"EFFECT OF CORROSION ON MECHANICAL PROPERTIES OF RC BEAMS USING ULTRASONIC GUIDED WAVES"

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CERTIFICATE

Certified that the thesis **"EFFECT OF CORROSION ON MECHANICAL PROPERTIES OF RC BEAMS USING ULTRASONIC GUIDED WAVES"** which is submitted by **Mr. Parvinder Singh**, in partial fulfillment of the requirements for the award of the degree of Masters of Engineering in the **Department of Civil Engineering (CED),** Thapar University, Patiala, is a record of the candidate's own independent and original research work carried out by him under her supervision and guidance. The matter embodied in this thesis has not been submitted in part or full to any other University or Institute for the award of any degree.

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PARVINDER SINGH

ABSTRACT

Reinforced concrete (RC) structures have been used in construction since ancient times in major and minor infrastructure, such as bridges, dams and buildings. However, RC structures face deterioration due to several problems such as ageing, disastrous damage due to earthquakes and environmental effects. These factors affect the condition and performance of RC structures. Consequently, assessment of damage deterioration in concrete structures is in great demand and is vital to maintain the structure both for safety and economic considerations. Cracking of concrete due to corrosion of reinforcement is one of critical problems in reinforced concrete (RC) structures. Here, an application of ultrasonic guided waves to corrosion monitoring is studied. The initial part of the report highlights Structural Health Monitoring and Ultrasonic Monitoring methods which are slowly being used in the realm of Civil Infrastructure. It is demonstrated that the onset of corrosion and nucleation of cracking are readily identified by Ultrasonic monitoring. Guided ultrasonic waves offer a potentially attractive solution .In the present study, bars embedded in concrete are subjected to corrosion. These specimens are monitored ultrasonically using longitudinal guided waves specific core seeking and surface seeking modes are used for detection of a particular type of damage due to corrosion. For this purpose, we conduct the Pulse Transmission Investigations. The reinforcements have been excited at one end with an ultrasonic pulse using piezoelectric transducer which acts as the transmitter and on the othe end piezoelectric transducer which acts as receiver. It is observed that corrosion of reinforcing bars in concrete is discernible using ultrasonic guided waves. Further the effect of corrosion on load carrying capacity of RC beams is investigated. Parameters of modulus of rupture, maximum deflection and percent mass loss are determined. A correlation is established between ultrasonic voltage and static parameters of modulus of rupture and mass loss to predict the level of deterioration due to corrosion using ultrasonic guided waves.

CONTENTS

LIST OF FIGURES

	peak voltage ratio (a) for 25 mm bar samples (b) for 12 mm bar samples	

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1.1 GENERAL

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

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

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

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

1.2 CORROSION MONITORING OF RC STRUCTURES

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

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

Various techniques for measuring the corrosion rate have been used to detect the corrosion at an early stage, in order to predict residual lives and accordingly decide what preventive or repair systems are to be applied (Song and Saraswathy, 2007). New RC structures incorporating one or more of these new strategies are likely to have much longer durable service life than those constructed before.

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

Non-destructive techniques such as visual inspection of the surface of the structure are simple and cost-effective technique. However, it relies on the skill of the inspector and cannot provide accurate information on crack depth. Moreover, cracks that have just started to appear may be too small to be visible. Therefore, other non-destructive techniques such as radiography, ultrasonic testing, magnetic particle testing, acoustic emission etc, are necessary to complement visual inspection.

The most common non–destructive techniques to monitor corrosion in reinforced concrete structures are given below which are discussed in detail in Chapter 3 (Song and Saraswathy, 2007):

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

1.3 AIMS AND OBJECTIVES

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

1.4 FORMAT OF THESIS

The main aim of the study is to monitor the corrosion behaviour of RC elements by using NDT techniques .

The thesis has been divided into six chapters.

1st Chapter discuss about general introduction about corrosion, its monitoring.

2nd Chapter explains in detail the causes and mechanism of rebar corrosion and description on different types of corrosion is been given also deals with various NDT methods used for monitoring of RC structures

3rd Chapter presents a thorough review of literature on non-destructive monitoring techniques as well as the Ultrasonic guided waves for monitoring rebar corrosion in concrete.

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

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

6th Chapter deals with the conclusions.

CHAPTER 2

CORROSION AND ITS MONITORING IN RC STRUCTURES

2.1 CORROSION OF STEEL IN CONCRETE

Metal tends to revert to its more stable and natural state as an ore. This reversion process is known as corrosion (oxidation). A refined metal such as iron or steel has a natural tendency to corrode and thereby return to the stable state that exists in nature, iron ore (Fe_2O_3). The rate of steel corrosion depends on its composition and the surrounding environment A closer look at the chemical reactions involved will help in understanding the mechanisms behind the corrosion of reinforcing steel in concrete. There are four mechanisms that cause fluids and ions (dissolved in fluid) to move through the concrete:

Capillary suction, permeation, diffusion, and migration (Bertolini et al. 2004). Concrete has a very high alkalinity - with a pH of 12 to 13 due to the presence of abundant amount of calcium hydroxide and relatively small amount of alkaline elements, such as sodium and potassium. A protective iron oxide or hydroxide film forms on the surface of the reinforcing steel bar as a result of high alkalinity. As long as this film is not disturbed, it will keep the steel passive and protect it from corrosion (Bazant 1979). However, concrete structures, (especially bridges) are often exposed to salts, salt splashes, salt spray, or seawater. Chloride ions slowly penetrate into the concrete through cracks, or through the pores in the hydrated cement paste. The chloride ions eventually reach the steel and then accumulate beyond a certain concentration level, at which the protective film is destroyed and the steel begins to corrode, when oxygen and moisture are present in the steel-concrete interface (US Department of Transportation 1998). Once corrosion sets in on the reinforcing steel bars, it continues forming electrochemical cells on the surface of the metal and the electrolyte or solution surrounding the metal. Each cell consists of a pair of electrodes (the anode and its counterpart, the cathode) on the surface of the metal, a return circuit, and an electrolyte. Basically, on a relatively anodic spot on the metal, the metal undergoes oxidation (ionization), which is accompanied by the production of electrons, and subsequent dissolution. These electrons move through a return circuit, which is a path in the metal itself to reach a relatively cathodic spot on the metal, where these electrons are consumed through reaction involving substances found in the electrolyte.

In reinforced concrete, the anode and the cathode are located on the steel bars, which also serve as the return circuits, with the surrounding concrete acting as the electrolyte (US Department of Transportation 1998). When corrosion occurs on reinforcing steel in concrete, the electrochemical reactions involved are dependent on the environment at the steel-concrete interface.

2.2 CORROSION MECHANISMS

2.2.1 In the Presence of Oxygen

$Fe \rightarrow Fe^{2+} + 2e-$ (2.1)

At the cathode, the two electrons created in the anodic reaction combine with oxygen and moisture to form hydroxide ions.

$2e- + H_2O + 1/2O_2 \rightarrow 2OH^-$ (2.2)

The anodic and cathodic reactions are only the first steps; yet they play a very important role in the corrosion process. The ferrous ions combine with hydroxyl ions to produce ferrous hydroxide. The latter is further oxidized in the presence of moisture to form ferric oxide.

$Fe^{+2} + 2OH - \rightarrow Fe(OH)_2$: Ferrous hydroxide (2.3)

$4Fe(OH) + O_2 + 2H_2O \rightarrow 4Fe(OH)_3$: Ferric hydroxide (2.4)

$2Fe(OH)_3 \rightarrow Fe_2 O_3H_2 O + 2H_2 O$: Hydrated ferric oxide (rust) (2.5)

2.2.2 In the Absence of Oxygen

At the anode, in the upper layer of steel in a bridge deck, the oxidized iron reacts with chloride ions to form an intermediate iron complex.

$Fe \rightarrow Fe^{2+} + 2e-$ (2.6a)

$Fe^{2+} + 4 Cl^- \rightarrow (FeCl4)^{2-} + 2 e-$ (2.6b)

This compound then reacts with moisture to form ferrous hydroxide.

$(FeCl_4)^{-2} + 2\ H_2O \rightarrow Fe(OH)_2 + 2\ H^+ + 4\ Cl^-$ (2.7)

At the cathode, the hydrogen ions are reduced or combined with electrons to form Hydrogen gas.

$2H^+ + 2e^- \rightarrow H_2$ (2.8)

It has been suggested that the chloride complex ions formed in reaction (2.7) may react with calcium hydroxide in the surrounding cement paste as shown below:

$(FeCl_4)^{2-} + Ca(OH)_2 \rightarrow Fe(OH)_2 + CaCl_2 + 2\ Cl^-$ (2.9)

It is apparent from the above reactions that, unfortunately, none of the chloride ions in the concrete are consumed and are, therefore, available again to contribute to corrosion. By forming hydrogen ions, or acid, in reaction 2.7, the pH at a local anodic site can reduce rapidly to values of 5 to 6. The resulting low-pH anode on a rebar is so different from that of other nearby rebars, which are surrounded by concrete of a higher pH, that a powerful macro-cathode is created, which then feeds the original anodic spot. It is obvious that moisture is required, not only to support the cathodic reactions but also to enhance the electrical conductivity of the concrete (US Department of Transportation 1998).

2.2.3 In the Absence of Chloride

Corrosion can also occur even in absence of chloride ions. For example, when the concrete comes into contact with carbonic acid resulting from carbon dioxide in the atmosphere, the ensuing carbonation of the calcium hydroxide in the hydrated cement paste leads to reduction of the alkalinity, to a pH level as low as 8.5, thereby permitting corrosion of the embedded steel (US Department of Transportation 1998). The rate of carbonation in concrete is directly dependent on the water/cement ratio (w/c) of the concrete, i.e., the higher the ratio the greater is the depth of carbonation in the concrete.

$CO_2 + H_2O \rightarrow H_2CO_3$ (2.10)

$H_2CO_3 + Ca(OH)_2 \rightarrow CaCO_3 + 2H_2O$ (2.11)

The corrosion product (rust) occupies a greater volume than the steel and exerts substantial stress on the surrounding concrete. Hydrated ferric oxide ($Fe_2O_3H_2O$) has a volume about twice that of steel. When it becomes hydrated, the volume increases even more and becomes porous. The volume increase at the steel/concrete interface can be two to ten times. This leads to the delamination, cracking and eventual spalling of the concrete, forming flaky rust on the bar, and the creation of rust stains seen at cracks. Estimates of the expansive force exerted on concrete when steel converts to rust varies from 32 to 500 MPa. Similarly, different estimates have been made on the amount of corrosion product necessary to crack the concrete or mortar, and these have ranged from 0.1 to 20 mils. As corrosion takes place, the cross section area of the steel is reduced, which leads to loss of bonding between the steel and the concrete. This effect can be of serious concern in prestressed concrete bridge members, where the bonding between the high-strength tendons and the concrete is critical (US Department of Transportation 1998).

It is important to remember that corrosion is not the only deterioration mechanism in reinforced concrete. Alkali-silica reactivity (ASR), freeze-thaw, plastic shrinkage, thermal movement, uneven settlement and other movement can all lead to the cracking and spalling of concrete. Some structures may be prone to unusual chemical attacks of the reinforcing steel or concrete. For example, septic tanks are subjected to sulfuric attack; storage vessels are attacked by its liquid content; offshore structures are often attacked by seawater, and carbonates in water can attack concrete pipelines and underground structures. However, the scope of discussion in this thesis is limited to corrosion of atmospherically exposed structures.

2.3 GENERAL INTRODUCTION TO NDT

Non-Destructive Testing is the examination of an object with technology that does not affect the objects future usefulness. We find both the general concepts and uses of NDT not only in industry but in our everyday lives. For example, imagine you are at the fruit counter at the local market. You glance over the selection of melons ,pick one and look it over for flaws- that’s visual NDT .Then you test the melon’s ripeness by tapping the surface and listening for the hollow response-that’s acoustic NDT .Finally,depending on the response to these tests relative to your preset NDT criteria (Does the melon look OK?Is it ripe enough?) , you either look for another melon, or accept the product and head to the checkout counter.

The basic principle of NDT is simple . To determine the quality or integrity of an item nondestructively , simply find a physical phenomenon (the interrogating parameter) that will interact with and be influenced by your test specimen (the interrogated parameter) without altering the specimen’s function.

For example, some questions can be answered non invasively by passing X – rays(interrogating parameter) through an object, and monitoring the X-rays absorption (the interaction of the X-rays and the object is the interrogated parameter). You could answer the questions “Is my arm broken?” and “Is there a mouse in my beer can?” using this method.

In structural health monitoring, nondestructive evaluation (NDT) can be used to determine the nature of the damage. NDT methods to determine local damage are also becoming more accepted in practice.

2.3.1 Non-Destructive Testing Techniques

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

Various NDT techniques used for corrosion monitoring of RC structures are given below:

- Visual Inspection
- Infrared thermograph Electrochemical measurements
- Open Circuit Potential (OCP) measurements
- Surface Potential (SP) measurements
- Concrete Resistivity measurements
- Linear Polarisation Resistance (LPR) measurements
- Galvanostatic pulse transient method
- Electrochemical Impedence Spectroscopy (EIS)
- Embeddable Corrosion monitoring sensor

- Cover thickness measure
- Ultrasonic pulse velocity techniques
- X-ray, Gamma Radiography measurement

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

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

Open Circuit Potential (OCP) Measurement: OCP measurement is a non-destructive test that diagnoses the corrosion risk in RC structures. In RC structures, the pore solution in concrete acts as an electrolyte and thus, a potential is developed on the reinforcement that may vary from place to place depending on the concrete environment. OCP Measurement is based on the principle of measuring corrosion potential of steel with respect to a standard reference electrode. The reference electrode can be a saturated calomel electrode (SCE), Cu/C $_4$ electrode (CSE), Ag/AgCl electrode etc. A large number of observations are taken from RC structure to deduce the corrosion risk. The schematic representation of OCP measurement is as shown in the **Fig. 2.1**.

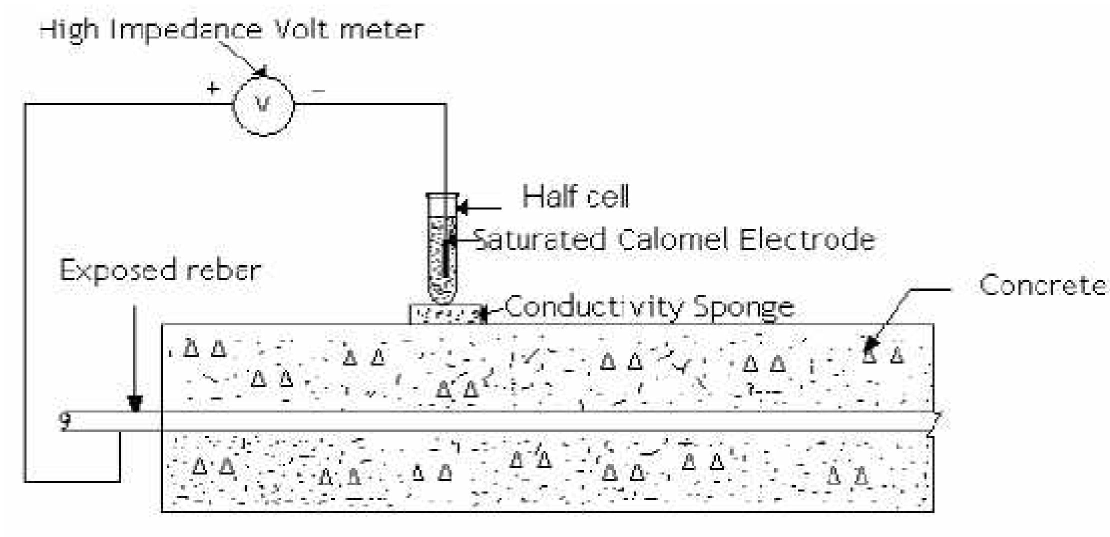


Fig. 2.1: Schematic representation of Open circuit potential (OCP) measurement (*Song and Saraswathy, 2007*)

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

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

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

Surface Potential Measurement: SP measurement is a useful technique to identify the anodic and cathodic regions in a RC structure and determines the probability of corrosion reinforcement indirectly. During corrosion process, electric current flows from anode to cathode, i.e., from higher potential to lower potential. SP measurements are based on measuring the potential drop from anode to cathode. The schematic representation of SP Measurement is as shown in **Fig. 2.2**.

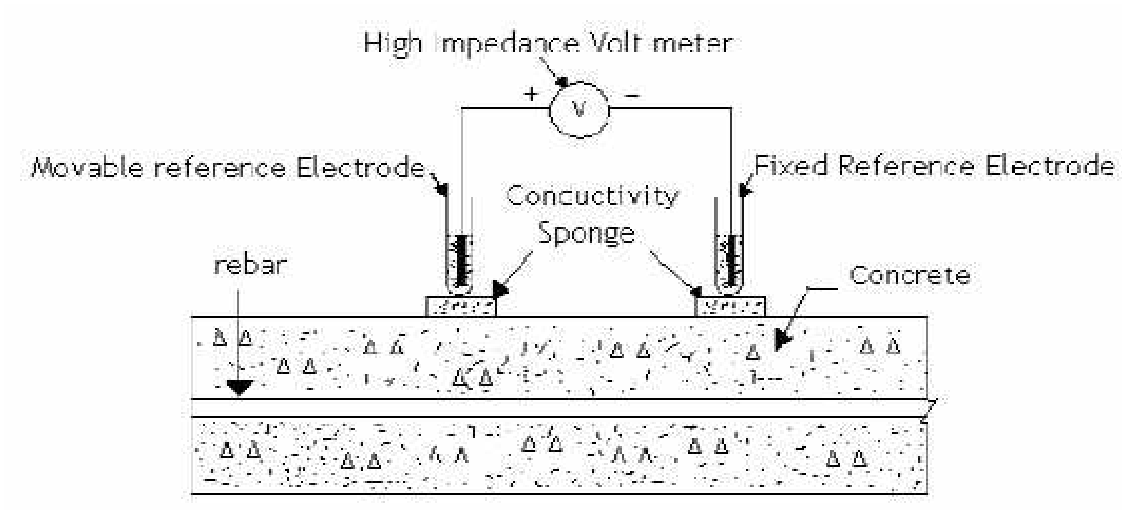


Fig. 2.2: Schematic representation of Surface potential (SP) measurements (*Song and Saraswathy, 2007*)

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

Concrete Resistivity Measurement: It is a NDT technique that evaluates corrosion risk on the reinforcement based on electrical resistivity measurements. The parameter “electrical resistivity” plays an important role in determining the intensity of corrosion. Greater the electrical resistivity of concrete material, slower will be the corrosion process. It has been reported that electrical resistivity is inversely proportional to the corrosion rate. Electrical resistivity is an important parameter that provides useful information about corrosion performance of steel embedded in concrete. **Fig. 2.3** shows the circuit for electrical resistance measurements.

