for Top bar in a 2-Bar Accelerated Beam specimen

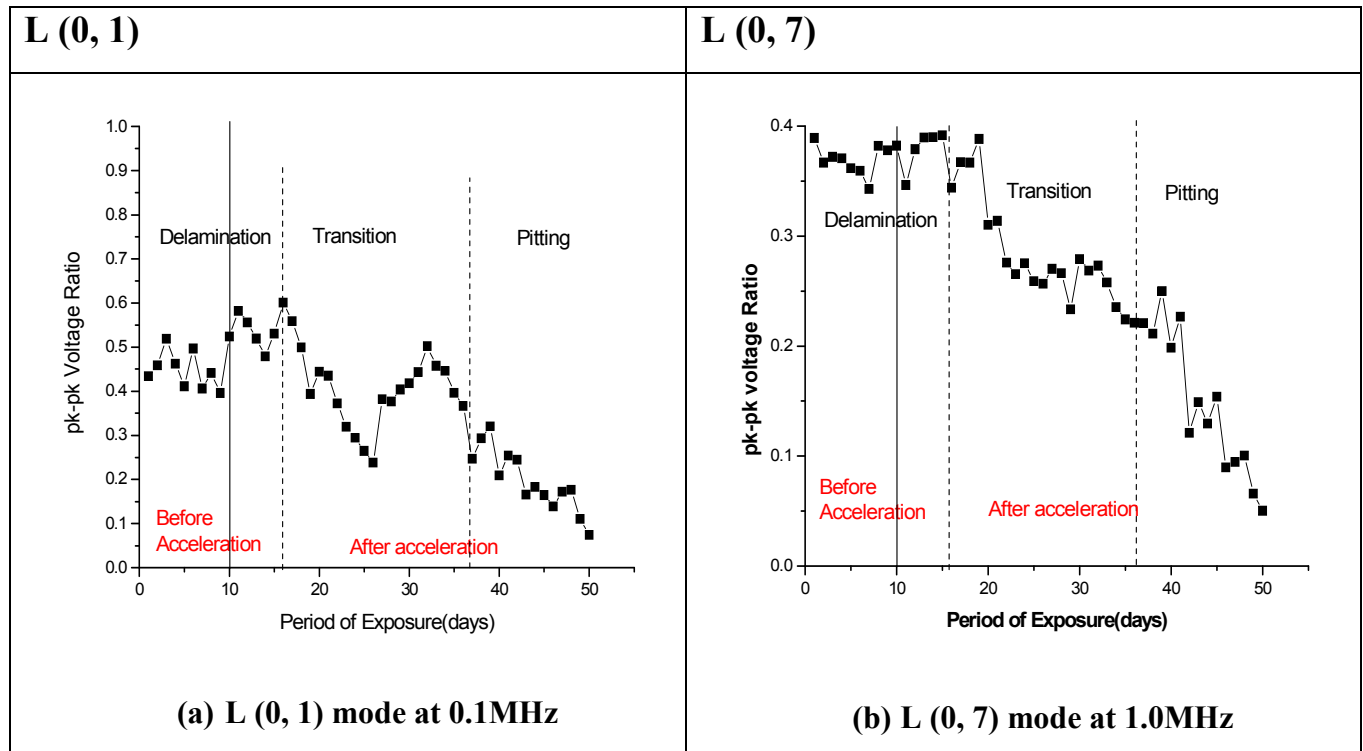


Fig 4.9: Peak to Peak Voltage ratio trends of transmitted pulse for Bottom bar in a 2-Bar Accelerated Beam specimen

