

CORROSION MONITORING OF FRP PROTECTED RC STRUCTURE USING ULTRASONIC GUIDED WAVE AND ACOUSTIC EMISSION TECHNIQUE

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in partial fulfillment of the requirements
for the degree of

**MASTER OF ENGINEERING
IN
STRUCTURE ENGINEERING**

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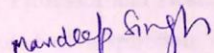


**DEPARTMENT OF CIVIL ENGINEERING
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JULY 2016**

DECLARATION

I, Mandeep Singh Walia, hereby declare that this thesis entitled "**CORROSION MONITORING OF PASSIVELY PROTECTED RC STRUCTURES USING VARIOUS DESTRUCTIVE AND NON DESTRUCTIVE TECHNIQUES** " in fulfillment of the requirement for the award of the Degree of **Master of Engineering in Civil Structure Engineering** and submitted in the Civil Engineering Department, Thapar University, Patiala is an authentic record of my work carried out during a period from July 2015 to July 2016 under the supervision of **Dr. Shruti Sharma, Associate professor**, Department of Civil Engineering and **Dr. Sandeep Sharma, Assistant professor**, Department of Mechanical Engineering, Thapar University, Patiala .This matter presented in this thesis has not been submitted by me for the award of any other degree of this or any other University.

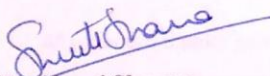
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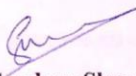

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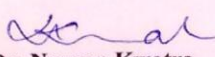
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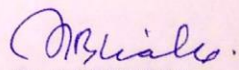
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ABSTRACT

Non-destructive testing is needed for localizing and characterizing the growing damage in existing structures and also for the quality control of new structures. Visual inspection is a commonly used method; however it is not very suitable for early detection of damage and is very much dependent on the experience of the inspector. Ultrasonic guided wave monitoring and acoustic emission technique are the methods that can be used effectively for the structural health diagnosis.

In the present study, a RC Cylinders, of dimensions 150mm diameter and 300mm length has an embedded steel bar of dia. 25 mm and 600mm in length, is subjected to accelerated induced corrosion. Ultrasonic guided wave monitoring is done periodically after every 24 hours for 28 days along with this regular AE monitoring 24 hours a day for 28days was done.. A mode with minimum attenuation and mode shape that is sensitive to particular type of damage due to corrosion is chosen from dispersion curves. For this purpose, Pulse-echo investigation is used using peizo-electric transducers. Also, AE sensors detecting acoustic emission signals are mounted on the RC Cylinder specimen before it is subjected to accelerated corrosion. AE set up simultaneously records the events and hits continuously for 28 days relating to crack initiation and progression due to corrosion in RC beams as the exposure to corrosion increases. It is observed that corrosion of reinforcing bars in concrete is discernible using ultrasonic guided wave and acoustic emission technique.

Ultrasonic guided wave monitoring is done using surface seeking mode and core seeking mode for detecting corrosion. These modes are able to explain the delamination as well as the pitting of the rebar in the RC beam due to corrosion. From acoustic emission monitoring it is observed that there is an immediate increase in cumulative hits and events which corresponds to the development of cracks in the RC beam due to corrosion. Comparing the results from both ultrasonic monitoring and acoustic emission monitoring it is observed that acoustic emission is very effective in detecting the initiation of the corrosion during the initial stages whereas ultrasonic guided waves monitoring gives very clear data during the later age of corrosion propagation.

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1.1 GENERAL

Reinforced Concrete is the major material used for construction. High elasticity, high stiffness, tensile strength, cost-adequacy are one of major qualities, that makes it the basic component in most concrete structures existing today. As the structures are presented to environment, numerous construction problems and maintenance issues emerge with time that seriously decrease the quality and life of these structures which result in higher maintenance cost. The worst issue that influences the strength of structures is the corrosion of the reinforced steel in concrete. Fresh Concrete is alkali in nature hence provides alkaline environment to reinforced steel in concrete due to the presence of namely NaOH, KOH and Ca(OH)_2 present. Reinforced steel in concrete is prevented by the formation of passive layer around the reinforcement. The Passivity of the structures is influenced essentially by the nearness of chlorides and carbonates in the environment. Marine structures or roads bridges in colder regions where de-icing salts are sprayed are generally subjected to chloride attack and carbonic emission as well as carbon dioxide in environment results in attacks by carbonates. These climatic toxins (chlorides and carbon dioxide) infiltrate into the concrete and once they cross the limit, they diminish pH of the pore arrangement at fortification profundity from 13 to 12-8.5 the corrosion products can take up a volume as much as six times that of the steel... In addition, the bond amongst concrete and steel gets weak.