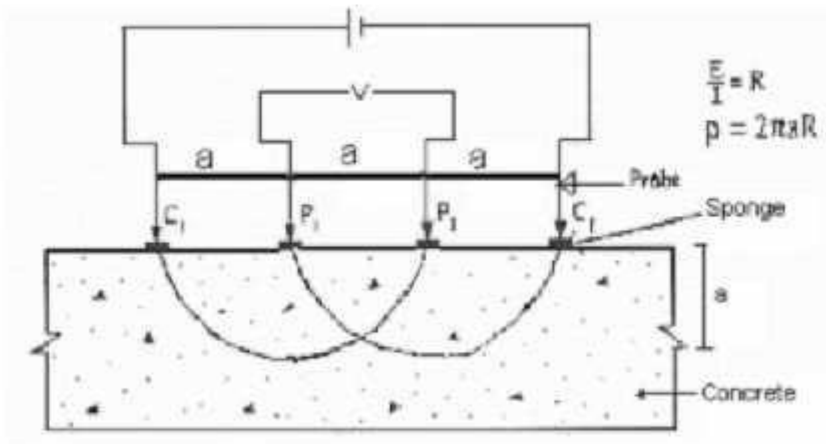


Fig. 2.3: Circuit for Electrical resistance measurements (*Song and Saraswathy, 2007*)

Linear Polarization Resistance (LPR) Measurements: It is a useful NDT technique that determines the instantaneous corrosion rate of reinforcing steel. **Fig 2.4** shows the schematic representation of Linear Polarization Resistance (LPR) Measurement. This method provides more detailed information as compared to simple potential survey. Moreover, it is rapid, non-intrusive and enables accurate assessment of the condition of RC structures. However, this technique requires localised damage on the concrete cover in order to enable a concrete connection to the reinforcing steel. In this method, the potential of reinforcing steel is changed by a fixed amount ΔE and the current ΔI is monitored after a fixed time period. The change in potential ΔE should be between 10 – 30 mV (Stern-Geary range).

The polarization resistance, R_p is given as:

$$R_p = \Delta E / \Delta I \qquad (2.12)$$

The corrosion rate, I_c is expressed in terms of polarisation resistance (R_p)

$$I_c = B / R_p \qquad (2.13)$$

where, B is Stern–Geary constant.

B = 25 mV (for active steel)

B = 50 mV (for passive steel)

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

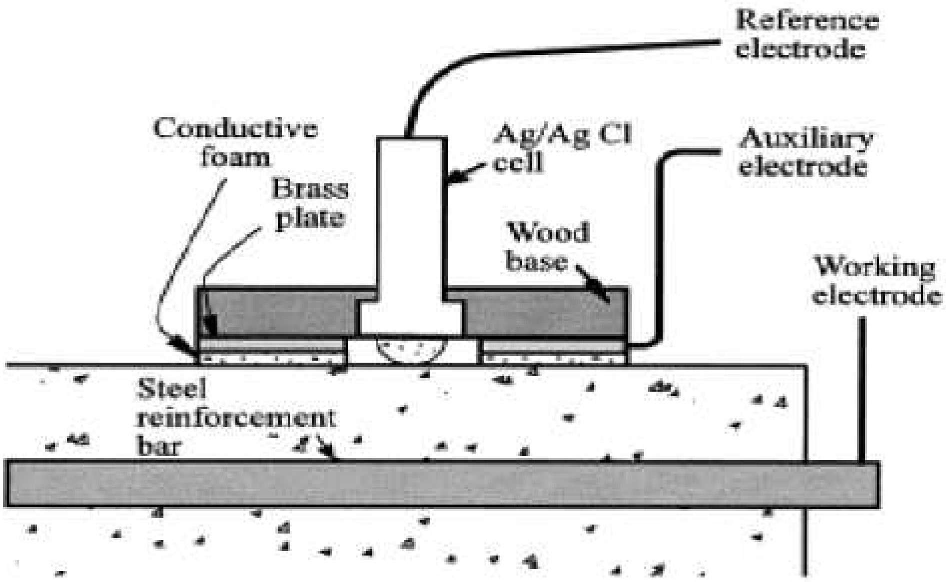


Fig. 2.4: Linear Polarization resistance measurement (*Song and Saraswathy, 2007*)

Galvanostatic Pulse Transient Method: It is a NDT technique based on transient polarization that operates in time domain. In this method, a short time anodic current pulse (10-200 μA) is imposed on the reinforcing steel by a counter electrode placed on the surface of concrete. This leads to polarization of the reinforcement with respect to its free corrosion potential in anodic direction. The resulting potential difference is recorded by a reference electrode as a function of polarization time. T he set up for galvanostatic pulse technique is as shown in **Fig. 2.5**. A limitation of this technique is that the pulse response must be stabilized to give an accurate value of potential.

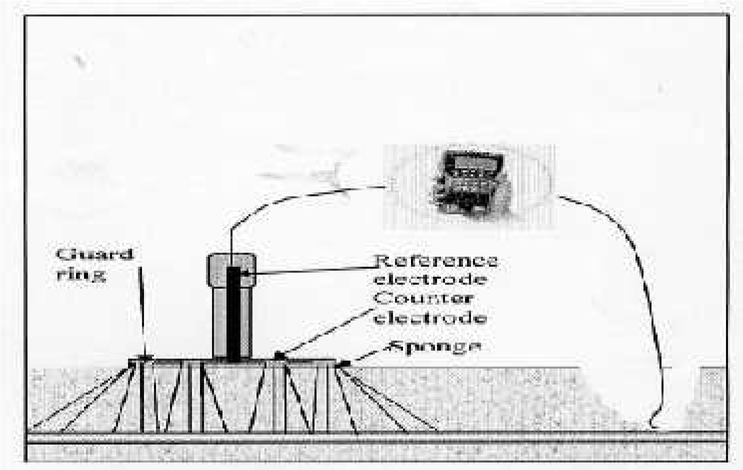


Fig. 2.5: Set-up for Galvanostatic pulse technique (*Song and Saraswathy, 2007*)

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

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

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

- Temperature

The ECI monitors are connected to form an embedded corrosion sensor that can be easily installed on a structure to provide adequate coverage of the structure during construction. **Fig. 2.6** shows an ECI sensor:

Fig. 2.6: ECI sensor during operation (*Song and Saraswathy, 2007)*

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

Cover Thickness Measurement: This NDT technique employs a device known as cover meter or profmeter to measure the concrete cover for detecting rebar size, position and direction. **Fig. 2.7** shows a cover meter to monitor corrosion of reinforcing steel:

Fig. 2.7: Cover meter (*Song and Saraswathy, 2007*)

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

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

$$\text{PulseVelocity}, V = L/T \tag{2.14}$$

The value of pulse velocity determines the quality of concrete.

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

CHAPTER 3

ULTRASONIC MONITORING IN RC STRUCTURES

3.1GENERAL

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

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

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

3.2 ULTRASONIC GUIDED WAVES

This section provides an understanding of ultrasonic guided waves.

3.2.1 Introduction

Elastic waves in all frequency ranges-ultrasonic, sonic and subsonic- can be classified into two groups: Body Waves or Bulk waves and, Surface Waves or Guided Waves (**Fig. 3.1**). Body waves travel through the bulk material while surface waves propagate along the surface. Sound waves travel as a bulk wave in any elastic material where the sound does not interact with the edges of material therefore acting as infinite extent of material. The velocity of sound in materials varies with its elastic properties which can be calculated by measuring the time of flight between the two points.

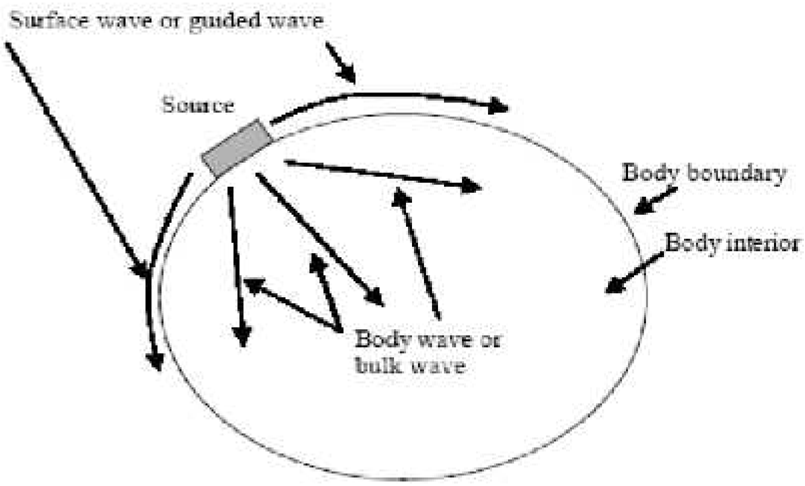


Fig. 3.1: Body waves and Surface waves generated by an ultrasonic source (*Kundu, 2004*)

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

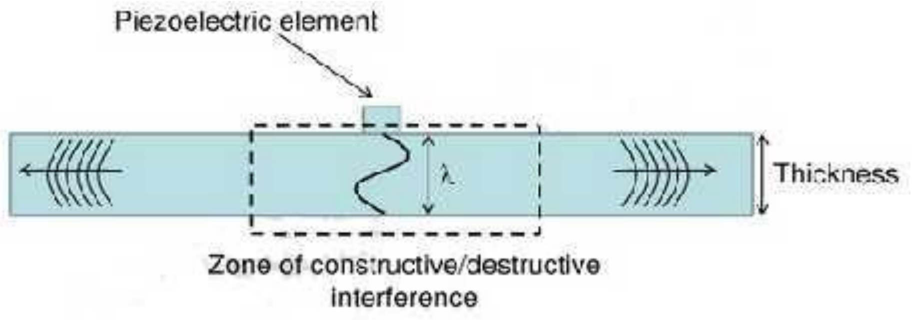


Fig. 3.2: Propagation of guided waves through a structure (*www.wins-ndt.com*)

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

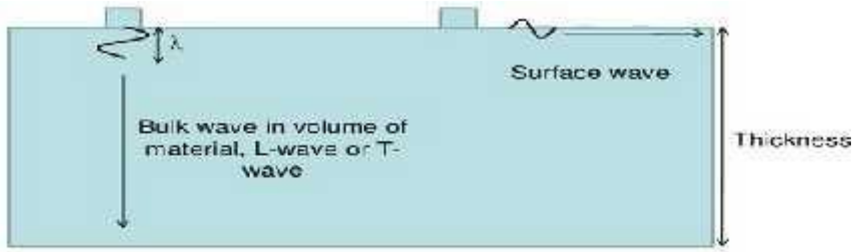


Fig. 3.3: Wave Propagation when thickness of material >> wavelength (*www.wins-ndt.com*)

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

There are numerous advantages of Ultrasonic Guided Wave testing such as:

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

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

3.2.2 Types of Guided Waves

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

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

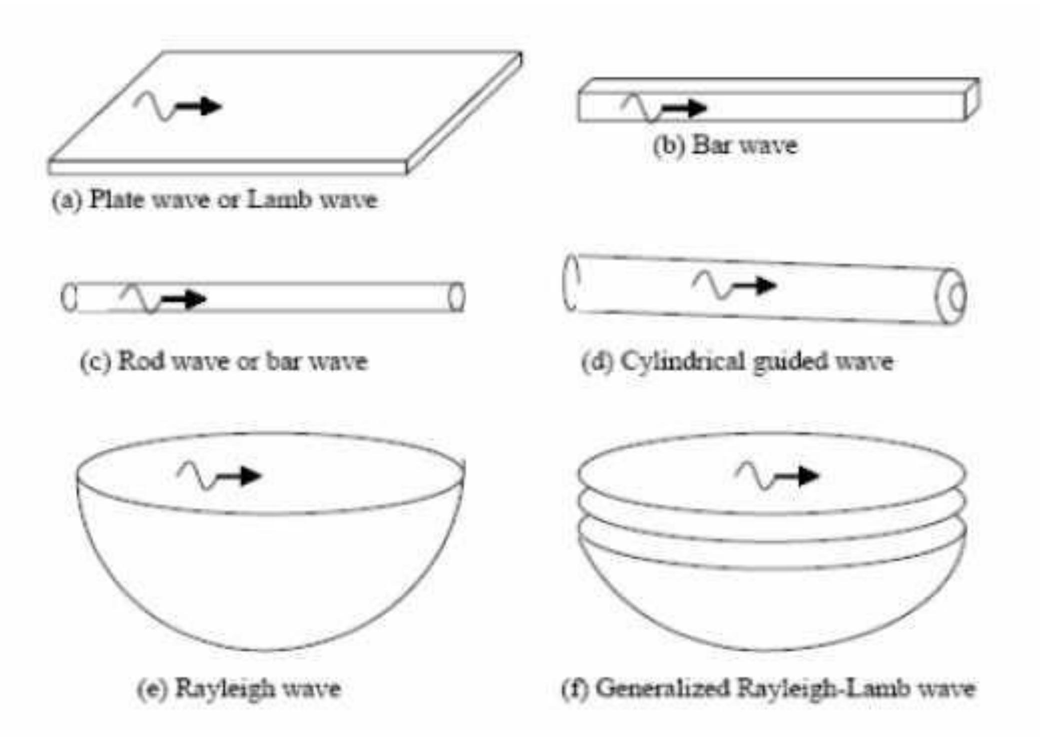


Fig. 3.4: Different types of guided waves (*Kundu, 2004*)

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

3.2.3 Modes of propagation of Ultrasonic Guided Waves

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

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

Longitudinal modes have radial and axial displacements, torsional modes have angular displacements and flexural modes have axial, radial and angular displacements. These modes are represented by the notation L(m,n), T(m,n) and F(m,n) respectively. In this notation, ‘m’ represents the circumferential displacement and is a function of $\cos(m\theta)$, and ‘n’ represents the sequential order of mode. For longitudinal modes, the variable ‘m’ is zero as they are axially symmetric. For flexural modes, the variable ‘m’ varies as $\cos(m\theta)$ around the circumference of the steel bar. For e.g., L(0,1) is the notation for first longitudinal mode.

3.2.4 Limitations of Guided Waves

There are few limitations of guided waves such as:

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

3.3 ULTRASONIC TESTING

3.3.1 Basic Principle

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

Ultrasonic testing is a safe and well-established NDT technique that involves the propagation of high frequency sound waves to predict material strength, and detect the presence of internal flaws such as cracking, voids, honeycomb, decay and other damage. The generation and detection of ultrasonic waves require a transducer that is made of piezoelectric ceramics, composites or polymer. The transducer has the capability of converting a high voltage electrical pulse to a burst of sound waves and vice-versa. There are five types of transducers commonly used for ultrasonic flaw detection: Contact Transducers, Angle Beam Transducers, Delay Line Transducers, Immersion Transducers and Dual Element Transducers. The current research uses Contact Transducers. As the name implies, contact transducers are kept in direct contact to the surface of the material (**Fig. 3.5**). Sometimes good contact requires the use of a coupling gel between the transducers and the structure. These transducers introduce a sound wave perpendicular to the surface that is guided by the geometry of the structure. These transducers are typically used for detecting voids, porosity, cracks, or delaminations, and for measuring the thickness of the material.

The set up for ultrasonic flaw detection includes a function generator that generates an electric signal, an electro-acoustic transducer that converts the electric signal to sound wave, and a PC to display the initial and reflected pulses. Pulses of longitudinal, elastic stress waves are generated by an electro-acoustical transducer that is held in direct contact with the surface of the concrete under test.

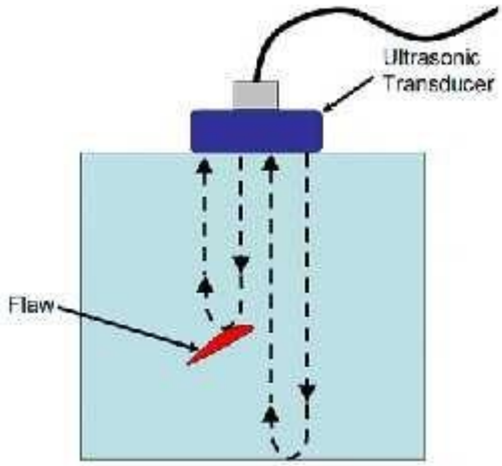


Fig. 3.5: Principle of Ultrasonic wave generation and detection (*www.ni.com*)

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

$$T = V\,t / 2 \tag{3.1}$$

where,

T = Material Thickness

V = Material Sound Velocity

t = Time of Flight

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

$$A_{d} = 20 \log_{1} \frac{}{A_{2}} \tag{3.2}$$

dB = Decibels

A1 = Amplitude of Input Signal

A2 = Amplitude of Transmitted/ Received Signal

Song and Saraswathy (2007) demonstrated ultrasonic pulse velocity (UPV) technique for corrosion monitoring. This technique measures the speed of sound for flaw detection. The interpretation of data is very difficult in UPV technique as a large number of factors affect the pulse velocity. The relationship between ultrasonic pulse velocity and the quality of concrete is given as follows in **Table 3.1**.