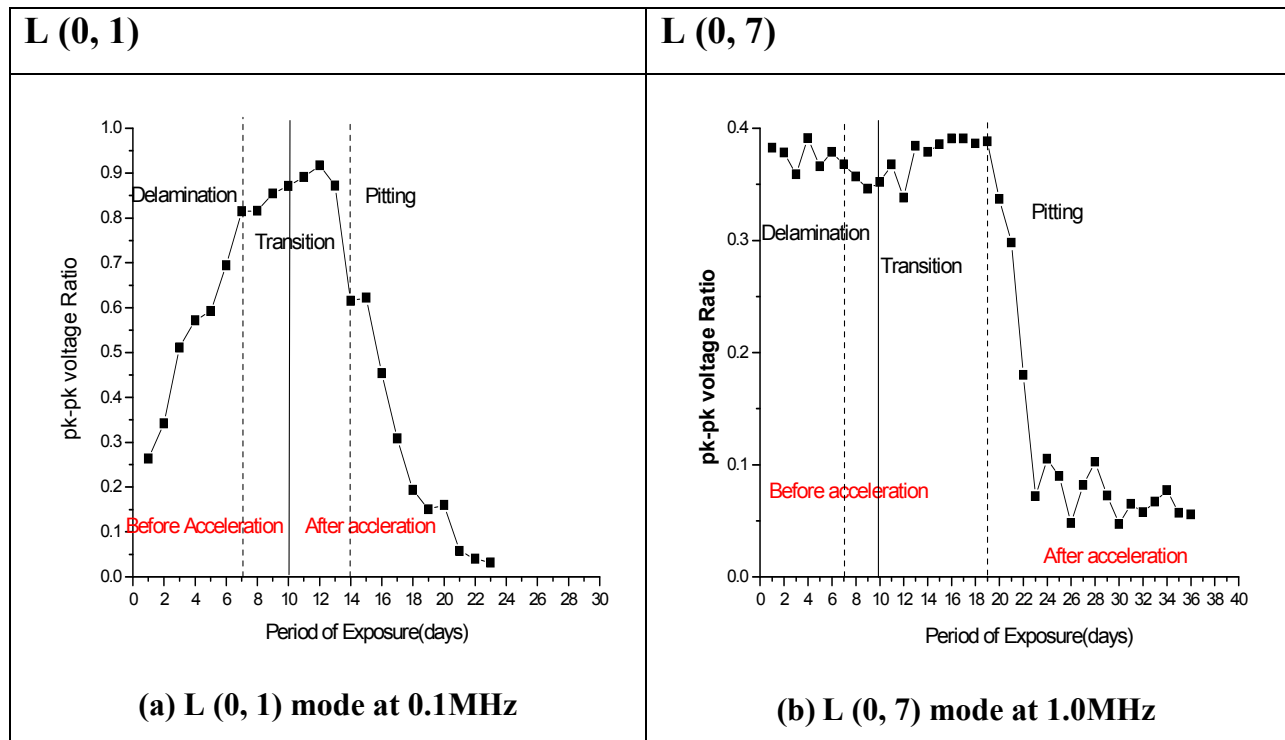


Fig 4.10: Peak to Peak Voltage ratio trends of transmitted pulse for Top bar in a 3-Bar Accelerated Beam specimen

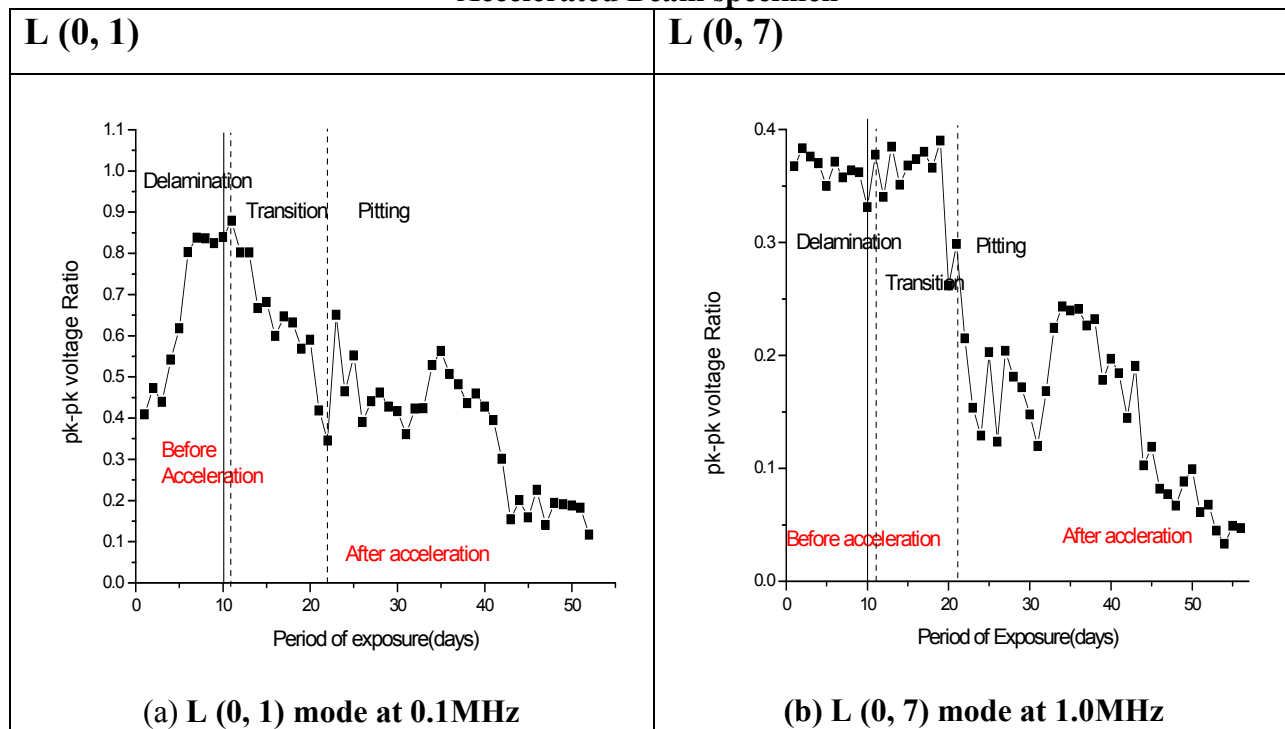


Fig 4.11: Peak to Peak Voltage ratio trends of transmitted pulse for middle bar in a 3-Bar accelerated beam specimen