The issues connected with corrosion in reinforced concrete structures are significant in India as roughly 80 % of the yearly precipitation happens in two months of monsoon in northern India. 1-2% cost of the new structure is beared yearly due to repair needed in structures. Corrosion is an unavoidable issue being confronted by the cement and concrete industry nowadays and involves awesome concern. Hence it gets important to know the causes of corrosion and the prevention techniques.

1.2 AIMS AND OBJECTIVES

It is an established fact that FRP (CFRP and GFRP) protects the reinforced concrete structure from corrosion. The aim of this study is to evaluate the efficacy of ultrasonic guided waves and acoustic emission to pick up corrosion of RC cylindrical specimens, when subjected to accelerated chloride corrosion. The guided waves and acoustic emission technique were then used to investigate FRP protected specimens against corrosion. The specimens were passively protected against corrosion using CFRP and GFRP and monitored using Ultrasonic guided waves as well as Acoustic Emission techniques.

1.3 CORROSION MONITORING OF RC STRUCTURES

Because of the ill effect of corrosion in RC structures, it is important to postpone the impact of corrosion as it can't be halted. As corrosion monitoring is a quantities method that checks the adequacy of corrosion prevention and its process The traditional technique for visual examination of corrosion monitoring relies on the physical appearances changes in the structure example cracking delamination, and spalling of concrete. However these physical changes might be observed at a very later stage hence failing to prevent corrosion in initial stages hence other techniques are preferred. The rate of disintegration of a structure with time can be seen by installing corrosion monitoring gadgets on new or existing RC structure.

Now a days various techniques are available to monitor corrosion depending upon the requirements they are chosen. Every device has an alternate capacity and is picked relying upon the requirement of structure and its environment. Corrosion Monitoring Technique are mainly classified as Destructive Methods and Non Destructive Methods.

Non-destructive testing techniques monitor material quality without destroying the specimen. In this work, it is proposed to use ultrasonic measurements and acoustic emissions as NDT for monitoring corrosion. Destructive techniques result in accurate measurement of corrosion and various parameters could be studied by these techniques but the structure gets completely damaged

1.4 FRP REPAIR OF RC STRUCTURES

To prevent early damage of RC Structure, few preventive procedures have been distinguished in recent times. Fibre Reinforced Polymer is one such material that is usually utilized for the repair and recovery of damaged RC structures. The main advantage of FRP are –

- It provides high resistance
- High strength to weight ratio
- Resistance to electrochemical /electromechanical deterioration
- Easy bondage to reinforced concrete members resulting in a negligible increase in cross-sectional dimensions.

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

CFRP sheets are thinner, exhibit greater tensile strength and, tensile modulus as compared to GFRP sheets. But GFRP wraps provide higher electrical resistance in passive protection of reinforced steel. Therefore, both CFRP and GFRP sheets are used in concrete industry depending on the application as they prevent atmospheric pollutants (chlorides, carbon dioxide) to penetrate into the concrete.

1.5 FORMAT OF THESIS

The thesis has been divided into six chapters.

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

2nd chapter explains in detail the process of corrosion in RC structures, types of corrosion of steel.

3rd chapter explains various corrosion monitoring techniques i.e. the ultrasonic guided wave and acoustic emission technique.

4th chapter deals with thorough review of literature on feasibility of ultrasonic guided waves and acoustic emission for monitoring of rebar corrosion in RC structures.

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

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

7th chapter is the concluding chapter.

8th chapter discusses the future scope of work.