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

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

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

3.3.2 Methods for Ultrasonic Testing

Most commonly used methods for ultrasonic testing are:

(a) Pulse Transmission method

(b) Pulse Echo method

(a) Pulse Transmission method

In the pulse-transmission method, an ultrasonic transmitter is used on one side of the material while a detector is placed on the opposite side. One unit acts as transmitter and the other unit as receiver. The beam from the transmitter T travels through the material to its opposite surface where the receiving transducer R is placed. Scanning of the material using this method will result in the location of defects, flaws, and inclusions in the X-Y plane (**Fig. 3.6**)

By measuring the relative change of the amplitudes of the input and the received signals, the relative severity of the flaw is assessed.

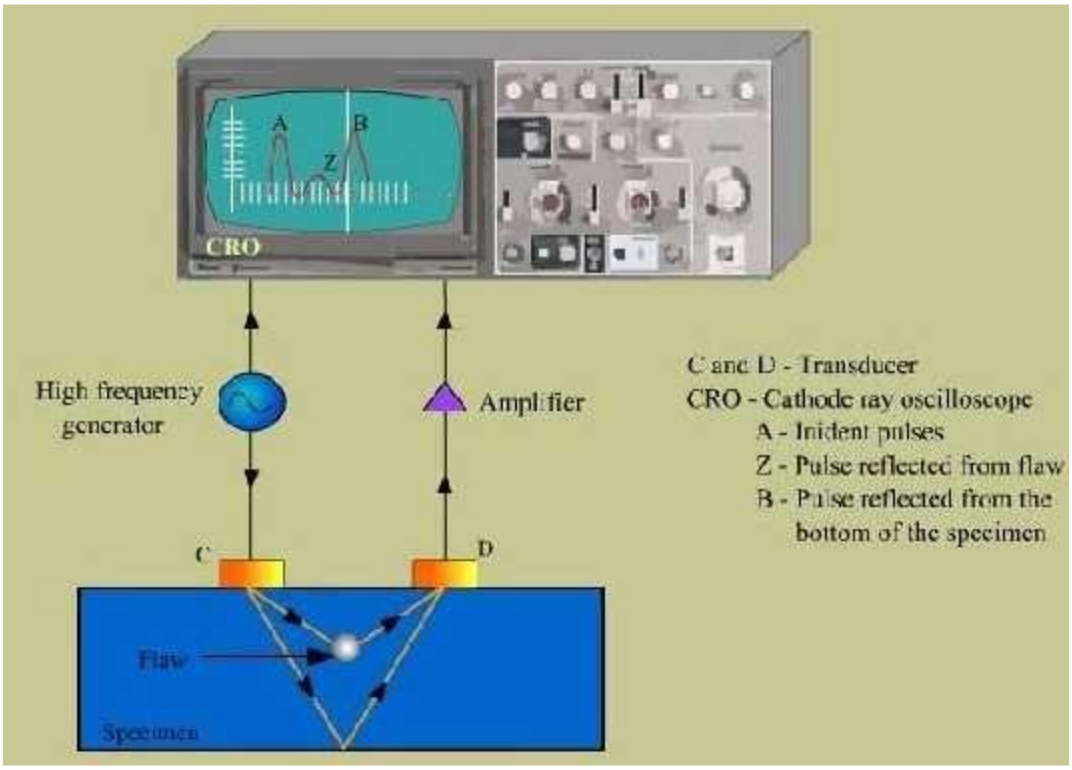
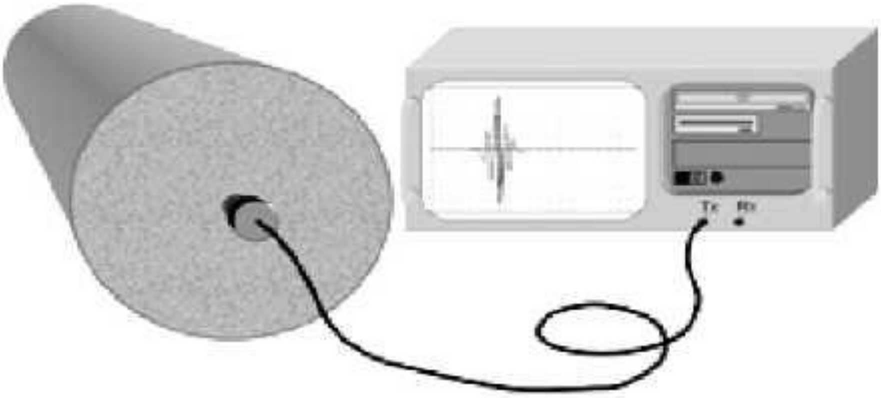


Fig. 3.6: Pulse Transmission method of testing

(*www.msheiksirajuddeen.blogspot.in*)

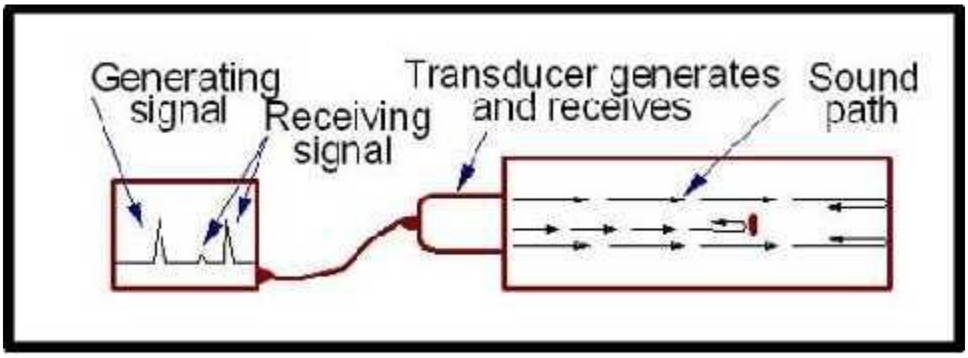
(b) Pulse Echo method

In the pulse-echo method, a piezoelectric transducer with its longitudinal axis located perpendicular to and mounted on or near the surface of the test material is used to transmit and receive ultrasonic energy (**Fig 3.7**).



(a)

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



(b)

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

The ultrasonic waves are reflected by the opposite face of the material or by discontinuities, layers, voids, or inclusions in the material, and received by the same transducer where the reflected energy is converted into an electrical signal. The electrical signal is computer processed for display on a video monitor or TV screen. The display can show the relative thickness of the material, depth into the material where flaws are located, and (with proper scanning hardware and software) where the flaws are located in the X-Y plane.

When there is an interface such as a crack, void or flaw in the wave path, part of the energy is reflected back from the interface and received by the same transmitting transducer. The reflected energy is converted into an electrical signal which is processed in a computer and digitized for display.

The most commonly used method to analyze the reflected ultrasonic wave is time-of-flight (TOF) display, or A-scan. The discontinuities closer to the ultrasonic transducer are detected sooner than those farther away from the transducer. **Fig. 3.8** depicts TOF display.

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

$$D = V\ t \tag{3.3}$$

where,

D = Distance of defect from transducer end,

V = Velocity of wave and,

t = Time of Flight

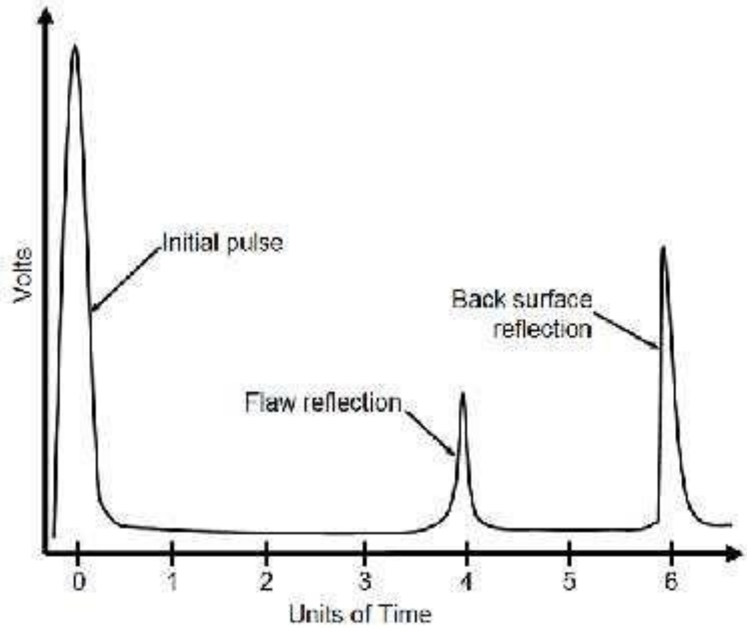


Fig 3.8: Pulse Echo method of testing (*www.ni.com*)

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

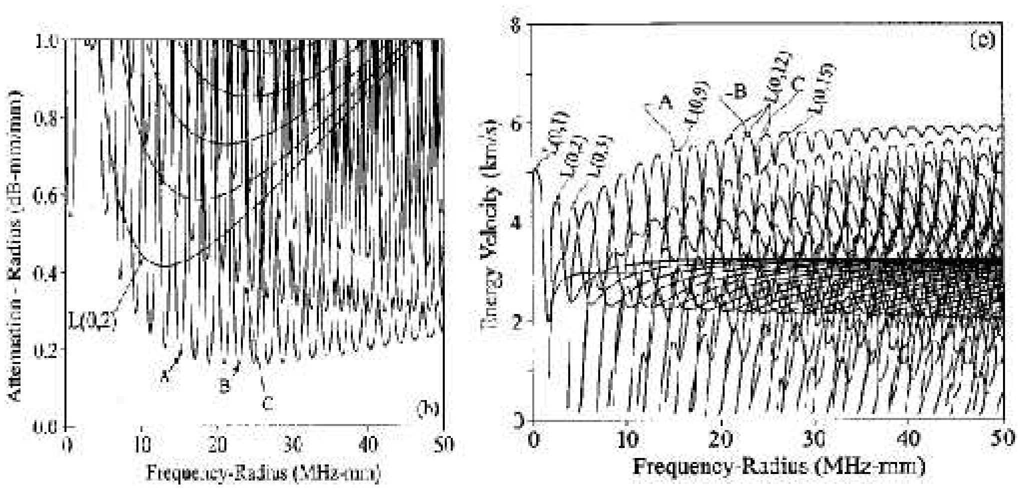
3.3.3 Limitations of Ultrasonic guided wave testing

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

3.4 LITERATURE REVIEW ON ULTRASONIC GUIDED WAVES FOR MONITORING RC STRUCTURES

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

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



(a) **(b)**

Fig. 3.9: Dispersion curves of axisymmetric L(0,n) modes of steel bar imbedded in grout (a) attenuation; (b) energy velocity

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

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

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

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

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

Ervin et al. (2008) investigated guided wave modes in both low and high frequency ranges capable of monitoring corrosion in reinforced concrete. The fundamental longitudinal modes L(0,1) and L(0,9) were chosen for experimental testing at low and high frequency respectively. L(0,1) mode was chosen because it shows negligible signal loss due to material absorption. It was used to access interfacial damage between steel and mortar. L(0,9) mode was selected because it is the fastest and lowest attenuating mode in the system. Experiments were conducted to examine the effect of reinforcing ribs, water and mortar on low and high frequency guided waves. Ultrasonic testing was carried out in a through transmission mode on rebar in air, rebar immersed in water, rebar embedded in mortar, corroded rebar in air and reinforced mortar specimens undergoing accelerated corrosion(**Fig. 3.10**).

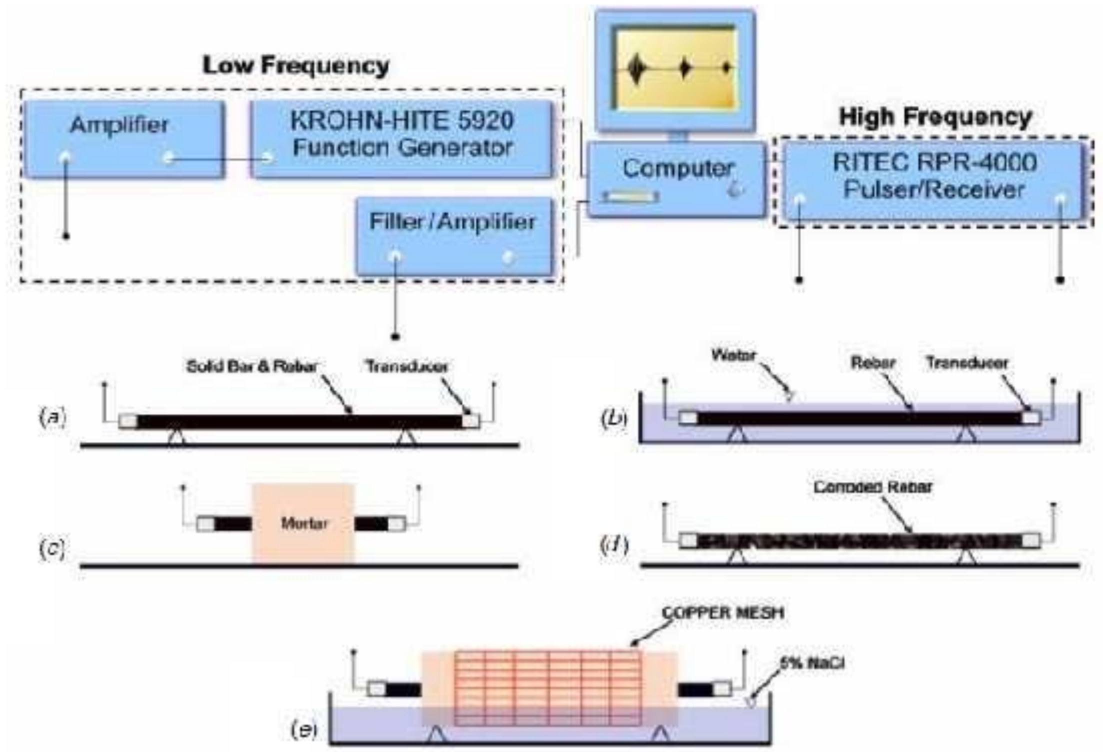


Fig. 3.10: Through-transmission testing for low- and high-frequency longitudinal wave testing on (a) a solid bar and rebar in air, (b) rebar immersed in water, (c) rebar embedded in mortar, (d) corroded rebar in air and (e) reinforced mortar specimens undergoing accelerated uniform corrosion.

Testing showed that reinforcing ribs has an attenuative effect on guided wave propagation only in certain frequency ranges. Guided wave was less affected at higher frequencies where the wave displacement structure is predominately concentrated at the center of the bar, and negligibly affected when the wavelength is much longer than the characteristic dimension of the rib. Testing confirmed that L(0,1) mode has some sensitivity to water over the frequency range tested, with attenuation increasing with frequency. It was observed that the lowest frequencies of L(0,9) mode show sensitivity to water while the higher frequencies show diminished sensitivity. For the bars embedded in mortar, testing showed that the low frequency mode was highly attenuated, resulting in monitoring of relatively short distances (e.g. 1 m). The attenuation shown by L(0,9) mode was much smaller than L(0,1) mode. For rebar specimens extracted from accelerated corrosion tests, testing showed that L(0,1) was not substantially affected in the lowest range. However, interesting results were seen for L(0,9) mode. It was observed that there was no frequency content between frequency domain peaks when the corrosion damage frequency was low. As the corrosion level increased, the frequency content between frequency domain peaks, referred to as 'web' frequencies started to increase. The attenuation curves for rebar in air, water and mortar are shown in F**ig. 3.11**.

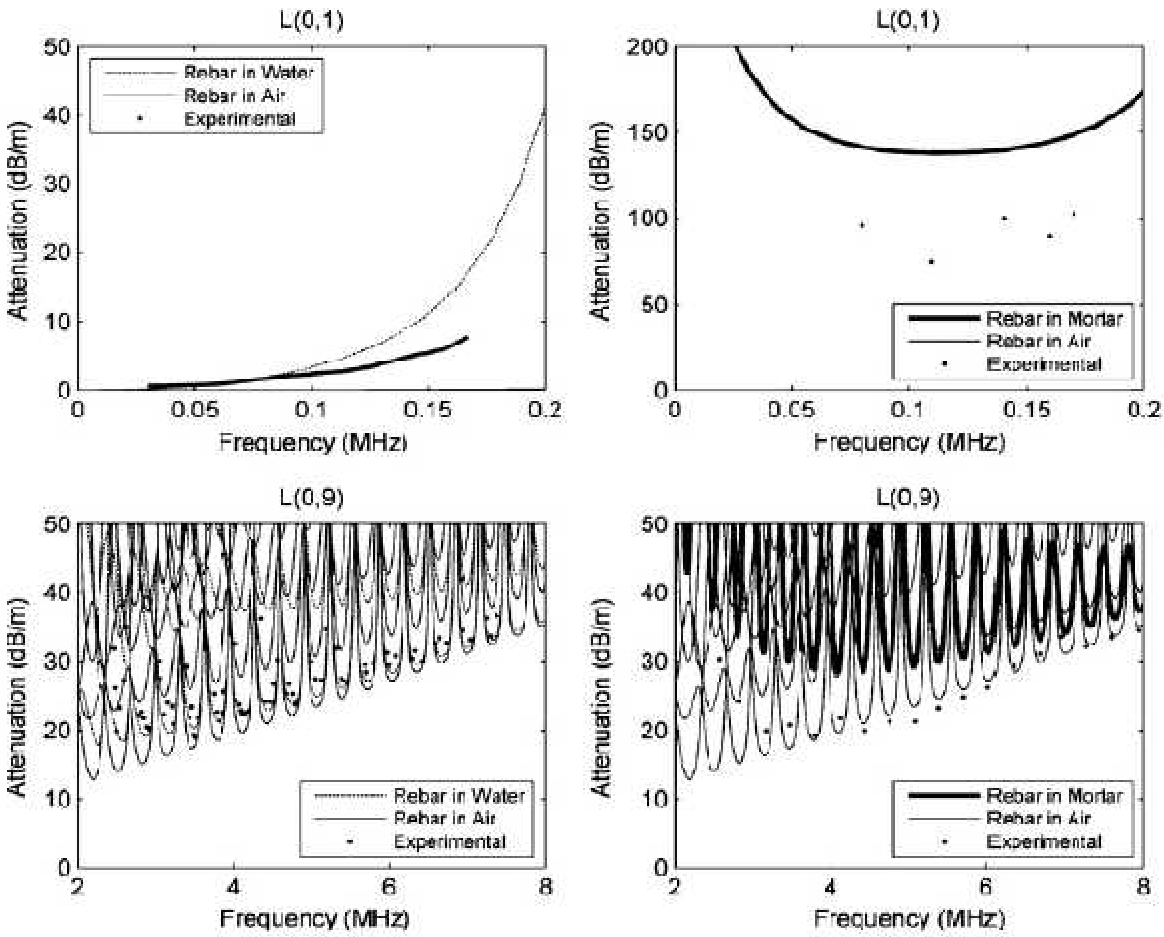


Fig. 3.11: Theoretical attenuation curves with experimental attenuation measurements for rebar in air, immersion in water and embedment in mortar at low and high frequencies

For rebar specimens undergoing accelerated corrosion, testing showed that L(0,1) was highly attenuated such that it was not detected until after corrosion had initiated and corrosion product accumulation caused mortar cracking. Once detected, L(0,1) mode was sensitive to the combined effect of bond deterioration and mortar stiffness reduction. The results indicate that the signal strength of L(0,1) mode was increasing as the mass loss was advancing (**Fig. 3.12**).