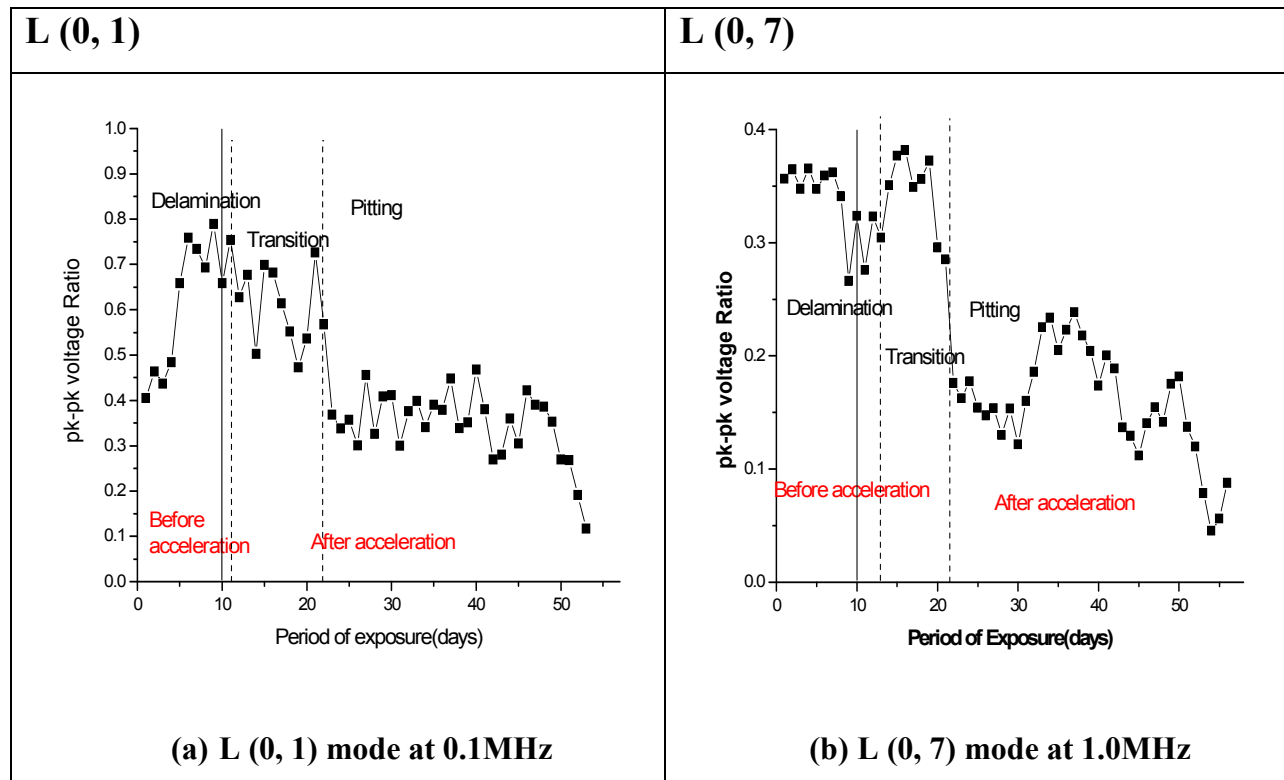


Fig 4.12: Peak to Peak Voltage ratio trends of transmitted pulse for bottom bar in a 3-Bar accelerated beam specimen

From the ultrasonic plots, the mechanism of corrosion of reinforcing bar begins with the formation of flaky rust product having large volume causing the Delamination of the bar from the surrounding concrete resulting in increased signal amplitudes. The delamination zone marks the onset of corrosion phenomenon in a bar undergoing accelerated corrosion and is well picked up by the surface seeking mode. As corrosion progresses, it is marked by local loss of area in the form of pitting and crevices as well as debonding of bar. It begins with transition zone shown by signal rise in L (0, 1) mode and signal attenuation in L (0, 7) core seeking mode. It marks the progress of corrosion causing surface modification as well as non-uniform area loss in the form of pits. As exposure increases, there is a drastic fall in signal amplitude in both L (0, 1) and L (0, 7) modes due to increase in loss of energy caused by scattering, multiple reflections and mode conversions. The most likely cause of this phenomenon is that corrosion affects the waveguide. In the fresh bar the diameter is uniform through the length. Thus, a smooth waveguide forms. Corrosion reduces the diameter of the bar non-uniformity. Thus, the waveguide is disturbed and scattering takes place from the rough surface.

Therefore, delamination is indicated when in the mode L (0, 1) that is the surface seeking mode the peak rise. A steady state of few days indicates the transition zone. Then a drastic fall in the peak represents the Pitting of the reinforcing steel bar. Moreover, in mode L (0, 7) that is core seeking mode the peak remain steady for some period of time and then falls to vanish. The bars at shorter cover depth (Rod1) in both the beam specimens, 2-Bar and 3-Bar beam specimens, follow a very similar trend. Whereas the other bars corrode gradually with time.

4.3.3 NON-ACCELERATED BEAMS

In non-accelerated set of specimens, corrosion is done only by ponding. After corrosion initiation, progression is monitored by ultrasonic modes. The investigation is done to study the progression of corrosion in ponding without acceleration of corrosion by impressed current. Rise in the peak in L (0, 1) mode is observed right from day 1 indicating the loss of bond between steel and concrete for non-accelerated beams. With L (0, 7) mode, the transmitted pulse remains steady for longer duration. This trend indicated the progression of corrosion causing surface modification but there is no change in the L (0, 7) core seeking mode. For 2-Bar beam specimen and 3-Bar beam specimen following observations are made.

- **2-Bar Beam specimen:** In case of Top bar (Rod 1), in L (0, 1) mode the peak initially rises. After 10 days the peak becomes steady and the same trend continues for the rest of the period of exposure as presented in **Fig 4.13(a)**. At the same time, in core seeking L (0, 7) mode remains steady for 10 days. After a very small fall in the amplitude it becomes almost steady throughout the rest of the exposure period as observed in **Fig 4.13(b)**.

In case of Bottom bar (Rod 2), for first 12 days the peak in surface seeking mode L (0, 1) rises and becomes steady for the rest of the period of exposure by ponding as observed in **Fig 4.14(a)**. In the core seeking mode L (0, 7) the peak is observed to be steady for first 10 days. A small fall is observed in the peak and then it remains steady as the period of exposure increases as shown in **Fig 4.14(b)**.