CHAPTER 2

CORROSION IN RC STRUCTURES AND PROTECTION USING WRAPS

This chapter deals with theory of corrosion and its propagation in RC structures. The various types of corrosion and corrosion protection using FRP's.

2.1 CORROSION IN REINFORCED CONCRETE

2.1.1 General

Concrete industry is facing the major issue of corrosion as it diminishes the durability of structure. It is a threat to the durability of structures. Due to widespread use of RC structures, this problem is so common and has become unavoidable. The reinforcement corrosion is initiated when the protective layer formed on steel is depassivated and the porosity of concrete increases. Once it is initiated, it has adverse effect on steel as well as concrete. The cross-sectional area of the steel bar reduces eventually due to the formation of expansive corrosion products that create tensile stresses. This introduces notches on the steel bar surface resulting in the reduction of strength and ductility of corroded steel bar. The increase in volume of the corrosion products also affects the internal structure of concrete resulting in spalling and cracking of the concrete cover [1] (**Fig. 2.1**).

The load carrying capacity and structural life decreases due to the formation of corrosion by products [2]. Generally the pore solution of concrete and the chemical; properties of metal identifies the behaviour of corrosion.

The corrosion of steel in concrete is not determined by a single factor, but the influence of many other factors are also considered. The various factors that are responsible for rebar corrosion are:

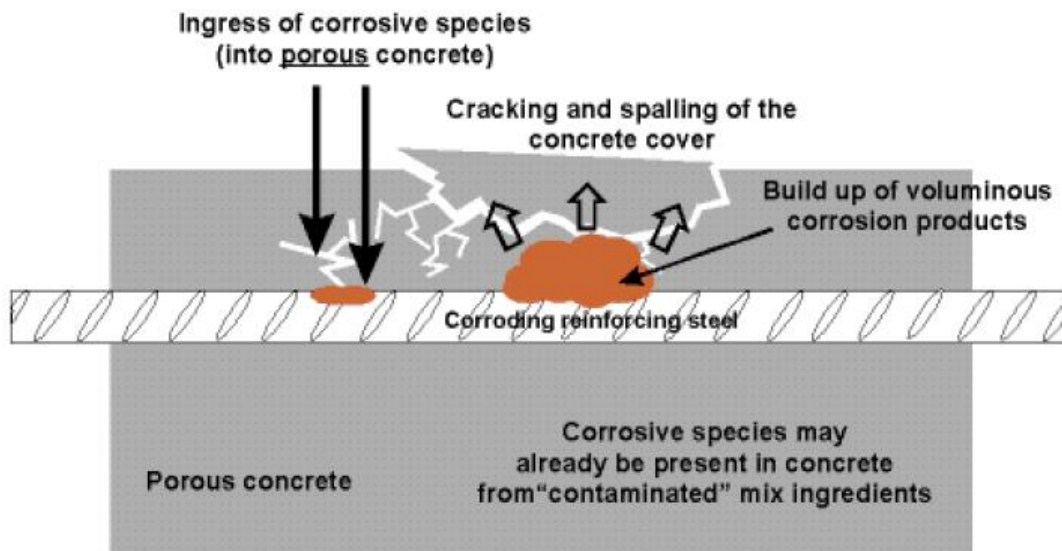


Fig. 2.1: Cracking and spalling of concrete cover due to corrosion of reinforcement [1]

- Carbon Dioxide
- Chlorides
- Co-intact of .dissimilar metal
- Moisture
- Type of steel
- Pore. Solution of concrete
- Permeability of concrete:
- Temperature
- Thickness .and defects of .Cover Concrete
- Concrete Resistivity

2.1.2 Corrosion Mechanism

The corrosion of reinforcing steel in concrete is a type of electrochemical process .An electrochemical process involves transfer of electrons form one material (anode) to the other (cathode). When no external electrical source is present, two half-cell reactions occur, one at the anode and other at the cathode. The anode produces electrons resulting in the oxidation of iron (Fe) and the cathode consumes these electrons i.e. reduction of oxygen takes place to form hydroxyl ions (OH^-)