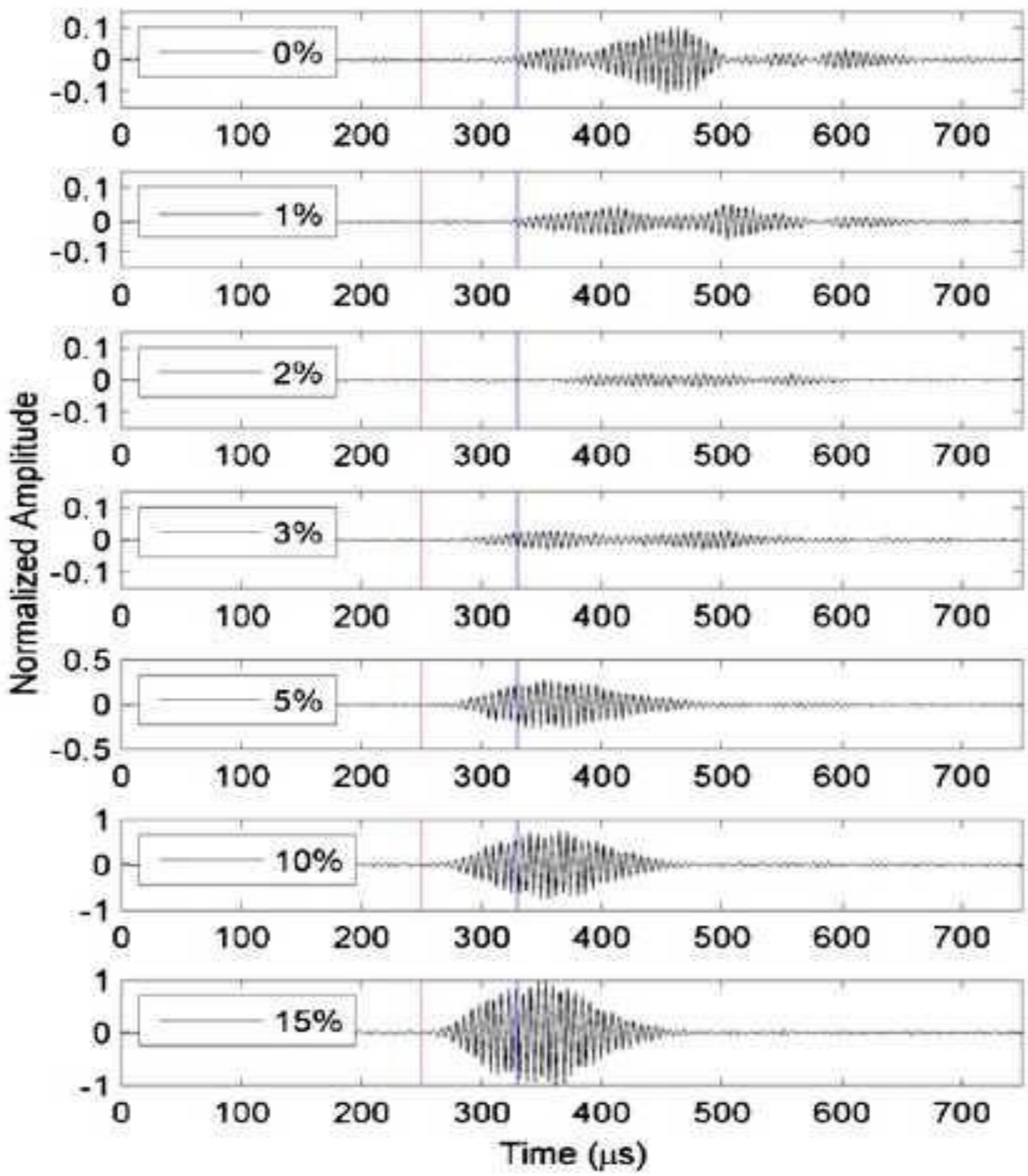


Fig. 3.12: Time domains at different levels of mass loss for low-frequency monitoring of accelerated corrosion. Left and right vertical lines are the arrival times for the L(0, 1) and F(1, 1) modes, respectively. The input signal was a 164 kHz 15-cycle pulse, with a band pass of 159 kHz and 169 kHz.

L(0,9) mode was relatively insensitive to the surrounding interface conditions at high frequencies. This allowed the monitoring of steel cross sectional area and bar topography, from the onset of corrosion to severe pitting (**Fig. 3.13**).

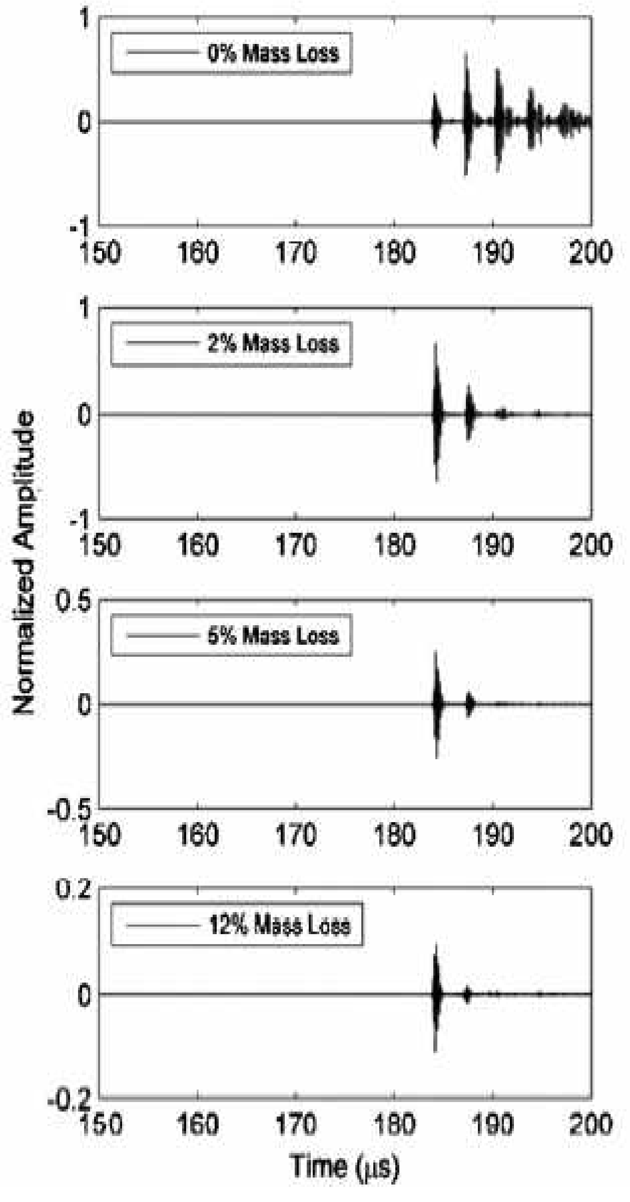
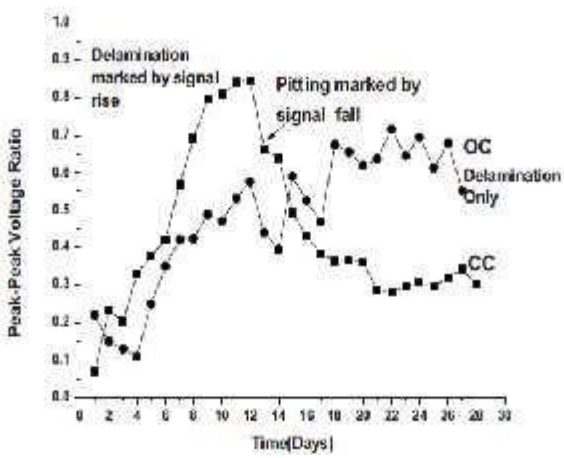


Fig. 3.13: Time domain response at different levels of mass loss for high-frequency monitoring of accelerated corrosion. The input signal was a 5.08 MHz single cycle pulse, with a bandpass of 2 MHz and 10 MHz.

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

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

Sharma and Mukherjee (2011) investigated the type of corrosion mechanism in chloride and oxide environments in RC beams. Ultrasonic guided waves with specific core and surface seeking modes were used for monitoring rebar corrosion in beams. It was observed that in case of Chloride corrosion in beams, when core-seeking mode was propagated, the signal was highly attenuated, thus indicating pitting and non-uniform area loss. When surface seeking mode was propagated, there was an initial rise in the signal strength and then a fall, thus indicating delamination followed by local loss of material. In case of Oxide corrosion in beams, it was observed that when core-seeking mode was propagated, there was a slow fall in signal strength, indicating the absence of pitting. When the surface-seeking mode was propagated, there was an initial drop in the signal due to the pressure build up by the formation of corrosion products, indicating a slow corrosion rate and localized corrosion and eventually, a gradual rise in signal strength was observed, indicating slow bond deterioration. The ultrasonic voltage trends of the received signal in both chloride and oxide corrosion specimens using surface-seeking and core-seeking mode are shown in **figures 3.14 (a) and (b)** respectively



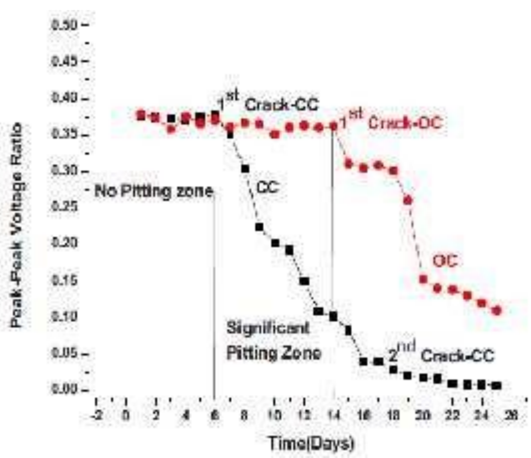


Fig. 3.14(a) : Peak-peak voltage ratio with core-seeking mode

Fig. 3.14(b) : Peak-peak voltage ratio with surface seeking mode

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

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

3.5 CLOSING REMARKS

This chapter highlights the work done by some researchers on effect of corrosion on RC structures. They explain that RC structures exposed to corrosion environment results in its deterioration. It decreases its service life by introducing early cracks and spalling of concrete. Their works predicts that as the corrosion level increases the load carrying capacity of RC structure decreases. And the structures fail earlier than to its design life. So corrosion is a very serious problem which needs to be monitor.

Further this chapter explains the work on Ultrasonic testing as a non-destructive technique to monitor defects in the RC structures.

CHAPTER 4

EXPERIMENTAL INVESTIGATIONS AND METHODOLOGY

4.1 GENERAL

The objective of this study is to evaluate the efficacy of ultrasonic guided waves to be able to monitor the behaviour of RC beams during various stages i.e., after the initiation of corrosion. Also, the destructive tests are conducted in order to evaluate the damage done by the corrosion.

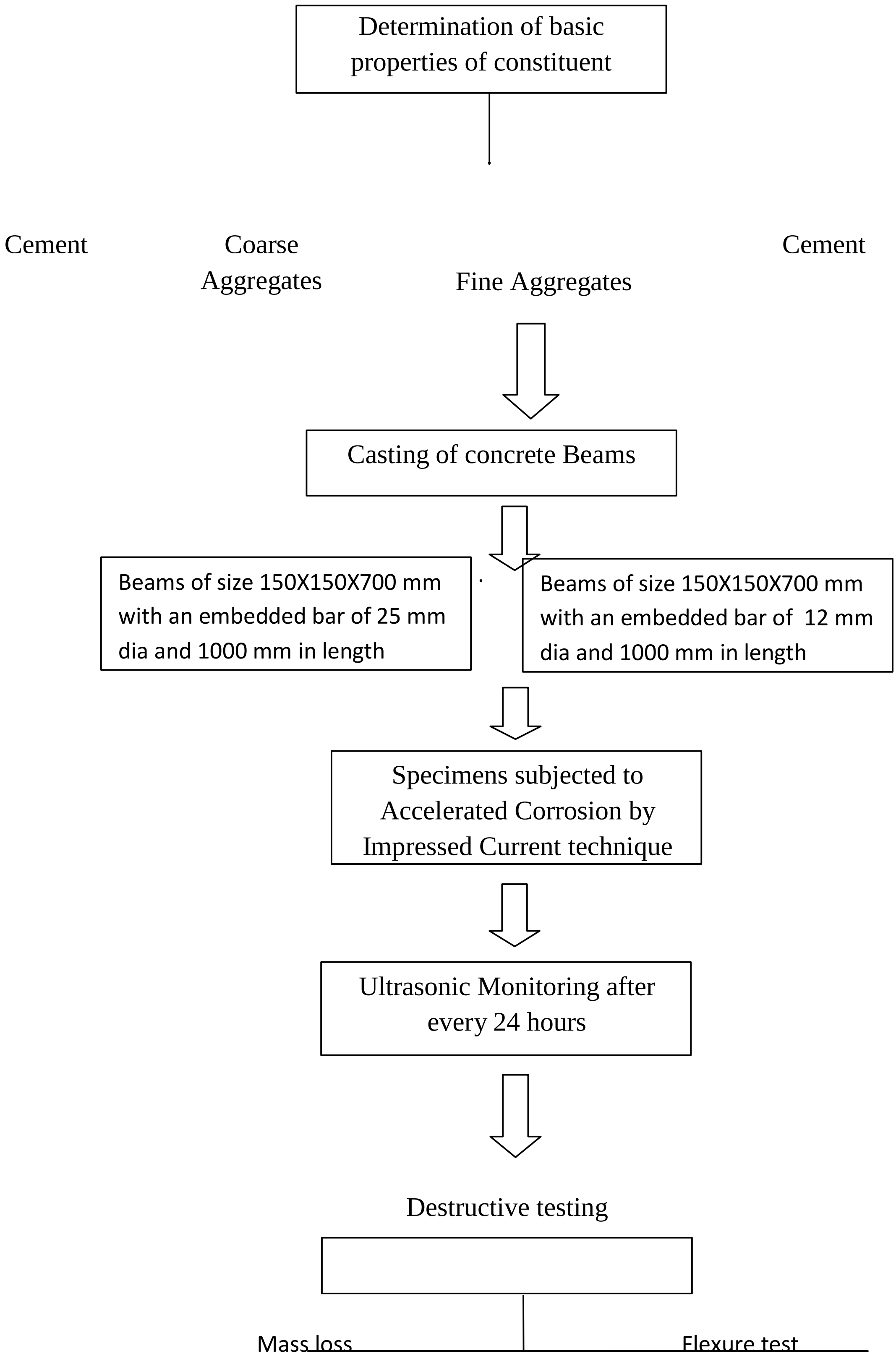
4.2 TEST PROGRAM

The test program involved:

1. Determination of basic properties of constituent materials namely cement, fine aggregates, coarse aggregates and steel bars as per relevant Indian standard Specifications.
2. Casting of RC beams of set 1 of dimensions150 X 150 X 700 mm with a 1000mm steel rod of 25 mm dia embedded in it such that 700 mm of steel rod is inside the concrete cover using M20 grade concrete.
3. Casting of RC beams of set 2 of dimensions150 X 150 X 700 mm with a 1000mm steel rod of 12 mm dia embedded in it such that 700 mm of steel rod is inside the concrete cover using M20 grade concrete.
4. Subjecting the specimens to accelerated corrosion at a constant voltage of 20V was continuously monitored to ensure that corrosion is taking place.
5. Corrosion is continued for 3, 6 ,12 , 18 and 30 days for samples with steel rod of 25 mm dia and 6 and 18 days for samples with steel rod of 12 mm dia..
6. Ultrasonic guided waves monitoring of the specimens after every 24 hours till the signals vanished in both sets of beams .

7. After ultrasonic guided waves monitoring to respective days of corrosion , the beams were subjected to flexural strength test to investigate the effect of corrosion on flexural characteristic of beams.
8. Modulus of rupture(f_t) of beams subjected to different levels of corrosion was obtained.
9. The static deflection of the beams at different corrosion levels was also determined from the P-Δ curves.
10. The bars were extracted with the help of hammer from the corresponding beams to find out percent mass loss.
11. Correlation of static characteristics of modulus of rupture, maximum deflection and mass loss is done with ultrasonic voltage using only core seeking mode.

Fig. 4.1 Shows the complete test procedure.



4.3 MATERIALS USED

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

- ***Cement:*** Ordinary Portland cement of 43 grades is used for the present investigation. The cement is of uniform colour i.e. grey with a light greenish shade and is free from any hard lumps. Summary of various tests conducted on cement are given in **Table 4.1**. All these tests are carried out in accordance with procedure laid down in IS: 8112-1989.
- ***Fine aggregates:*** The fine aggregates used for the experimental work is locally procured and conformed to grading zone III .Sieve analysis of the fine aggregate is carried out in the laboratory as per IS 383-1870.The sand is first sieved through 4.75 mm sieve to remove any particle greater than 4.75 mm sieve and then washed to remove the dust. The physical properties and sieve analysis of fine aggregates are shown in **Table 4.2** and **4.3**.