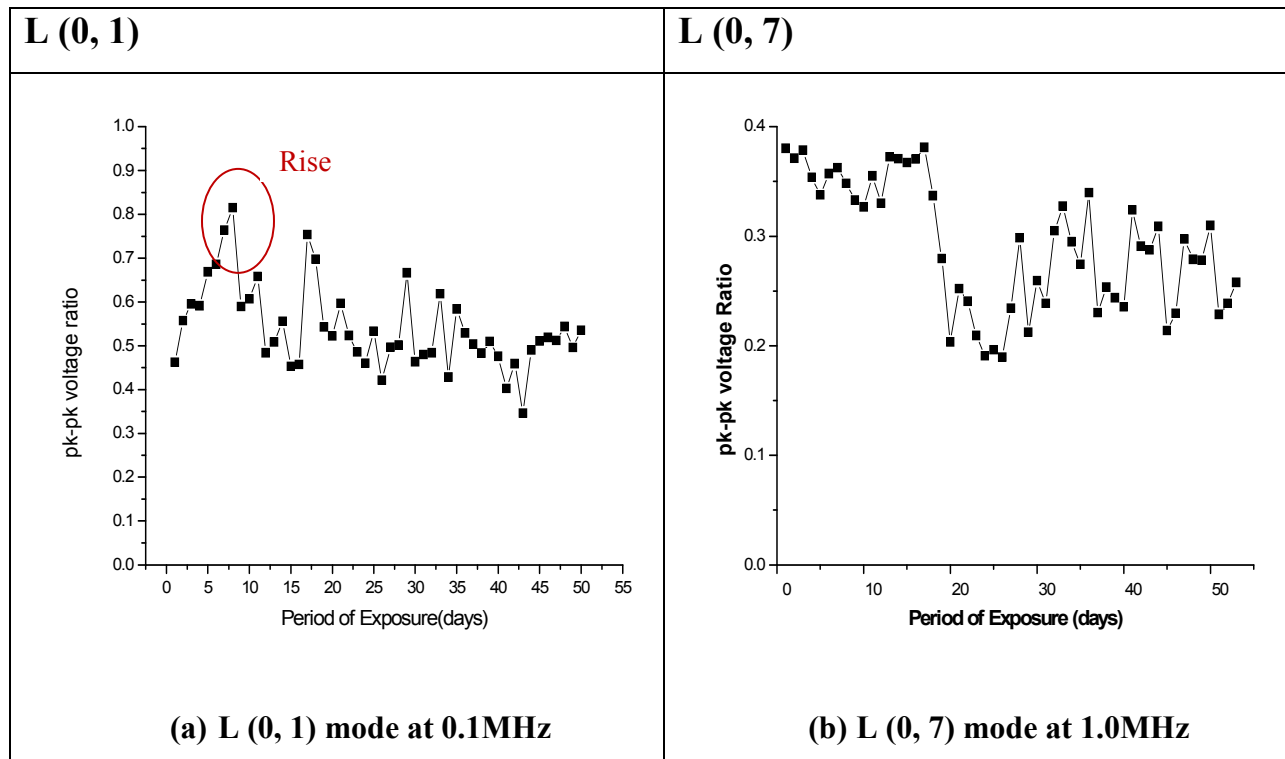


Fig 4.13: Peak to Peak voltage ratio trends of transmitted pulse for Top Bar in a 2-Bar non-accelerated beam specimen

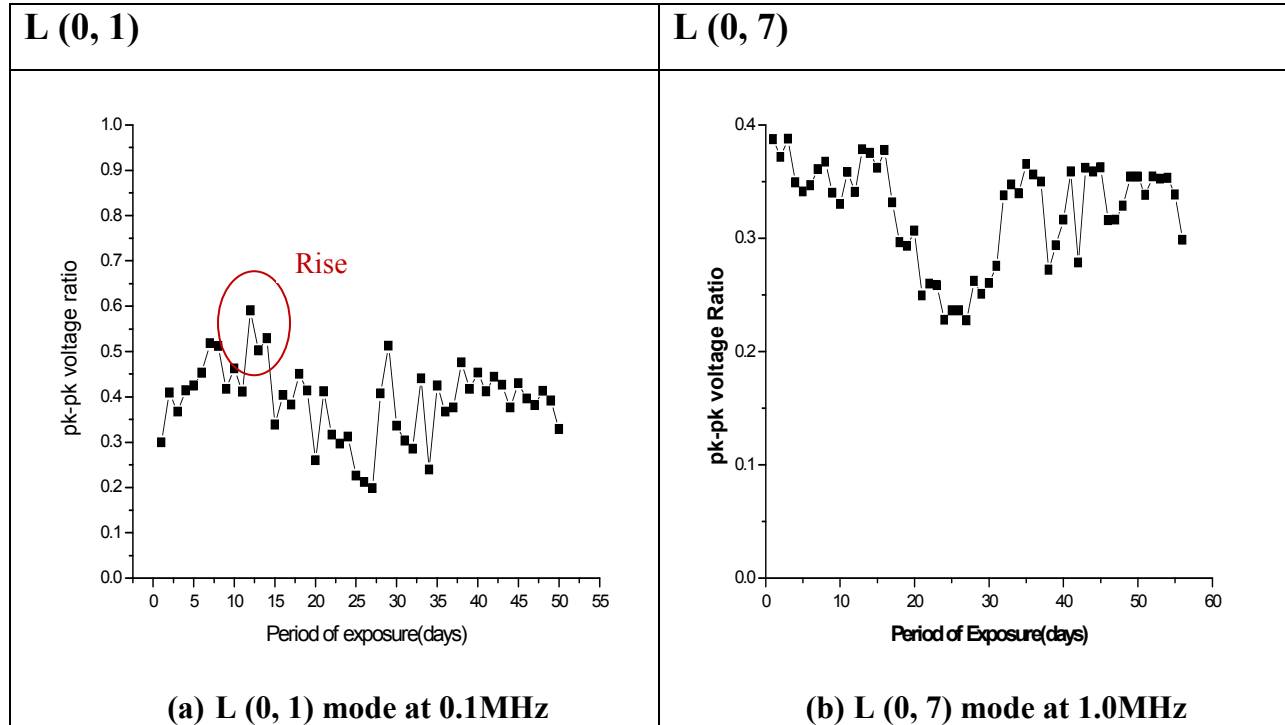


Fig 4.14: Peak to Peak voltage ratio trends of transmitted pulse for Bottom bar in a 2-Bar non-accelerated beam specimen

- 3-Rod Beam specimen:** In case of Top bar (Rod1), in surface seeking mode L (0, 1) the pulse transmission peak rises for 10 days. After that the peak becomes steady as the period of exposure increases for next 20 days as observed in **Fig 4.15(a)**. In the core seeking mode L (0, 7) the pulse transmission peak remains steady and this continuous trend is observed as the period of exposure increases as shown in **Fig 4.15(b)**.