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

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

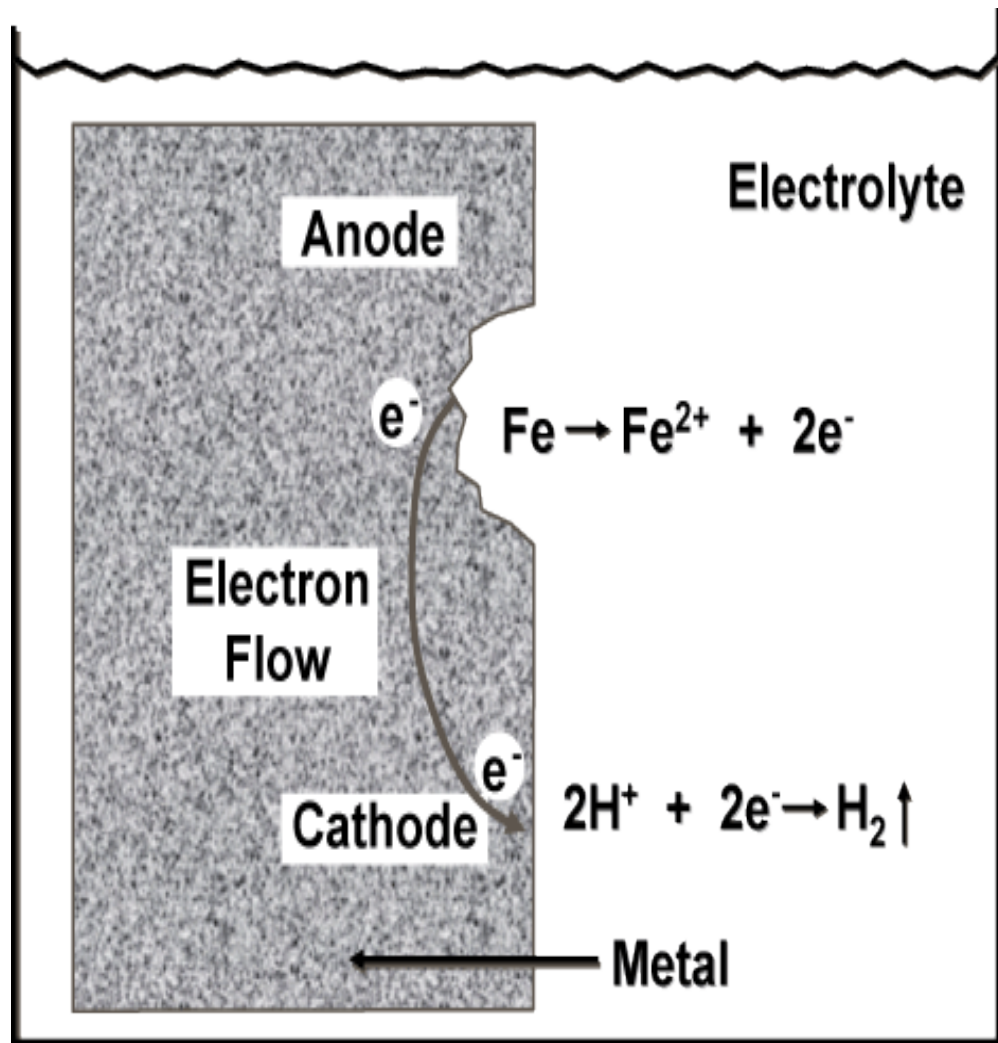
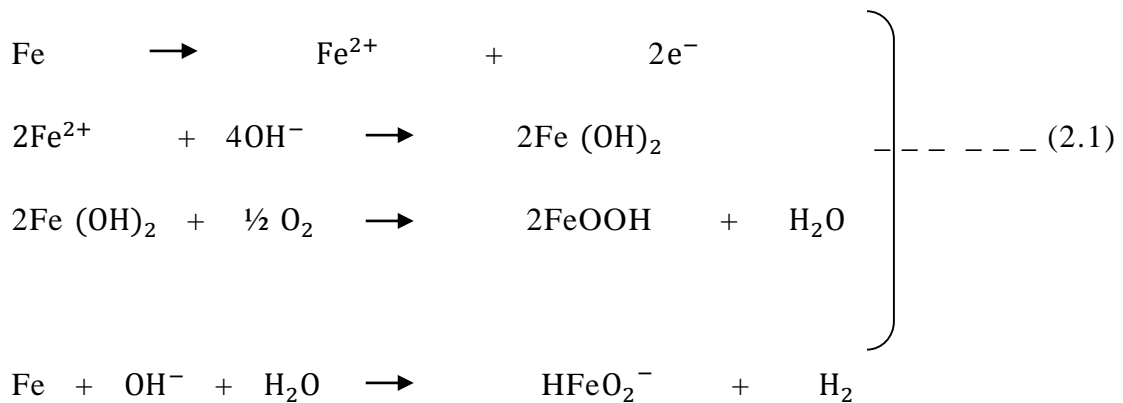