Table 4.1: Physical properties of cement

S. No.	Characteristics	Values obtained	Standard Values
1	Normal consistency	33%	_
2	Initial setting time	48 min	Not less than 30 min
3	Final setting time	240 min	Not more than 600 min
4	Fineness	4.8 %	_
5	Specific gravity	3.09	_
6	Compressive strength		
S. No.	**Days**	**Values Obtained Experimentally**	
1	3	24.8 MPa	
2	7	37.5 MPa	

3	28	47.6 MPa

Table 4.2: Physical properties of fine aggregates

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

Table 4.3: Sieve analysis of fine aggregates

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

Total weight taken: 1000gm

Fineness modulus of fine aggregates = 2.62

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

Table 4.4: Physical properties of coarse aggregates

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

Table 4.5: Sieve Analysis of Coarse aggregates

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

FM of 10 mm coarse aggregates= (195.73+500)/100 = 6.95

- ***Water:*** Fresh and clean tap water is used for casting slabs in the present study. The water is relatively free organic matter, silt, oil, sugar, chloride and acidic material as per Indian standard.
- ***Steel reinforcement:*** Mild steel bars of 25 mm and 12 mm diameter with 1000 mm length are used as reinforcement. 700mm of rebar is embedded in concrete and 300mm remains exposed to environment, in order to make electrical connections. **Table 4.6** shows the properties of reinforcing bars used for casting of RC cylindrical structures.

Table 4.6: Properties of reinforcing bars used for casting specimens

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

4.4 DESIGN OF CONCRETE MIX

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

4.5 TEST PROCEDURE

4.5.1 General

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

4.5.2 Preparation and Preconditioning of Steel bars

Steel bars are cut to the required length of 1000 mm. Each bar is then wire brushed to remove any surface scale. These are then cleaned by soaking in analytical reagent grade hexane and allowed to dry in air. Before casting of the test specimens, each reinforcing bar is 0.1 gm accuracy.

4.5.3 Preparation of Specimens

In the present program, the RC beams are cast in mould of 150 X 150 X 700 mm with 700 mm of steel bar embedded in concrete cover and 300 mm of length exposed to the surrounding environment. First of all, interior of the beam mould is oiled, so that beams could easily be removed from the mould after 24 hours. Initial weight of the bars is measured. When the bars have been placed in position, concrete mix is poured and vibrations are given so that the mix gets compacted. The vibration is done until the moulding is completely filled and there are no gaps left. The beams are then removed from the mould after 24 hours. After demoulding, the beams are cured for 28 days using a open tank. The concrete surface of the beams is then cleaned up and all dirt and loose materials are removed.

Fig.4.2 Preparation of moulds. **Fig.4.3 Pouring of concrete mix placed on vibrator.**

4.5.4 Inducing Corrosion in RC STRUCTURES

The objective of inducing corrosion to the reinforcing bar is to simulate the corrosion damaged concrete. The commonly used methods of inducing corrosion in RC specimens can be recalled as Salt spray (*Gadve et al., 2008*), Chloride diffusion (*Masoud and Soudki, 2006*) and impressed current method. Previous studies have shown that the test specimens kept in a salt spray chamber for more than 100 days did not show any visible signs of corrosion. This method was not found suitable considering the time constraint. This method was not considered because it did not simulate the present condition of interest.

Alternate immersion into NaCl solution and drying of the specimens also induces corrosion. However, the quickest method of inducing corrosion is by impressing anodic current. In this method, NaCl solution is supplied to the specimens and a direct current is passed making the reinforcement bar as an anode and another metal nobler than it in electrochemical series as cathode.

Fig.4.4 SS mesh around sample

Fig.4.5 Electrical connection to the steel

In this investigation, the specimens are kept fully saturated by continuously dripping with 5% NaCl solution as shown in **Fig.4.4**. Mats are placed over the tops to provide even distribution of NaCl solution. The rebar is used as anode. A stainless steel (SS) mesh is rolled around 600 mm length of specimen and tied together with metal ties in order to assure electrical continuity and is used as cathode The reinforcement extended 150 mm on both sides past the concrete to allow easy access for making electrical connections to the steel(**Fig.4.5**). The constant voltage of 20 V is impressed in order to accelerate corrosion by the DC regulated power supplier (DCRPS) as shown in **Fig 4.6**.

Fig. 4.6 Constant voltage supply of 20V

Stainless steel mesh used in the present study could supply 1000mA DC at 64V. The rebar is connected to the positive terminal of the external DC source and negative terminal is connected to the SS mesh. It is more common to maintain a constant voltage between the cathode and the anode (Soudki 2006; Gadve et al. 2009.

4.6 ULTRASONIC GUIDED WAVE INVESTIGATION

4.6.1 Method of Testing

For ultrasonic guided wave investigation, pulse-transmission (PT) testing method is adopted. In the pulse-transmisson method, 2 piezoelectric transducers with their longitudinal axis located perpendicular to and mounted on or near the surface of the test material are used to transmit and receive ultrasonic energy. The set-up for ultrasonic guided wave investigation is shown in **Fig. 4.7.** The ultrasonic waves are emitted from transmitter and are received on the other side by the reciever , enegy is converted into an electrical signal. The digital to analog converter (DAC) digitizes the input and received pulse and is displayed on the display. The signals received are in form of voltage-time (V-t) graphs. The ultrasonic test set-up in this study uses DPR-300 pulse receiver system (**Fig. 4.8**) and Karl deutsch contact transducers (**Fig. 4.9**)

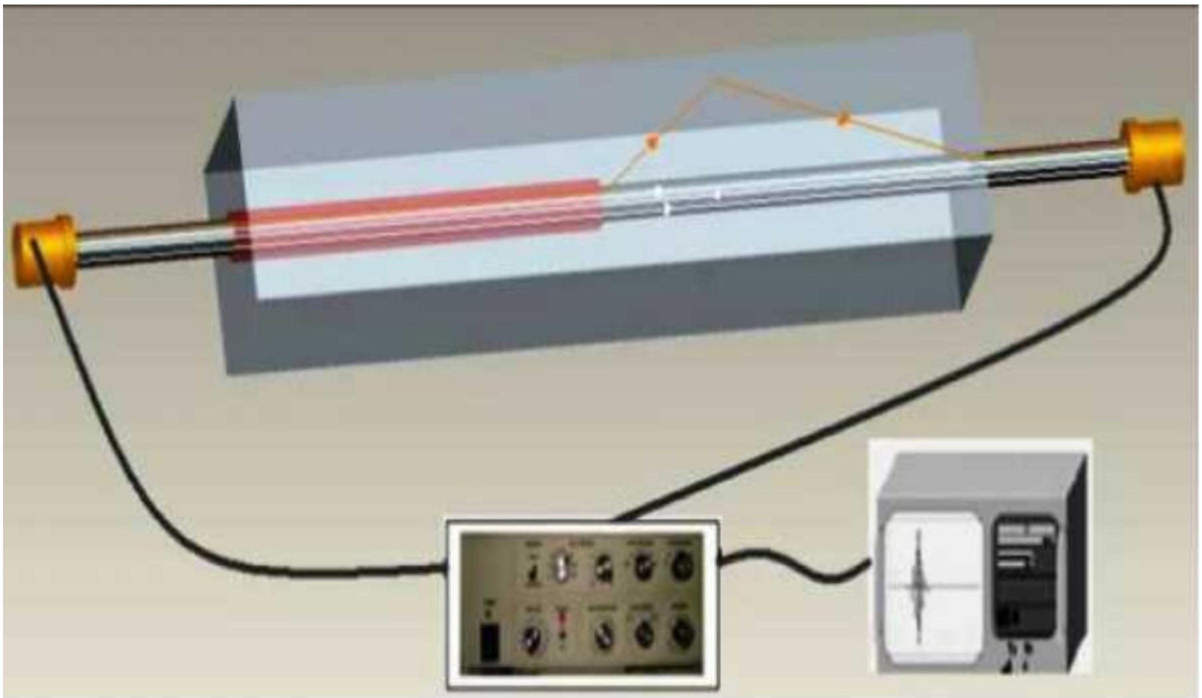


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Fig. 4.7: Set up for P-E Ultrasonic investigations (Sharma and Mukherjee)

Fig. 4.8: Pulse Receiver DPR300

Fig. 4.9: Contact type transducers

4.6.2 Selection of Excitation mode and Frequency

Reinforcing bars of 12 mm and 25 mm diameter embedded in concrete are used in the study. The selection of excitation mode and frequency for ultrasonic testing of bars in concrete is done using dispersion curves. Dispersion curves for a 12 mm bar embedded in concrete are plotted **(Fig. 4. 10**) for the steel and concrete properties mentioned in **Table 4.7.**

Only longitudinal modes have been considered in the study as the flexural and torsional modes experience high theoretical attenuation especially in bars in concrete. Guided longitudinal waves are again produced in the embedded bars by keeping compressional transducers parallel to the guiding configuration at the two ends of the bars embedded in concrete as in case of bars in air. 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 the bar to minimize leakage (Pavlakovic et al., 2001) are found to be the best for layered systems. The selection of frequencies for testing of embedded reinforcing bars is done based on the phase velocity dispersion curves **(Fig 4.10 a)**.

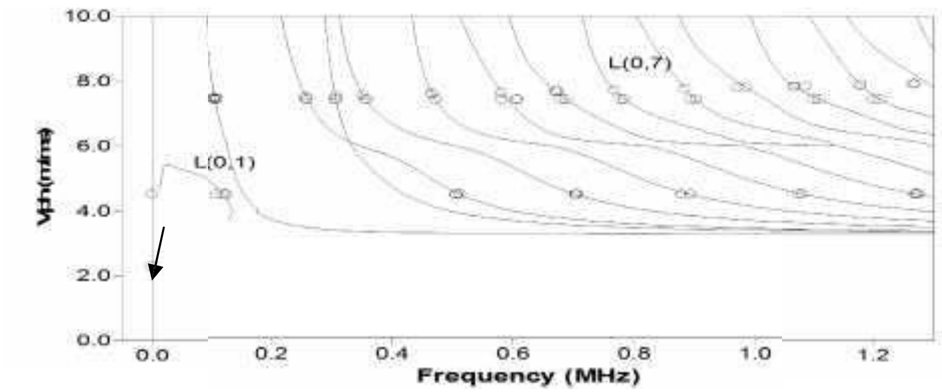
Phase velocity dispersion curves **(Fig. 4.10 a)** show the fundamental L (0, 1) mode starting at zero frequency with each higher order mode starting from a higher cut off frequency. Each of the higher modes shows a plateau region around the steel longitudinal bulk velocity line. But L (0, 7) mode shows 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 low leakage mode that propagates close to the longitudinal bulk velocity of steel.

Table 4.7: Material properties of steel & concrete used for modeling in Disperse (Pavlakovic et al., 2000)

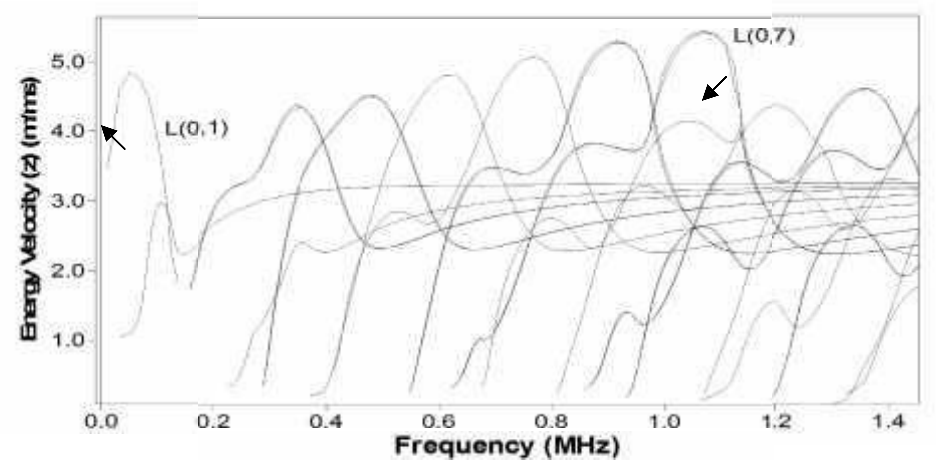
S.No.	MATERIAL PROPERTY	Steel	Concrete
1	Modulus, E (GPa)	210	29.6
2	Density(ρ),(kg/m3)	7932	2200
3	Longitudinal Attenuation (db /m)	0.003	0.2
4	Shear Attenuation (db/m)	0.008	0.5

5	Longitudinal Velocity (m/s)	5960	4100
6	Shear Velocity (m/s)	3260	2300
7	Poisson's Ratio	0.2865	0.27

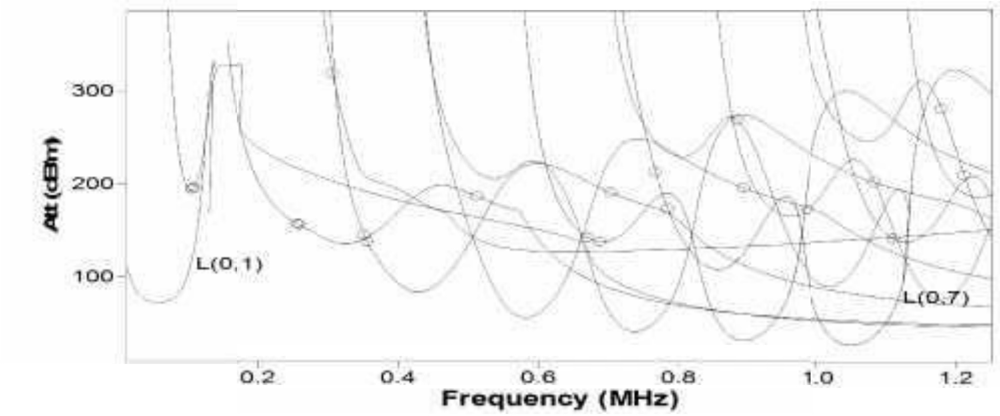
The plateau regions correspond to the points of maximum energy velocity **(Fig. 4. 10 b)** and minimum attenuation **(Fig 4.10 c)**. This L (0, 7) mode for 12 mm bar in concrete is chosen for testing because the lowest order low leakage mode has the lowest overall attenuation and is most useful in NDT. At a frequency of 3.5 MHz, the L (0, 7) mode exhibits global attenuation minima of 34.7dB/m and is selected for testing of 12 mm bar in concrete. Similarly, for a 25 mm bar embedded in concrete, ideal frequency for ultrasonic testing is 1 MHz and L (0, 7) mode **(Fig 4.10).** This 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. Hence, L (0, 7) modes at 1 MHz and 3.5 MHz for 25 mm and 12 mm diameter bars embedded in the concrete are selected for further ultrasonic investigations. These frequencies and modes are utilized for ultrasonic monitoring of simulated and then actually corroding RC specimens.



(a) Phase velocity Vs Frequency



(b) Energy Velocity Vs Frequency



(c)Attenuation Vs Frequency

Fig. 4.10: Dispersion curves for 25mm dia bar (*Sharma & Mukherjee, 2010*)

From the display, the time of flight between the excitation and reflected pulse is measured. Knowing the velocity of the wave

$$D = Vt \tag{4.1}$$

where,

D = Distance travelled by the signal from transmitter to reciever end,

V = Velocity of wave

t = Time of Flight.

Now in this case the distance travelled by the wave would be equal to the length of the bar that would be 1000 mm and the speed of wave would be the speed of wave varies from 5 km/s to 6 km/s.

Therefore the time at which the peak has to be noticed would be between 400µs and 500 µs.

4.7 Destructive Tests

4.7.1 Flexure strength : The beam specimens are subjected to two point loading with the help of universal testing machine , maximum peak load taken by the beam and maximum deflection undergone is noted. Flexural strength and maximum deflection is then compared with increase in exposure to corrosion.

From the peak load we can calculate flexural strength

$$\mathbf{f_t = P*10^3*100/150^3\ kN/mm^2} \qquad (4.2)$$

where P = peak load taken by the beam

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

4.8 CLOSING REMARKS

In this chapter, monitoring of corrosion in RC BEAMS by ultrasonic guided waves technique is discussed in detail. Corrosion monitoring gives a bright picture of the various changes in the structural behaviour of the building. Thus, we can say proper monitoring of structures for corrosion performance and taking suitable measures at appropriate time can be a lot of benefit.

CHAPTER 5

RESULTS AND DISCUSSIONS

5.1 INTRODUCTION

In this work, deterioration in RC beams subjected to varying degree of corrosion was studied by the applicability of ultrasonic guided waves. Effect of varying diameter on corrosion parameters is also studied. Since natural corrosion would take long time to occur, it is accelerated by impressing current technique. The effect of levels of corrosion on the static parameters of modulus of rupture and maximum deflection of beam at peak load when subjected to two point loading and percentage mass loss was studied. In the end an attempt has been done to correlate the static parameters with ultrasonic voltages.