For Middle Bar (Rod 2), in the L (0, 1) mode the peak increases for 15 days. After the rise is observed the peak becomes steady. The same trend is followed with the rise in the period of exposure as shown in **Fig 4.16(a)**. For core seeking mode L (0, 7) pulse transmission remain steady state as there is rise in the period of exposure as shown in **Fig 4.16(b)**.

In case Bottom Bar (Rod 3), in the surface seeking mode L (0, 1) the rise observed is not much significant and further it continuous to become steady with the increase in number of days of exposure as presented in **Fig 4.17(a)**. For L (0, 7) core seeking mode a continuous steady peak is observed with the increase in the period of exposure. This trend is observed to be very similar to the middle bar as shown in **Fig 4.17(b)**.

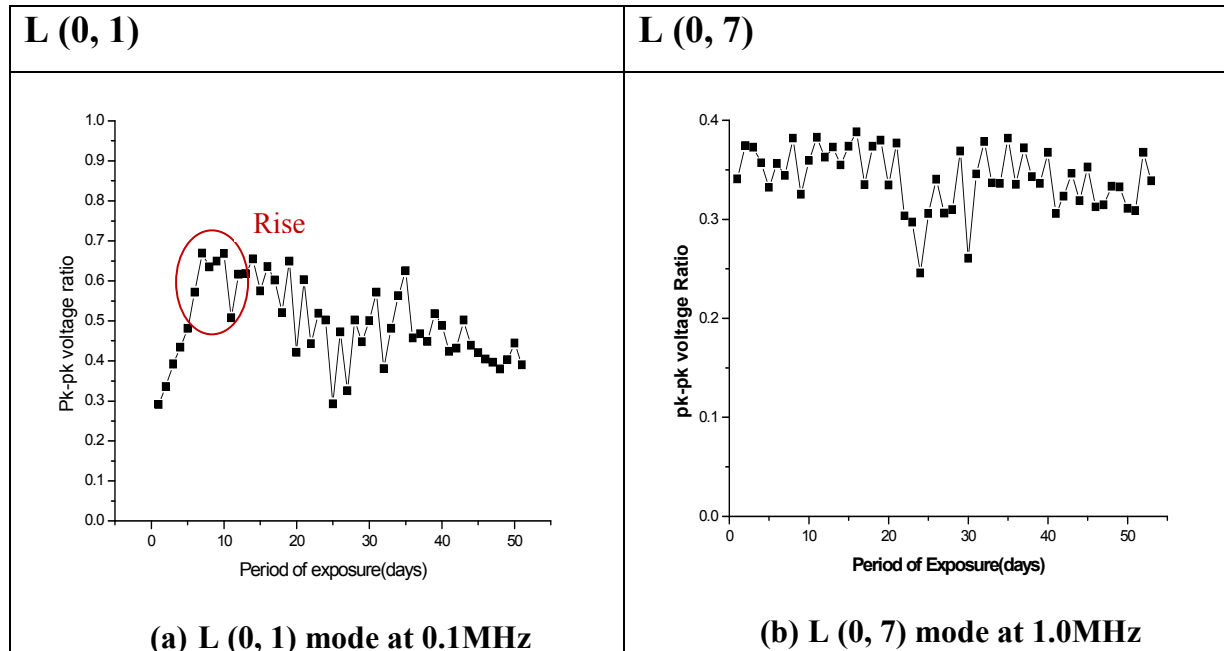


Fig 4.15: Peak to Peak voltage ratio trends of transmitted pulse for Top bar in a 3-Bar non-accelerated beam specimen