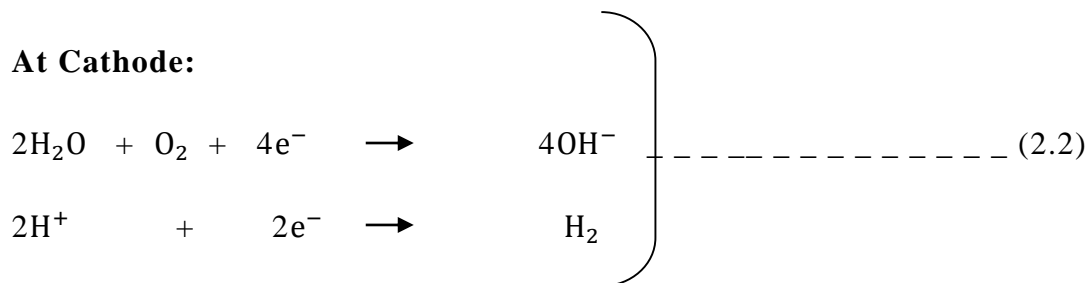
Fig. 2.2: Corrosion Mechanism (www.octane.nmt.edu)

The electrochemical half - cell reactions taking place are:

At Anode:



At Cathode:



The anodic reactions release intermediate corrosion product, Fe^{2+} into the solution continuously resulting in a loss of cross sectional area of steel bar. This may lead to external break down of the steel bar. Normally, the pH of pore solution ranges from 13 to 13.5 and only the first two anodic reactions take place. A protective passive layer is formed around the steel because of iron oxide Fe_3O_4 and Fe_2O_3 . However, the ingress of chlorides and carbonates reduce the pH, depassivates the protective layer formed by oxides and initiates corrosion. Once the corrosion is initiated, it ultimately leads to delamination and cracking of concrete cover, thus exposing the reinforcement to the outside environment (**Fig. 2.3**)

The various stages of corrosion are:

- Initiation
- Propagation
- Concrete Cracking

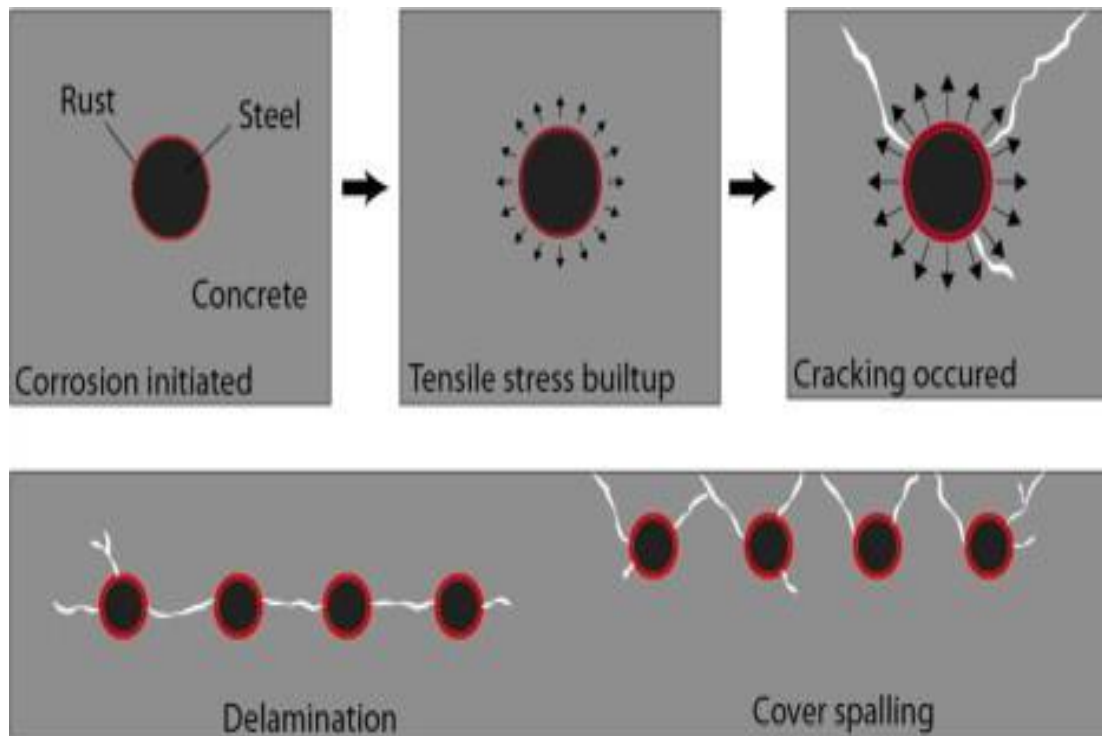


Fig. 2.3: (top) generally assumed mechanism of corrosion-induced cover cracking, (bottom) cracking modes [3]

Fig. 2.4 demonstrates the corrosion model. Primary Stage indicates the day and age required for the event of steel depassivation i.e., the time when reactive species, mostly chloride particles, carbon dioxide, and so forth infiltrate through cement to the surface of rebar (steel) and develop adequate grouping of consumption items to hampers the passivation layer of steel. Propagation Stage depicts the phase where active corrosion has of now started. The consumption rates at the underlying spreading stage increments extensively once the concrete cover has cracked.

The corrosion products framed on the metal because of the change of metallic particles to rust results in noteworthy increment in original metal as vast as 600 % (**Fig. 2.5**). The increment in volume is in charge of solid development and results in splitting, spalling and delamination in concrete solid structures

2.1.3 Types of Corrosion of Steel in RC Structures

Differentiating on the basis of mechanism of corrosion and partly the damaged caused by corrosion on steel bar are as follows:

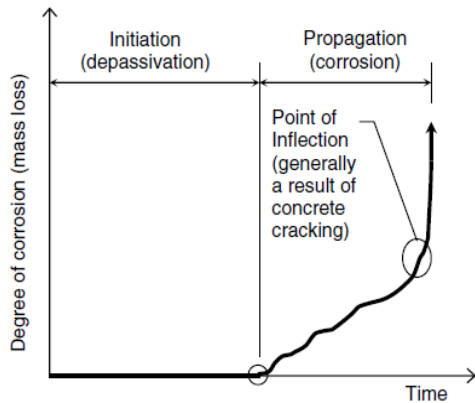


Fig. 2.4: Corrosion process model for steel in concrete [4]

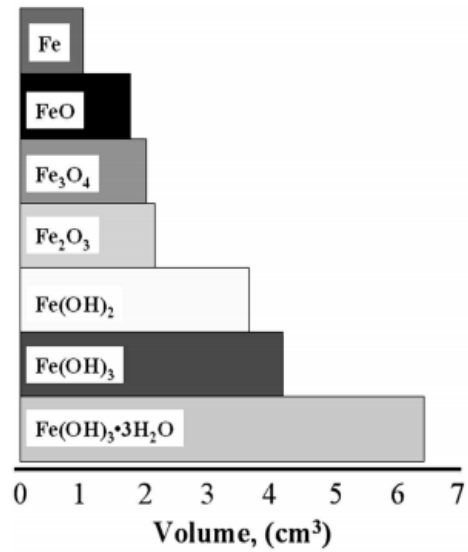


Fig. 2.5: Relative volumes of iron and its reaction product (Engineering .civil.com)

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

The classification of corrosion types is not absolute but conditional.