5.2 ULTRASONIC GUIDED WAVE MONITORING

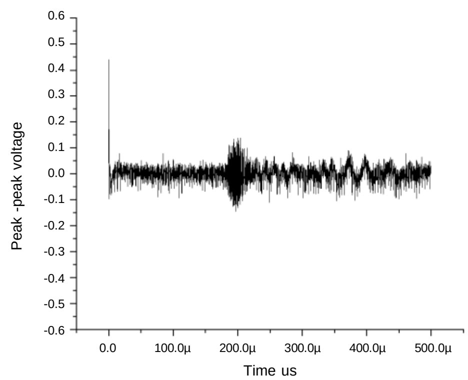
Ultrasonic guided wave monitoring can be done using pulse-echo method and pulse-transmission method. However, in this experimental work, pulse-transmission method has been used to monitor various stages of corrosion in R.C beam specimen. For that purpose two modes i.e. core seeking mode and surface seeking mode has been used to catch various corrosion phenomenon i.e. de lamination and pitting. It has been already established that the surface seeking mode is very much able to detect the de lamination of rebar with the concrete cover and the core seeking mode detects the pitting that occurs on rebar due to corrosion.(Sharma & Mukherjee,2013)

5.2.1 Surface Seeking Mode: For RC Beams with 25 mm Bars

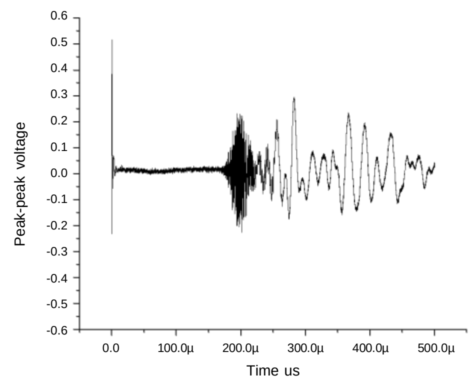
From the **Fig.5.1**, it can be clearly seen that the peak to peak voltage signal changes minutely for few days after the initiation of corrosion in RC beam specimen. But after 5 days of accelerated corrosion in RC beam specimen there is a significant rise in the signal strength up to 9 days. This period in which the signal strength reaches maximum signifies the de lamination of the rebar from the concrete cover. After 9 days it can be seen that there is a steep fall in the signal strength which corresponds to the pitting of bar due to corrosion.

The signatures of ultrasonic guided wave monitoring of RC beam subjected to accelerated corrosion using impressed current technique for 0,7,9,12,18,22,25 and 30 days is shown in **Fig.5.1.**

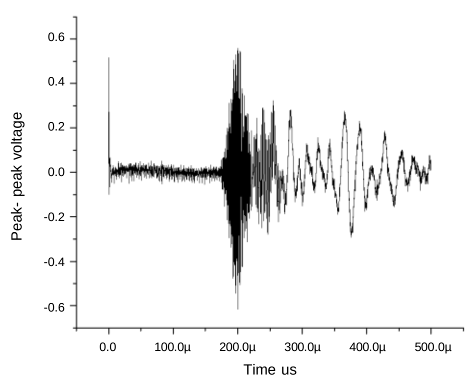
Fig.5.1 (a), (b), (c), (d), (e), (f), (g)& (h) shows Signature peaks of the RC beam fitted with 25mm bar in pulse transmission at 0.1MHz.



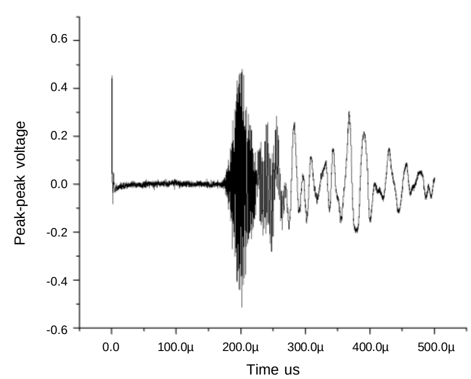
(a) HEALTHY SIGNAL



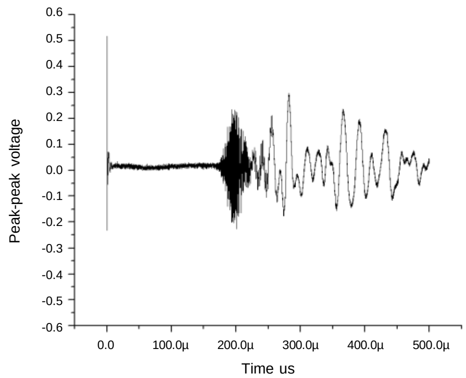
(b) AFTER 7 DAYS



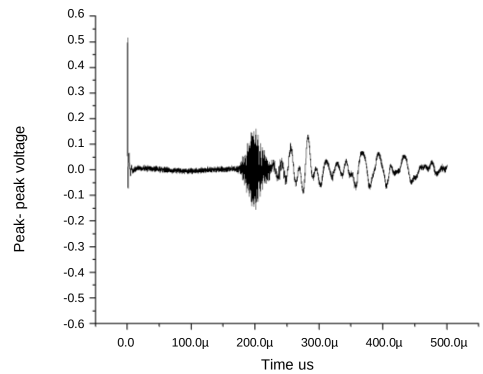
(c) AFTER 9 DAYS



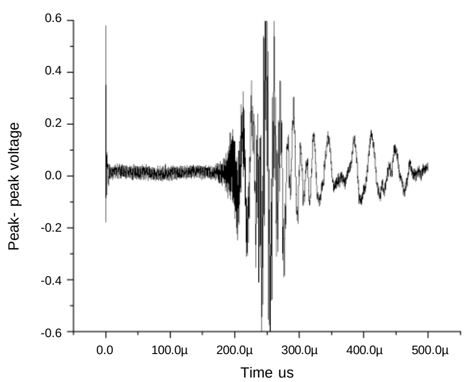
(d) AFTER 12 DAYS



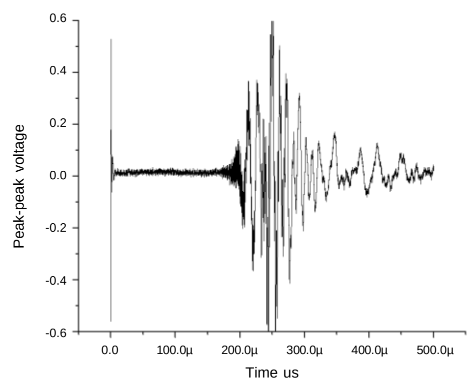
(e) AFTER 18 DAYS



(f)AFTER 22 DAYS



(g) AFTER 25 DAYS



(h) AFTER 30 DAYS

Initially, the reinforcing bar has a good bond with the surrounding concrete. As the corrosion takes place, it results in the formation of corrosion products and gets deposited on the length of bar. This delaminates the rebar from the surrounding concrete. Therefore, as the corrosion progresses, the delamination keeps on increasing which creates a barrier around the rebar and the leakage of the signal ceases. Due to this, the signal keeps on increasing with the increasing rate of corrosion upto 9 days. This is depicted by the signal rise as shown in the **Fig.5.1**. This continues till the whole bar delaminates from the concrete (9 days). Thereafter, the presence of chlorides results in deterioration of bar in the form of pits and mode shows continuous fall.

The trends of transmitted pulse using surface seeking mode has been plotted as in **Fig.5.2**

Fig. 5.2 shows P-T Trend for RC Beams fitted with 25 mm dia bar monitored for 30 days with 0.1 MHz transducer .

5.2.2 Core Seeking Mode: For RC Beams with 25 mm Bars

Fig.5.3 shows ultrasonic voltage trends of the received signal in pulse transmission in RC beam specimens using core seeking mode L (0, 7) at 1 MHz. The beam shows no significant change in voltage amplitude of the transmitted pulse till 6 days. After 6 days, there is a continuous drop in the amplitude of this pulse till it disappears completely on the 30th day. This point towards the drastic non-uniform area loss in the form of pits on the whole length of the bar due to severe chloride corrosion. The widespread loss of area is confirmed visually by opening the beam. As corrosion progresses, there is increase in loss of energy due to scattering, multiple reflections and mode.The extent of damage in the embedded bar can be ascertained by observing the peak-peak voltage ratio trends of the transmitted peak conversions. Hence, there is a drastic fall in signal amplitude

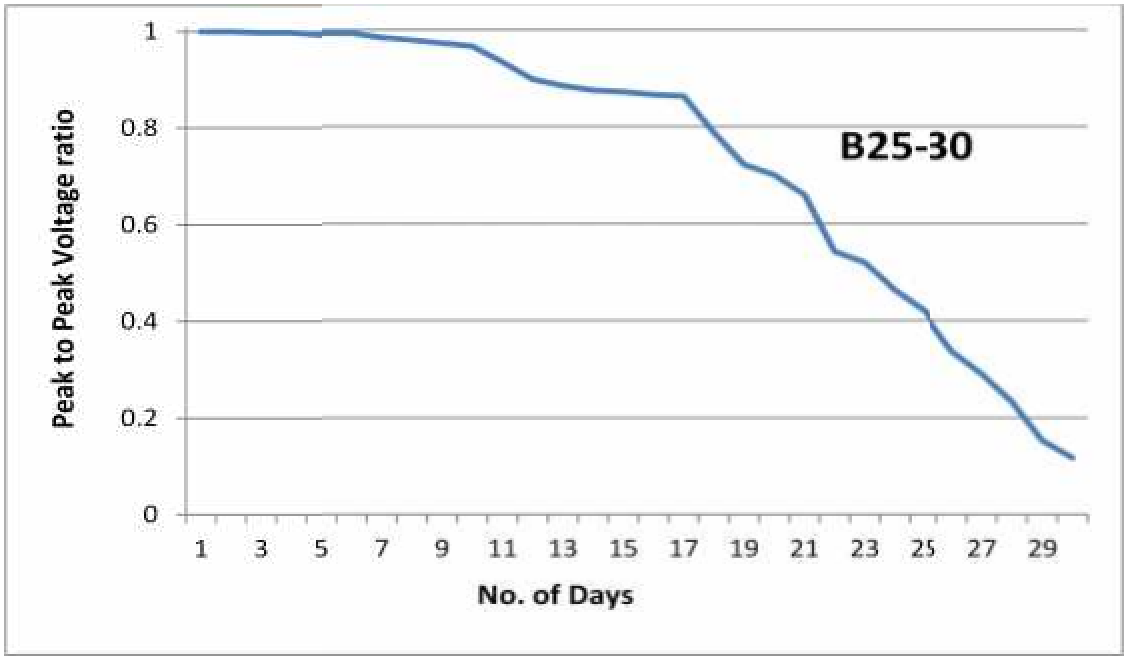
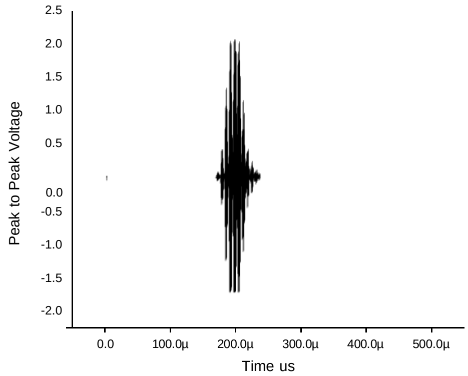


Fig. 5.3 shows P-T Trend for RC Beams fitted with 25 mm dia bar monitored for 30 days with 1 MHz transducer .

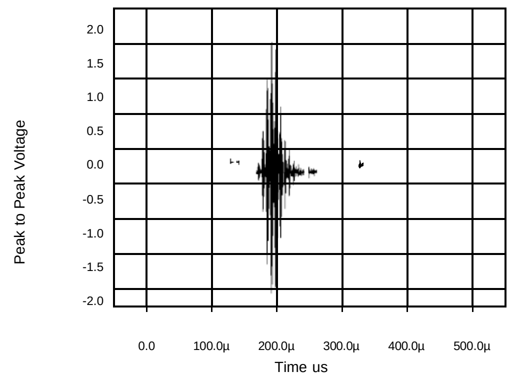
By observing the peak to peak voltage trend of transmitted peak as shown in **Fig: 5.3**, it can be said that by increasing the age of corrosion from 0-days to 30-days, the magnitude of transmitted peak decreases relative signal attenuation of the transmitted pulse, and can relate to the extent of the damage in the bar. Thus, peak-to-peak voltage amplitudes of transmitted peaks in pulse transmission method closely relate to the extent of damage.

The signatures of ultrasonic guided wave monitoring of RC beam subjected to accelerated corrosion using impressed current technique for 0,7,12,16,18,20,22 and 30 days is shown in **Fig.5.4**

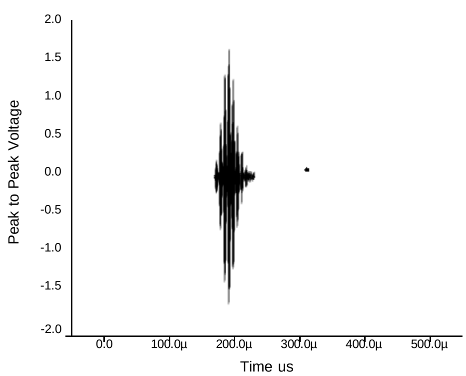
Fig.5.4 (a), (b), (c), (d), (e), (f), (g) & (h) Signature peaks of the RC beam fitted with 25 mm bar in pulse transmission at 1 MHz.



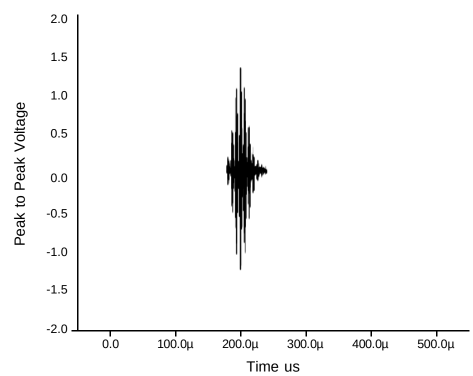
(a) HEALTHY SIGNAL



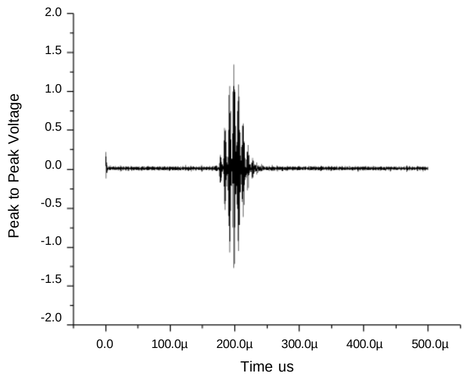
(b) AFTER 7 DAYS



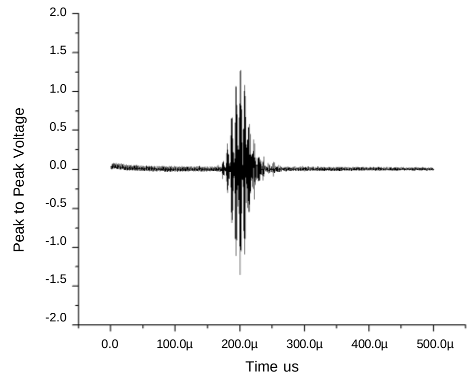
(c) AFTER 12 DAYS



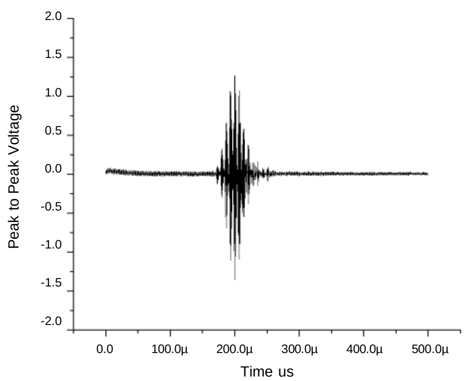
(d) AFTER 16 DAYS



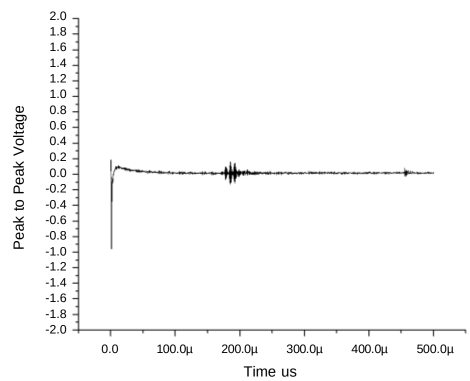
(e) AFTER 18 DAYS



(f)AFTER 20 DAYS



(g) AFTER 22 DAYS



(h) AFTER 30 DAYS

5.3 EFFECT OF BAR DIAMETER ON ULTRASONIC GUIDED WAVES SIGNALS WITH CORROSION.

5.3.1 Core seeking for RC beams with 12mm bars

In case of 12 mm bar, the ultrasonic pulse transmission readings are only taken with L(0,7) mode at 1 MHz (Sharma and Mukherjee,2010). The pulse transmission studies where corrosion is simulated as the loss of bond indicates that the transmitted signal strength goes up due to prevention of leakage into the concrete affected through the loss of bond. Contrary to this observation, the transmitted pulse steadily losses strength as the corrosion progresses. It disappears completely on the 18th day as shown in **Fig. 5.5** because high frequency modes are core sensitive mode, sensitive to only pitting of bar.