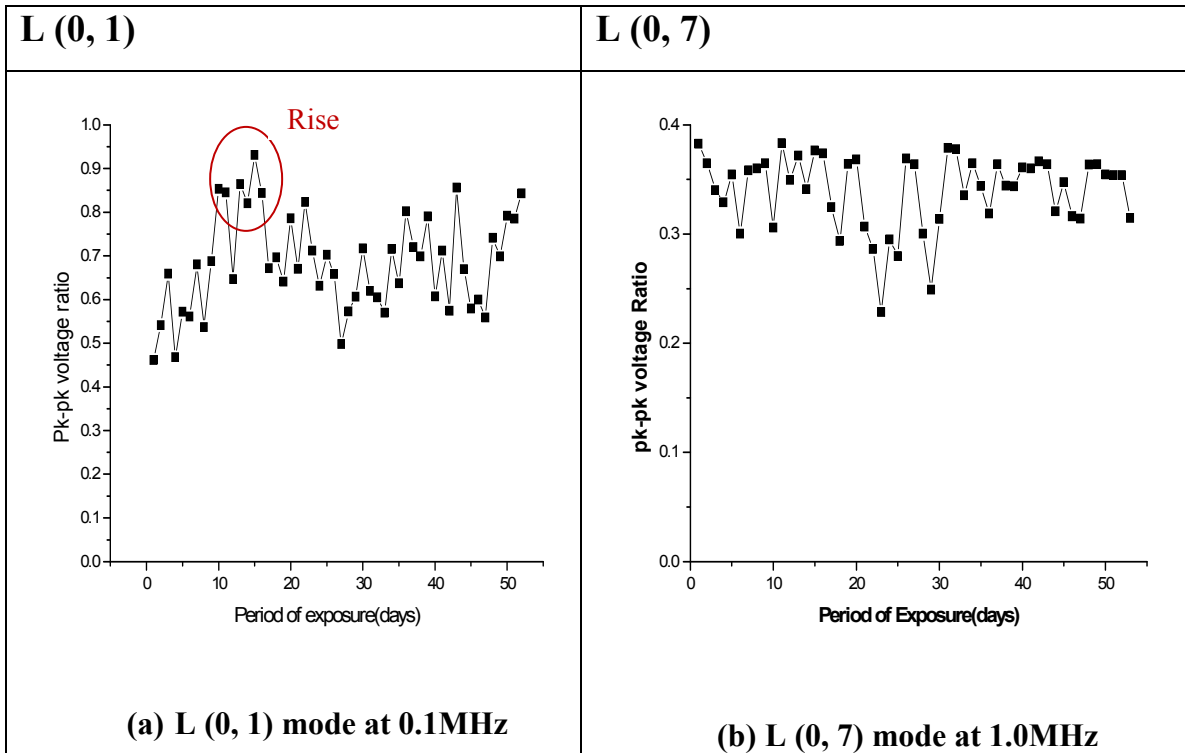


Fig 4.16: Peak to Peak voltage ratio trends of transmitted pulse for Middle bar in a 3-Bar non-accelerated beam specimen

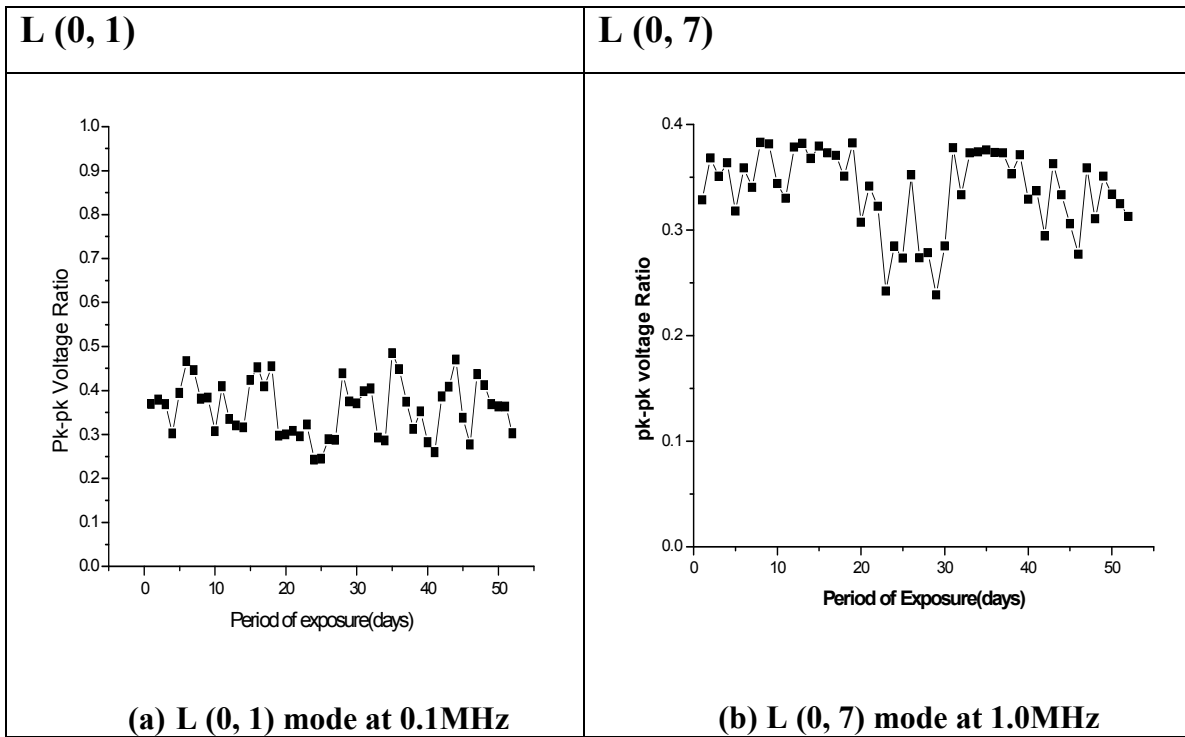


Fig 4.17: Peak to Peak voltage ratio trends of transmitted pulse for Bottom bar in a 3-Bar non-accelerated beam specimen

4.4 CLOSING REMARKS

Hence, for corrosion progression monitoring, the ultrasonic pulse transmission has been a satisfactory investigation. Ultrasonic guided waves utilizing core and surface seeking modes can successfully be utilized for monitoring of corrosion in a bar embedded in concrete. This is more easily discernible by the L (0, 1) mode that has higher surface component. Hence, to pick up early corrosion L (0, 1) mode is recommended. However, in the presence of chlorides, the bar experiences pitting that lead to deep crevices inside the bar. This is picked up by mode L (0, 7) that has higher component in the core of the bar. The use of different cover depths concludes that the ultrasonic measurement of the top bars in both, 2-Bar beam and 3-Bar beam specimens, gives early signs of corrosion with respect to the bars at other cover depth. Therefore, monitoring of corrosion at shortest cover depth is useful as it gives the sign of damage at a very early stage.

CHAPTER 5

CONCLUSIONS

5.1 SUMMARY OF WORK DONE

The basic aim of this thesis is to monitor the complete corrosion phenomenon in RC Beams undergoing chloride corrosion for the bars at different cover depths. The techniques of electrochemical LPR measurements and ultrasonic guided waves are used in combination to monitor the same.