- **Sub Uniform corrosion:** When the anodic and cathodic areas are very near, then the electrochemical reactions would take place uniformly along the steel surface and the dissolution when the electrochemical reaction occurs evenly on the metal surface due to the closeness of electrodes is known as Uniform corrosion
- **Sub Galvanic corrosion:** in realistic approach anodic and cathodic reaction are not evenly distributed. Galvanic corrosion is one of such types which is totally dependent on concrete resistivity lower the

concrete resistivity higher will be the e. Higher the resistivity of concrete, lower shall be the rate of galvanic corrosion.

- ***Sub Localised Corrosion:*** It is the corrosion that can be seen and is the worst type of corrosion Pitting and Crevice are its main type.
- ***Sub External current induced corrosion:*** The type of corrosion where externally induced current in an RC Structure causing higher corrosion and comparatively major loss of steel
- ***Sub Stress Corrosion Cracking (SCC) and Hydrogen Induced Embrittlement (HIE):*** SCC and HIE are found in some types of steel due to combination of particular corrosion media and stresses. These types of corrosion are not seen widely but damage by them cannot be neglected [5].

2.2 CORROSION PREVENTION METHODS

There are many Corrosion prevention methods discussed below:

- ***Alternative reinforcement method:*** the alternate reinforcement arrangement should be able to resist the damage and load. The alternative reinforcement should be economical as well as be able to validate the structural function for its design life.
- ***Barrier Method:*** There are many ways to protect reinforced steel mainly by blocking some of these restrict the chloride ions from penetrating others reduce the movement of air and moisture into the concrete.
- ***Electrochemical method:*** Electrochemical method has the ability to stop corrosion in chloride polluted concrete. It is most often used as a rehabilitation method. The electrochemical method of corrosion prevention includes anodic protection and cathodic protection.

2.3 PROTECTION USING FRP's

2.3.1 General

To find the best material for repair and rehabilitation of the structure various research has been done so as to strengthen new or old structures. FRP (Fiber Reinforced Polymer) is one of the majorly used composite material for repair and rehabilitation of structures.

2.3.2 Suitability of FRP in RC Structures

Many factors leads to the use FRP for repair and rehabilitation of RC Structures FRP can be very well used as inert anodes so as to delay corrosion of reinforced steel as they are easy to wrap with the help of adhesive (epoxy). FRP lamination on structures reduces corrosion significantly as it acts a barrier between the structure and the environment hence reducing permeability moreover there is an external pressure created on the structure which counters the expansion caused by the corrosion products and considerably reduces the cracking and spalling [2]. There is considerable increase in the shear , torsion and compressive strength , ductility , to structure seismic performance of the structure also increases [6] FRP protected structures has high resistance to corrosive effects and is also inert to electrochemical and electromechanically process .

2.3.3 Various Types of FRP's

Out of all the FRP material readily available for practice only two material are generally used in INDIA for protection from corrosion.

- (i) **Glass Fibre Reinforced Polymer (GFRP):** It is used in the form of sheets that are wrapped around the GFRP covering acts as barrier and reduces the permeability of aggressive chemicals like chlorides and carbon dioxide. The general properties of GFRP discussed in **Table 2.1** and **Fig. 2.6** shows **CFRP sheet**