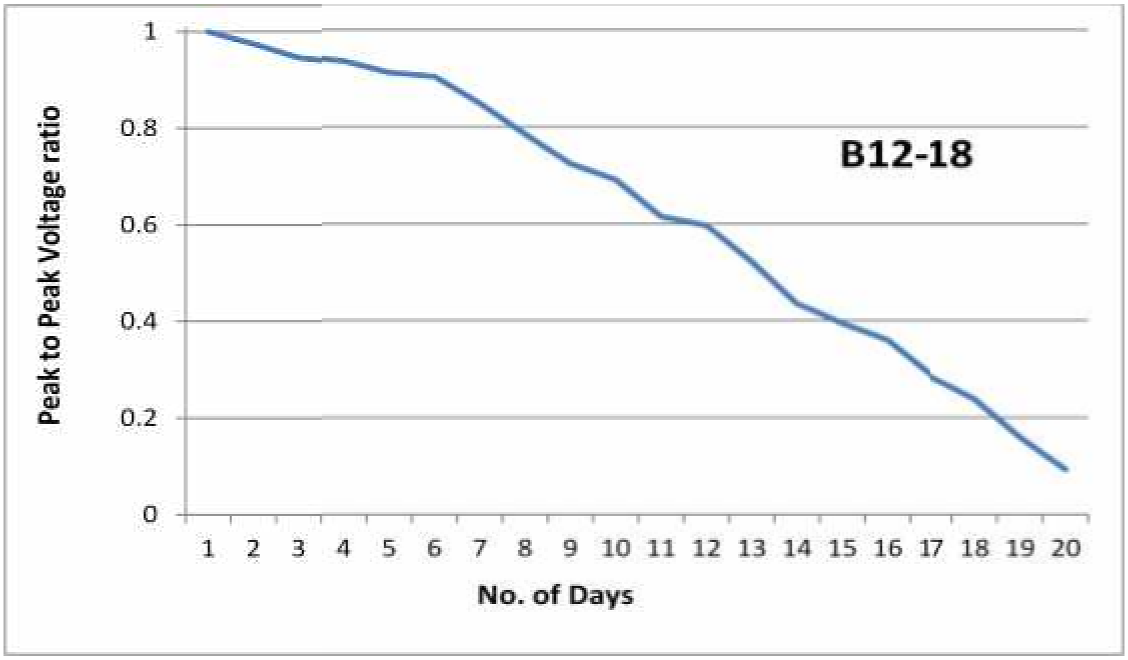
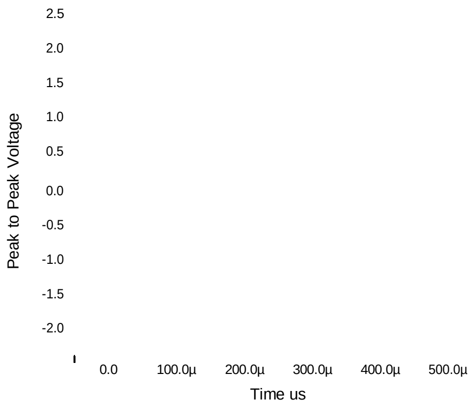


Fig. 5.5 shows P-T Trends for RC Beams fitted with 12mm bar samples monitored for 18 day with 1 MHz transducer .

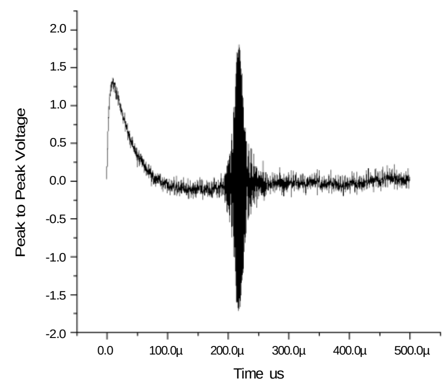
The low frequency mode cannot be used for small diameter bars because the diameter of probe with low frequency is very high and hence cannot be experimentally used.

The signal continuously falls due to pitting effect of corrosion resulting in mode scattering and reflections as shown in **Fig. 5.6.**

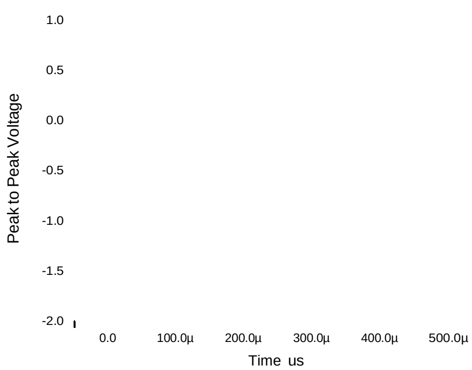
Fig.5.6 (a), (b), (c) &(d) Signature peaks of the RC beam specimen with 12 mm bar in pulse transmission at 1MHz.



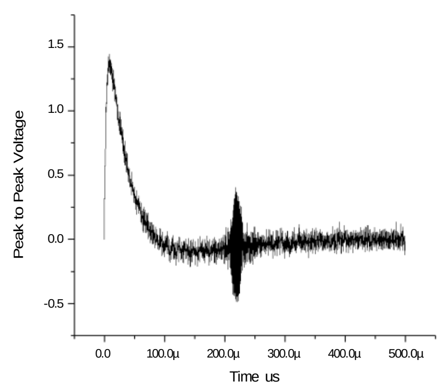
(a) HEALTHY SIGNAL



(b) AFTER 7 DAYS



(c) AFTER 12 DAYS



(d) AFTER 18 DAYS

As the diameter of bar changes from 25 mm to 12 mm , the corrosion affects the bar and the bar deteriorates rapidly in 18 days as compared to 30 days in 25 mm bar . The trend of signal fall remains same using core seeking mode.

5.4 EFFECT OF CORROSION ON FLEXURAL STRENGTH

Basic aim of the study is to investigate the effect of corrosion in similar conditions with different bars commonly used in civil engineering applications. The effect of corrosion is measured/monitored using ultrasonic guided waves and static tests of measurement of flexural strength and deflections . Destructive test of mass loss are also studied. Another aim is to establish correlation between Ultrasonic Pulse Transmission voltages and other static and destructive parameters.

Cracks in RC Structures occur when they are subjected to a tension that creates a tension stress in the concrete equal to the modulus of rupture. The modulus of rupture represents the tensile strength of the concrete. Therefore with the increase in corrosion of structure , the bar which takes mainly the tensile stress will reduce the load taking capacity and decrease in modulus of rupture.

Fig.5.7 Beams under 2 point load testing

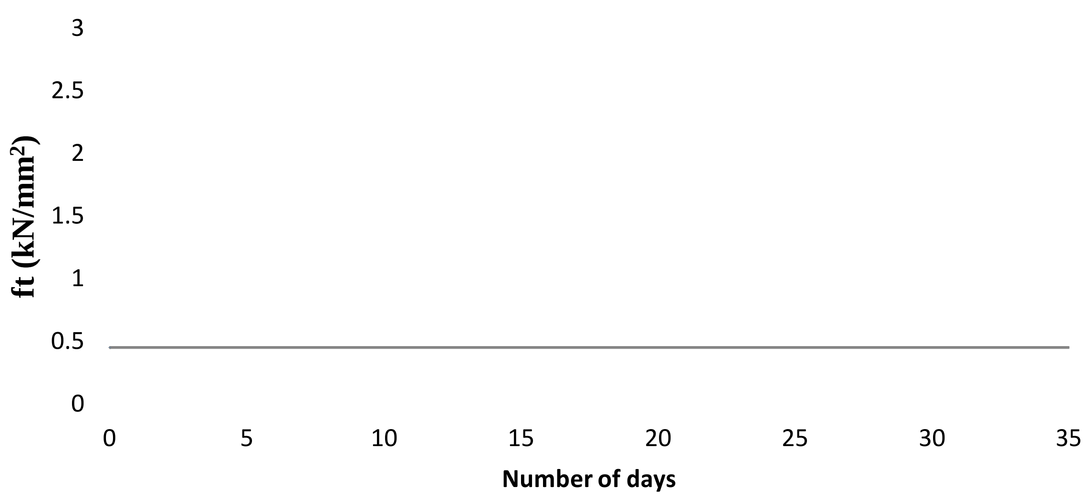
The flexural strength test conducted on RC beams with increasing exposure to corrosion represents the static load carrying capacity of beams with increasing corrosion. The maximum load taken by the specimen decreases with increase in exposure to corrosion .It is observed in **Table 5.1** and **Table 5.2** as the bar gets corroded less tensile stress is taken by the bar. **Fig.5.8** represents the trend and gives us the information how modulus of rupture decreases with increase in number of days for which corrosion is done on beams reinforced with 25 mm & 12 mm dia bars.

Table 5.1 Modulus of rupture for various beam specimens for 25 mm bar.

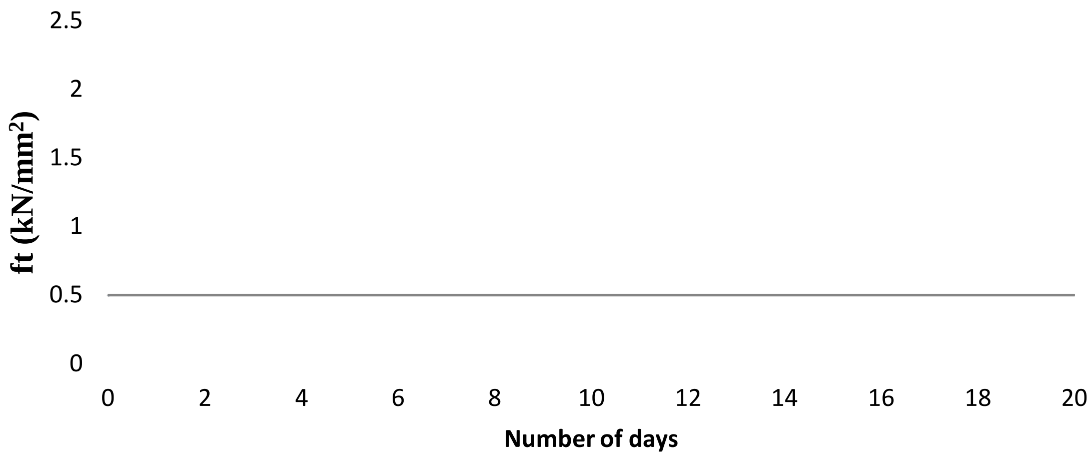
Specimen Details	Flexural load (kN)	Modulus of Rupture $f_{t,}$ kN/mm^2
B25 - 0	90.7942	2.6902
B25 - 3	84.0948	2.4917
B25 - 6	72.1338	2.1373
B25 - 12	70.6995	2.0948
B25 -18	60.939	1.8056
B25 -30	52.0425	1.542

Table 5.2 Modulus of rupture for various beam specimens for 12 mm bar.

Specimen Details	Flexural load (kN)	Modulus of Rupture $f_{t,}$ kN/mm^2
B12 – 0	68.414	2.0271
B12 – 6	56.531	1.675
B12 – 18	29.46	0.873



(a) Modulus of Rupture v/s Number of days of Corrosion for 25 mm bar RCC beams



(b)Modulus of Rupture v/s Number of days of Corrosion for 12 mm bar RCC beams

Fig. 5.8 (a)&(b) Effect on modulus of rupture with increase in number of days of corrosion for 25 mm bar and 12 mm bar respectively.

It is observed that irrespective of bar diameter modulus of rupture decreases with increasing exposure to corrosion due to increasing deterioration. Also the modulus of rupture values for larger diameter bar is more than that for smaller diameter bar. Hence it can be concluded that corrosion affects the larger diameter bar lesser than smaller diameter bar because of increased cross-sectional area.

5.5 EFFECT OF CORROSION ON MAXIMUM DEFLECTION

In addition to flexural strength determination with increasing corrosion , the effect on maximum deflection under flexural loading is also investigated. It is observed from **Table 5.3** and **Table 5.4** increasing number of days of corrosion the strength of RC beam decreases resulting in decrease in load carrying capacity of beam. When these beams are subjected to flexural loading it will fail at less deflection. Maximum deflection decreases with increasing corrosion for both 25 mm and 12 mm beams. **Fig.5.9** shows the trend of maximum deflection with increasing corrosion. It clearly shows that ultimate deflection capacity also decreases with increase in percent mass loss as the corrosion level increases. It shows that there is a decrease in deflection capacity even at initial stages i.e. from 0 to 6 days of corrosion**.**

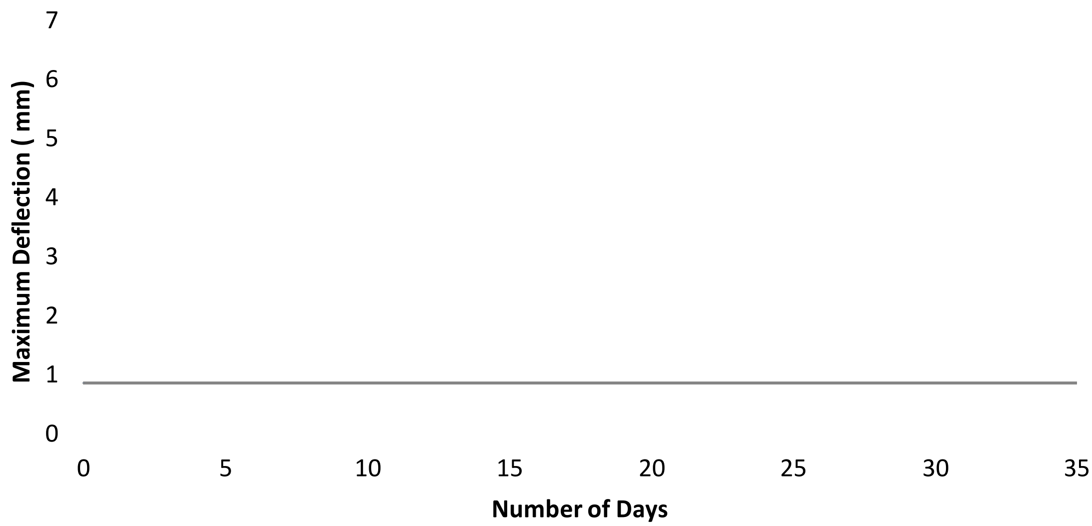
Table 5.3 Maximum deflection of various beams specimens for 25mm bar

Specimen Details	Flexural load (kN)	Maximum Deflection (mm)
B25 - 0	90.7942	6.045
B25 - 3	84.0948	5.985
B25 - 6	72.1338	5
B25 - 12	70.6995	4.83
B25 -18	60.939	4.6
B25 -30	52.0425	3.45

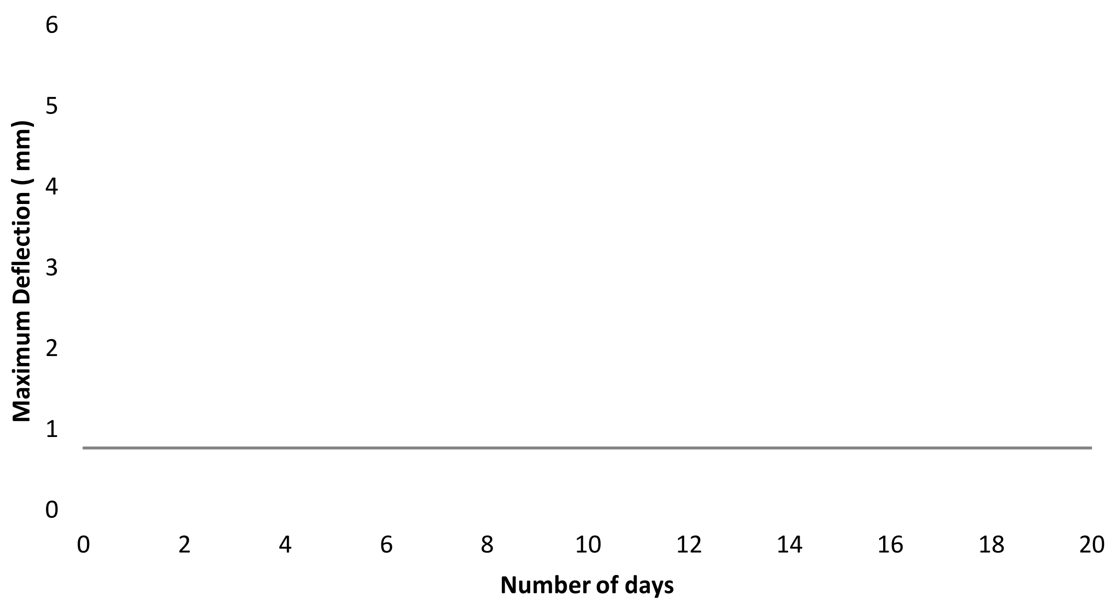
Table 5.4 Maximum deflection of various beams specimens for 12mm bar

Specimen Details	Flexural load (kN)	Maximum Deflection (mm)
B12 – 0	68.414	5.48
B12 – 6	56.531	4.24
B12 – 18	29.46	3.3

On comparing B-25 beams with B-12 beams , it is observed that maximum deflection are lesser for smaller diameter bar (12 mm bar) than 25 mm bar. B-12 beams fail at lower load and smaller deflections.



(a)Maximum Deflection v/s Number of days of Corrosion for 25 mm bar RCC beams



(b)Maximum Deflection v/s Number of days of Corrosion for 12 mm bar RCC beams

Fig.5.9 (a)&(b) shows effect on maximum deflection with increase in number of days of corrosion for RC Beams fitted with 25 mm & 12 mm bars respectively.

5.6 MASS LOSS DETERMINATION

Following the mechanical testing, the beams were dismantled with a hammer to retrieve the reinforcing steel in concrete. Once obtained, corroded portion of bar

Fig.5.10 Corroded Bar of 12 mm dia

Fig.5.11 Corroded Bars of 25 mm dia

was trimmed, cleaned to remove all corrosion products with acetone and concrete, and then weighed. The mass loss was then calculated relative to a predetermined benchmark called the control mass. Control mass was calculated for fresh uncorroded bars. The corroded reinforcing bars were characterized by percent mass loss (ML), which was calculated by eq. where *m* denotes mass and the subscript "i" represents the initial or reference mass and "cor" represents the residual mass.

$ML(\%) = (M_i – M_f)/ M_i * 100$

Where,**Mi = Initial or Reference Mass**

M_f = Final mass

ML= Mass loss

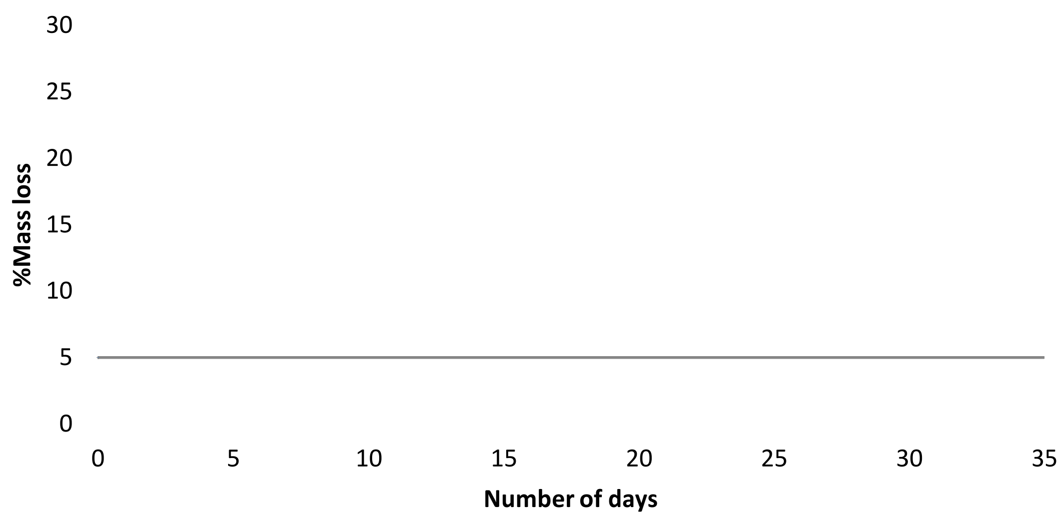
Fig: 5.12(a) clearly show that mass loss increases with the increases in corrosion level. It was noticed that beams of 25 mm bars were corroded for 3, 6 days, 12 days 18 days and 30 days has percent mass 4.54% ,11.48%, 19.05%, 22.75%, and 26.48% respectively.