5.2 CONCLUSIONS

Electrochemical measurements are effective only in monitoring corrosion initiation and are not useful to measure corrosion progression. Ultrasonic guided waves prove to be much more effective for the same. The effect of different cover depths on the ultrasonic voltages is also investigated. Main conclusions derived from the study can be summarised as discussed in the following sections. 30 days exposure to ponding with 5% NaCl solution is done and electrochemical measurements of corrosion current (I_{corr}) and corrosion potential (E_{corr}) are taken with ACM. The following important observations and conclusions are drawn from the study.

1. Initiation of corrosion is well picked up by electrochemical measurements.
2. Sudden change in corrosion potential (E_{corr}) and corrosion current (I_{corr}) values indicate corrosion initiation.
3. The sudden fall in corrosion potential (E_{corr}) and rise in corrosion current (I_{corr}) marks the initiation of corrosion process.
4. Moreover, the initiation of corrosion is observed in all the beam specimens, 2-Bar Beam and 3-Bar Beam specimens, for accelerated as well as non-accelerated beams.
5. To decide corrosion initiation point, the electrochemical I_{corr} and E_{corr} values for the topmost bar i.e bar at smallest cover are observed. The observation of bars at small cover depths indicates the initiation of corrosion at an early stage much before the damage is

observed through visual observation. Hence, electrochemical measurement is a good indicator of corrosion damage before any visual change/damage is observed in the beams. Fall in the value of corrosion potential (E_{corr}) and rise in the value of corrosion current (I_{corr}) indicates the initiation. Initiation is observed for both accelerated and non-accelerated beam specimens. Since the acceleration of corrosion with impressed current the value of E_{corr} becomes more negative and the value of I_{corr} further rises. This represents increase in corrosion in the reinforcing bars in accelerated beams. Whereas, in non-accelerated beam specimen after the initiation, the values of E_{corr} and I_{corr} remain constant.

6. In order to monitor the corrosion progression, ultrasonic measurements have proved to be a reliable method. The ultrasonic waves passing through the bar are measured everyday in both, 2-Bar and 3-Bar beam specimens, for both accelerated and non-accelerated conditions. The two modes L (0, 1), named as surface seeking mode, and L (0, 7), named as core seeking mode, are used to investigate delamination and pitting phenomenon accompanied by corrosion progression. These modes indicate the various zones observed in the ultrasonic plots i.e the Delamination, transition and pitting zone. Comparison of different bars at L (0, 1) and L (0, 7) mode show that the topmost bar corrodes in lesser time. Whereas, the other bars at the bottom corrodes slowly and takes more time. In non-accelerated beams the pulse transmission peak in L (0, 1) mode rises initially. After the rise, the peak remains constant in both the modes. Hence, no significant change is observed.

REFERENCES

- [1] Melchers, R.E., and Li, C.Q., “Phenomenological modeling of reinforcement corrosion in marine environments”. *ACI Mater J* 2006;103:25–32.
- [2] Almusallam, A.A., “Effect of degree of corrosion on the properties of reinforcing steel bars”. *Constr Build Mater* 2001;15:361–8.
- [3] Pradhan, B., and Bhattacharjee, B., “Performance evaluation of rebar in chloride contaminated concrete by corrosion rate” *Construction and Building Materials* 23 (2009) 2346–2356.
- [4] Ferraro, C.C., (2003) A Thesis “Advanced nondestructive monitoring and evaluation of damage in concrete materials”
- [5] Andrade, C., and Alonso, C., “Corrosion rate monitoring in the laboratory and on-site.” *Constr Build Mater* 1996;10:315–28.
- [6] Maheswaran, T., and Sanjayan, J.G., “A semi-closed-form solution for chloride diffusion in concrete with time-varying parameters.” *Mag Concr Res* 2004;56:359–66.
- [7] Elsener, B., “Macrocell corrosion of steel in concrete-implications for corrosion monitoring.” *Cem Concr Compos* 2002;24:65–72.
- [8] El-Gelany, M.A., “Short-term corrosion rate measurement of OPC and HPC reinforced concrete specimens by electrochemical techniques.” *Mater Struct* 2001;34:426–32.
- [9] Liu, T., and Weyers, R.W., “Modeling the dynamic corrosion process in chloride contaminated concrete structures.” *Cem Concr Res* 1998;28:365–79.
- [10] Hope, B.B., Page, J.A., and Ip, A.K.A., “Corrosion rates of steel in concrete.” *Cem Concr Res* 1986;16:771–81.
- [11] Kepler, J.L., Darwin, D., and Jr. Locke, C.E., “Evaluation of corrosion protection methods for reinforced concrete highway structures” University Of Kansas Center For Research, INC. Lawrence, Kansas .May 2000
- [12] Bentur, Arnon, Diamond, Sidney, and Berke, Neal S. (1997). “*Steel Corrosion in Concrete*”, E and FN Spon, New York, NY, 201 pp.
- [13] Viktorov, I.A. “Rayleigh and lamb waves—physical theory and application.” NewYork: Plenum Press; 1967
- [14] Ervin, B.J., and Reis, H., “Longitudinal guided waves for monitoring corrosion in reinforced mortar” *Meas. Sci. Technol.* **19** (2008) 055702 (19pp)