Table 5.5 Percent mass loss of various beams specimens for 25 mm bar

Specimen Details	Flexural load (kN)	% Mass Loss
B25 - 0	90.7942	0
B25 - 3	84.0948	4.54
B25 - 6	72.1338	11.48
B25 - 12	70.6995	19.05
B25 -18	60.939	22.75
B25 -30	52.0425	26.48

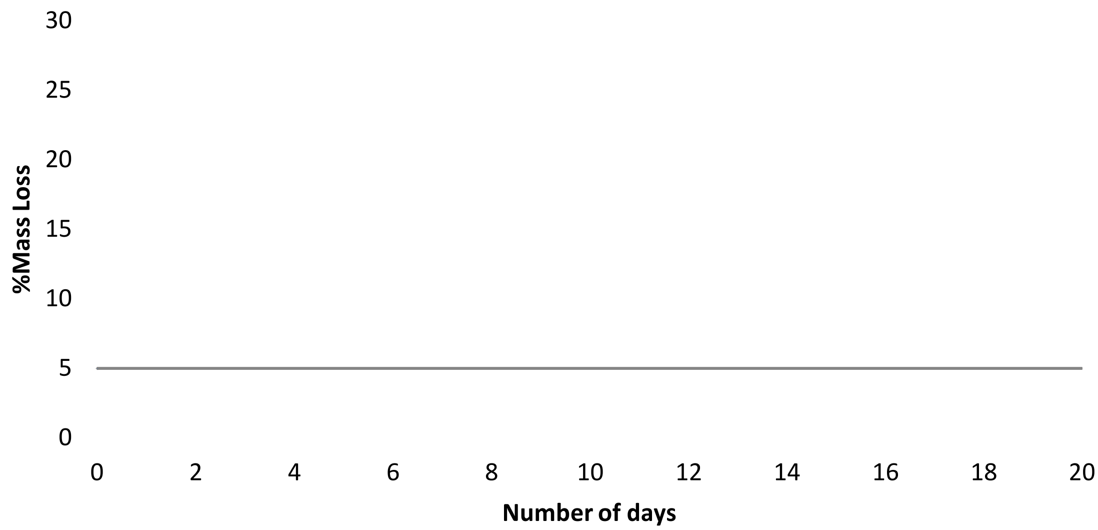
Table 5.6 Percent mass loss of various beams specimens for 12 mm bar

Specimen Details	Flexural load (kN)	% Mass Loss
B12 – 0	68.414	0
B12 – 6	56.531	12.87
B12 – 18	29.46	24.54



(a)%Mass loss v/s Number of days of Corrosion for 25 mm bar RCC beams

Fig: 5.12(b) clearly show that mass loss increases with the increases in corrosion level. It was noticed that beams of 12 mm bars were corroded for 6 days and18 days has percent mass 12.87%, and 24.54% respectively.



(b)%Mass loss v/s Number of days of Corrosion for 12 mm bar RCC beams

Fig.5.12 (a)&(b) shows effect on % mass loss with increase in number of days of corrosion for 25 mm & 12mm bars.

From the % Mass loss , it is observed that with increasing corrosion level , the % Mass loss increases pointing towards marked pitting due to chloride corrosion. Similar trends are observed with 12 mm bar. At 18 days the % mass loss in 12 mm bar is 24.54% relative to 22.75% in 25 mm bar.

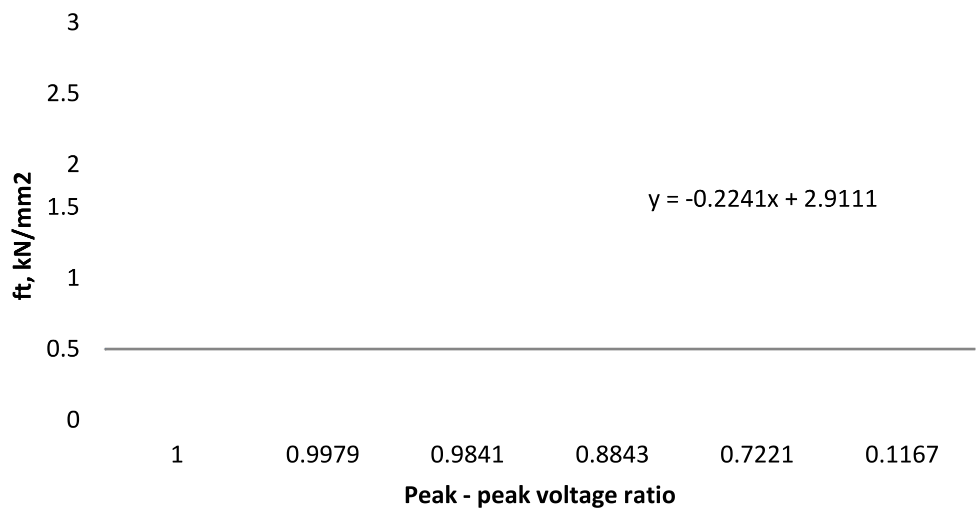
5.7 CORRELATION BETWEEN ULTRASONIC VOLTAGE AND DESTRUCTIVE PARAMETERS

5.7.1 Relation between ultrasonic voltage and modulus of rupture

It is observed from **Table 5.7** and **5.8** that irrespective of bar diameter modulus of rupture decreases with increasing exposure to corrosion due to increasing deterioration and follows linear relation with peak – peak voltage ratio. Peak – peak voltage also decreases because of drastic non-uniform area loss in the form of pits on the whole length of the bar due to severe chloride corrosion.

Table 5.7 Peak – peak voltage ratio , modulus of rupture of various beams for 25mm bar

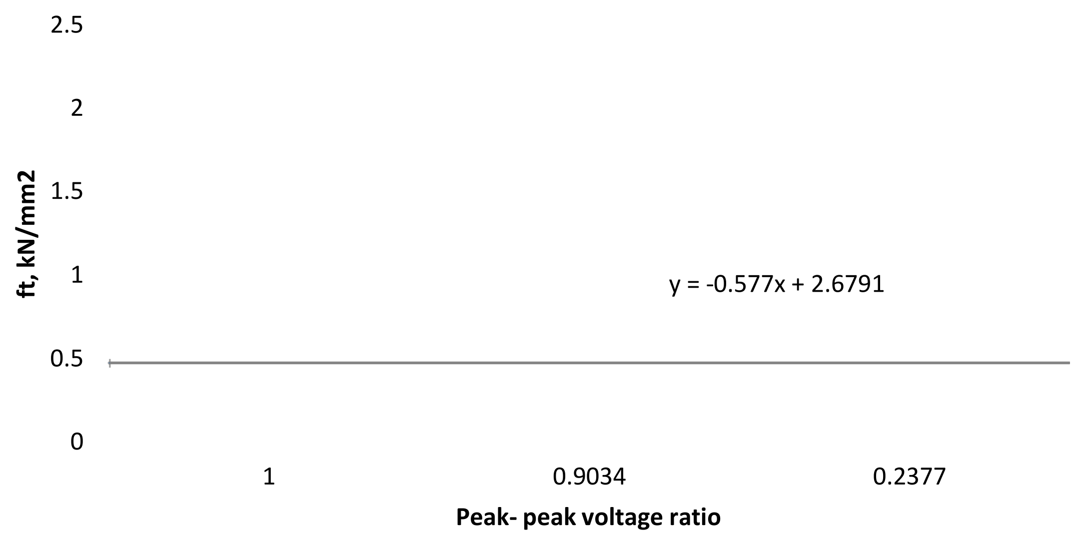
Specimen Details	Peak-Peak Voltage ratio	Modulus of Rupture $f_{t,}$ kN/mm^2
B25 - 0	1	2.6902
B25 - 3	0.9979	2.4917
B25 - 6	0.9841	2.1373
B25 - 12	0.8843	2.0948
B25 -18	0.7221	1.8056
B25 -30	0.1167	1.542



5.13(a) f_t v/s Peak- peak voltage ratio for 25 mm bar RCC beams

Table 5.8 Peak – peak voltage ratio , modulus of rupture of various beams for 12mm bar

Specimen Details	Peak-Peak Voltage ratio	Modulus of Rupture $f_{t,}$ kN/mm^2
B12 – 0	1	2.0271
B12 – 6	0.9034	1.675
B12 – 18	0.2377	0.873



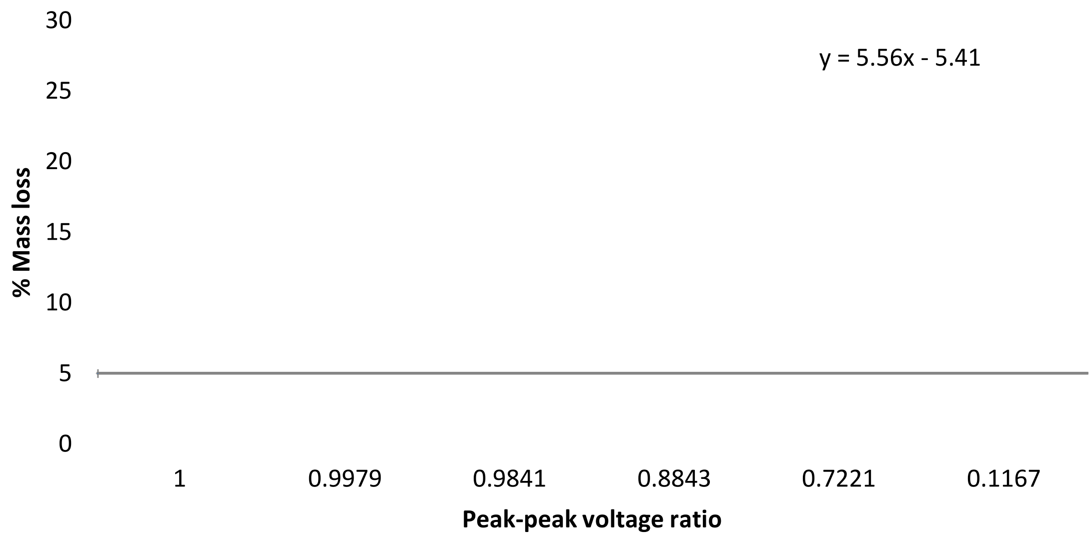
5.13(b) f_t v/s Peak- peak voltage ratio for 12 mm bar RCC beams

5.7.2 Relation between ultrasonic voltage and percent mass loss

It is observed from **Table 5.9** and **5.10** there is an inverse relation between peak- peak voltage ratio and percent mass loss , as the peak- peak voltage ratio decreases percent mass loss increases because of increase in exposure to corrosion which causes deterioration of bar.

Table 5.9 Peak – peak voltage ratio , percent mass loss of various beams for 25mm bar

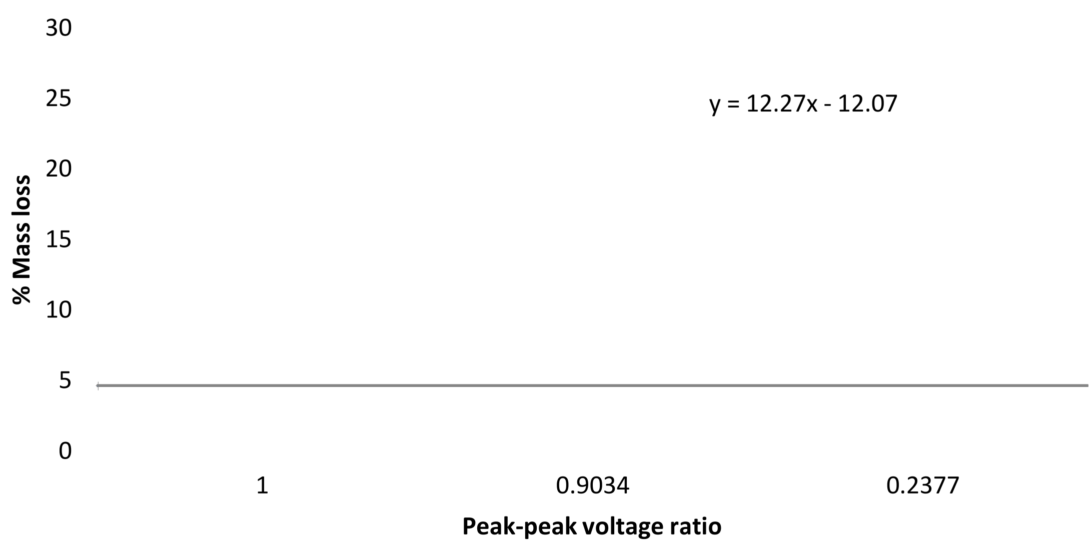
Specimen Details	Peak-Peak Voltage ratio	% Mass Loss
B25 - 0	1	0
B25 - 3	0.9979	4.54
B25 - 6	0.9841	11.48
B25 - 12	0.8843	19.05
B25 -18	0.7221	22.75
B25 -30	0.1167	26.48



5.14(a) Percent mass loss v/s Peak- peak voltage ratio for 25 mm bar RCC beams

Table 5.10 Peak – peak voltage ratio , percent mass loss of various beams for 12mm bar

Specimen Details	Peak-Peak Voltage ratio	% Mass Loss
B12 – 0	1	0
B12 – 6	0.9034	12.87
B12 – 18	0.2377	24.54



5.14(b) Percent mass loss v/s Peak- peak voltage ratio for 12 mm bar RCC beams

5.8 CLOSING REMARKS

This chapter highlights the results obtained from the experiments done during the thesis work. It shows results of RC beams subjected to different levels of corrosion and its effect on deflection and modulus of rupture behavior when the RC beams were tested under static loading.

The beam tests show a reduction in both the load-carrying capacity and the deflection capacity with this increase in corrosion level. This is due to the known effects of reductions in steel-concrete bond, reinforcing steel cross-sectional area, and concrete cracking and spalling due to corrosion. In this study, a decrease in load as well as deflection capacity is regarded as an indication of reduced ductility.

The ultrasonic testing of the bar at different stages and ages of corrosion and the correlation between ultrasonic and destructive test of mass loss, justifies the ability of ultrasonics to predict the level of deterioration of the embedded bars in reinforced concrete.

For 25 mm bar as cross-section is more, mass loss is less with increasing level of corrosion. It also points towards less effect of corrosion deterioration in larger diameter bars than smaller diameter bar. It is recommended to use larger diameter bar in severe corrosion environment.

CHAPTER 6

CONCLUSIONS

The ultrasonic monitoring of RC beams subjected to different levels of accelerated corrosion and subsequently investigating the effect of corrosion on load carrying mechanism and deflections is studied. Following major conclusions can be drawn from this study.

1. By observing the peak to peak voltage trend of transmitted peak in ultrasonic monitoring it is observed with core seeking mode that with 25 mm and 12 mm bar with increasing corrosion the magnitude of transmitted peak falls . Relative signal attenuation of the transmitted pulse can relate to the extent of the corrosion in the bar. Thus, peak to peak voltage amplitudes of transmitted peaks in pulse transmission methods closely relate to the extent of damage with increasing exposure to corrosion.

2. Ultrasonic pulse transmission with surface seeking mode in 25 mm bar the magnitude of transmitted peak first rises and then falls, this indicates the initial delamination of bar causing rise of signal due to reduce leakage into concrete which is picked up by this mode.Later on the pitting predominantly which causes overall fall in signal at later ages.

3. Using the particular guided waves modes, corrosion in RC beam can be successfully monitored .

4. After completing the corrosion process beams were subjected to static two-point loading at different stages of corrosion , load deflection behavior of the beams was studied . Load-deflection reveal much information concerning the behavior of RC beams and they are notably altered with the progression of corrosion. Static load test show the following results:

- As the exposure time of RC beams to corrosion environment increases , load carrying capacity of beams decreases.
- Modulus of rupture decreases with increase in corrosion level.
- Maximum deflection decreases with increase in corrosion level.

5. It is observed that it is advisable to use larger diameter bars to reduce the effect of corrosion in RC beam because of larger cross sectional areas which increases the load carrying capacity of beams and causes less percent mass loss.

6. Percent mass loss of the corroded bars was calculated and it was observed that mass loss increases with increase in age of corrosion at different levels. Maximum mass loss of 26.48% was calculated for beam corroded for 30 days with 25 mm bar.

7. The ultrasonic voltages in core seeking mode can be correlated with destructive parameters of mass loss and load carrying capacity of the beam to facilitate non destructive evaluation

8. The correlation between ultrasonic voltage and modulus of rupture shows a increasing linear trend with increasing corrosion.As corrosion increases , ultrasonic voltage decreases and so does the modulus of rupture.

The correlation between ultrasonic voltage and mass loss shows a decreasing linear variation . As corrosion increases mass loss increases but ultrasonic voltage decreases.

9. The degradation of bar at 6 days is also confirmed by 11.48% mass loss and 20.55% in modulus of rupture value. Hence, it points towards the importance of corrosion monitoring using Ultrasonic guided waves since it indicates huge degradation in intial stages of corrosion.

Further Scope of Work

Initial effect of corrosion on RC beams need to be studied in detail since it affects the RC beam badly and reduces its static parameters . It can be assisted by other corrosion monitoring NDT procedures like Acoustic emission technique, Half cell potential etc.

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