- [15] Montemor, M. F., Alves, J. H., Simões, A. M., Fernandes, J. C. S., Lourenço, Z., Costa, A. J. S., Appleton, A. J., and Ferreira, M. G. S., “Multiprobe chloride sensor for in situ monitoring of reinforced concrete structures”. *Cement & Concrete Composites* 28 (2006) 233–236
- [16] Broomfield, J.P., “Corrosion of steel in concrete, understanding investigation and repair”. 2nd ed. UK: Taylor & Francis; 2006
- [17] Ahmad, S., “Reinforcement corrosion in concrete structures, its monitoring and service life prediction—a review”. *Cement & Concrete Composites* 25 (2003) 459–471
- [18] www.googleimages.com
- [19] Bazant, Z. P., “Physical model for steel corrosion in concrete sea structures-theory”. *ASCE J Struct Div* 1979;105:1137–53.
- [20] Macdonald, D.D., El-Tantawy, Y.A., Rocha-Filho, R.C., and Macdonald, M.U.(1994) “Evaluation of Electrochemical Impedance Techniques for Detecting Corrosion On Rebar in Reinforced Concrete” SHRP-ID/UFR-91-524
- [21] Song, H.W., Saraswathy, V., “Corrosion monitoring of reinforced concrete structures – a review”. *Int.J. Electrochem.Sci.*2(2007)1-28
- [22] Bindal, V.N., “Transducers for Ultrasonic Flaw Detection”. Narosa Publishing house(1999).
- [23] Redwood, M., *Mechanical Waveguides, “The Propagation of Acoustic and Ultrasonic Waves in Fluids and Solids with Boundaries.”* Pergamon, New York (1960).
- [24] Achenbach, J.D., “Wave Propagation in Elastic Solids.” Elsevier, New York (1975).
- [25] Sang-Young Kim, Hegeon Kwun, Glenn M. Light, “Long-Range Guided Wave Inspection of Structures Using the Magnetostrictive Sensor.” Applied Physics Division, Department of NDE Science and Technology, Southwest Research Institute, San Antonio, Texas, U.S.A.(2001)
- [26] Demma, A. (2003) A Thesis report “The interaction of guided waves with discontinuities in the structure.” Imperial College of science, technology and medicine. University of London
- [27] Mal, A.K., and Singh, S.J.,(1991) “Deformation of elastic solids.” Prentice Hall, N.J.
- [28] Rose, J.L., (1999), “Ultrasonic waves in solid media.” Cambridge University Press

[29]Jung, Y.C., Kundu, T., and Ehsani, M.R.,(2002) “A new nondestructive inspection technique for reinforced concrete beams.” *ACI Materials Journal* ;99(3):292-299.

[30] Muktadi, O.M., Datta, S.K., and Dunn, M.L.(2001), “Elastic Guided Waves in a layered plate with Rectangular Cross-section.” *Proceedings of the 7th ASME NDE topical conference, C.Darneness & T.Kundu,eds.,San Antonio, Tex.,Apr.23-25.*

[31] Kermani, A., Edalati, K., Seiedi, M., and Movafeghi, M., “Defect detection in thin plates by ultrasonic lamb wave techniques” *The 8th International Conference of the Slovenian Society for Non-Destructive Testing »Application of Contemporary Non-Destructive Testing in Engineering«* September 1-3, 2005, Portorož, Slovenia, pp. 35-43

[32] Vermani. G., Mukherjee, A., and Sharma, S. (2008) A thesis report, “Damage Detection in Reinforcing Steel Bars using Ultrasonic Wave Propagation.” Thapar University, Patiala.

[33] Reis, H., Ervin, B.L., Kuchma, D.A., and Bernhard, J.T.,(2005) “Estimation of Corrosion Damage in Steel Reinforced Mortar Using Guided Waves” *Journal of Pressure Vessel Technology*;August 2005, Vol. 127 / 255-261.

[34] Rayleigh, J.W.S., “The Theory of Sound.” Dover,N.Y, 1945.

[35] Flis, J., Sabol, S., Pickering, H.W., Sehgal, A., Osseo-Asare, K., and Cady, P.D., (1993), “Electrochemical Measurements on Concrete Bridges for Evaluation of Reinforcement Corrosion Rates”. *NACE International; CORROSION–Vol. 49, No. 7*

[36] Jolley, M.J., “Evaluation of corrosion resistance of different steel reinforcement types”

[37] Shah, S.P., Weiss, W.J., Wang, K., and Yoon, S., “Interaction between Loading, Corrosion, and Serviceability of Reinforced Concrete” *ACI Materials Journal*, V. 97, No.6, November-December 2000.

[38] Sharma, S., Mukherjee, A., “Ultrasonics for corrosion monitoring in reinforcing bars in concrete in chloride environment.” *ACI Materials Journal*, 2010

[39] Beard, M. D., Lowe, M. J. S., and Cawley, P., “Ultrasonic Guided Waves for inspection of grouted tendons and bolts”. *Journal of Materials in civil engineering*.10.1061/(ASCE)0899-1561(2003)15:3(212).

[40]ACM Manual

- [41] Liu, Y., Dissertation, "Modeling the Time-to-Corrosion Cracking of the Cover Concrete in Chloride Contaminated Reinforced Concrete Structures" Virginia Polytechnic Institute and State University.
- [42] Gu, G. P., Beaudoin, J. J., Ramachandran, V. S., "Techniques for Corrosion Investigation in Reinforced Concrete"
- [43] Ervin, B. L., Kuchma, D.A., Bernhard, J.T., and Reis, H., (2009) "Monitoring corrosion of rebar in embedded mortar using high frequency guided ultrasonic waves." J. Engrg. Mech. Volume 135, Issue 1, pp.9-19.
- [44] Sharma, S., Bhise, P.C., and Mukherjee, A., "Damage detection in steel bars using ultrasonic guided waves: An Experimental & Analytical Study." SHM Journal
- [45] Pavlakovic, B.N., and Cawley, P., Disperse User's Manual Version 20.11.2000. Imperial college, University of London.