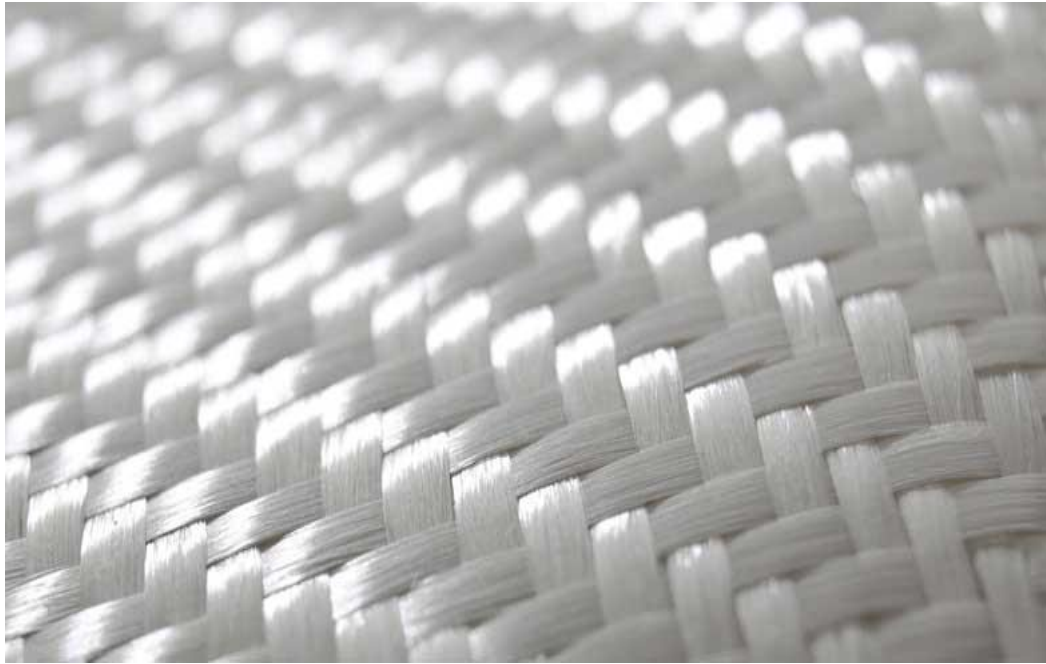


Fig. 2.6 GFRP sheet (www.fassmer.de)

- (ii) **Carbon Fibre Reinforced Polymer (CFRP):** CFRP sheets are comparatively thin than GFRP sheets and exhibit a greater tensile strength, greater tensile modulus and lower ultimate strain. The properties of CFRP are shown in **Table 2.1**. **Fig. 2.7** shows CFRP sheet.



Fig. 2.7: CFRP sheet (www.mechanical_engineeringblog.com)

Table 2.1: CFRP and GFRP general Properties [7]

MATERIAL	THICKNESS (mm)	TENSILE STRENGTH (GPa)	TENSILE MODULUS (GPa)	ULTRASONIC STRAIN
Carbon sheet (Net fibre) (CS)	0.13	3.79	230	0.015
Glass sheet (Net Fibre) (GS)	0.35	2.30	76	0.018
Adhesive	-	15	4.3	0.02

2.3.4 Use of FRP for Active and Passive Protection:-

- 1) Passive Protection:** an external pressure is created from the exterior on the walls such that restraining the cross sectional dimension to increase this is termed as Passive protection. Hence this passive protection provided by lamination of CFRP and GFRP shows greater Strength and decrease in mass loss as compared to unwrapped sample.
- 2) Active Protection:** When reinforced steel act as an anode and GFRP which is an electrical conducting material is electrically conductive and because of this property it can be used to provide ‘Active Protection’ the direction of current is altered and the corrosion process is stopped or slowed. Hence CFRP has dual advantages it provides as a barrier as well as can be used to alter the flow of current to stop the dissolution of ions.

It has been reported in latest literature that CFRP is used for providing cathodic protection to RC Structures. CFRP act an external inert anode that enables the deposition of negative charges on the reinforcing steel. Thus, reinforcement starts to behave as a cathode and corrosion process is stopped[2].It has been was investigated that CFRP repaired structures show greater flexural strengthening and a prolonged life as compared to unrepaired RC Structures,but significantly reduce the deflection capacity[2

]. Further research reported that FRP repaired structures show a higher rate of decrease in corrosion potential than the unrepaired structure [8]. Increasing the number of CFRP wraps, corrosion rate is slowed down, it was also observed that the type of epoxy used for wrapping CFRP sheets affects the corrosion rate and found that the epoxy Sika guard 62 is helpful in reducing corrosion rate [4]

Here in the present research we will passively protect the cylinder which are under induced corrosion and as the wrapping or the protection being provided at different intervals to the corroded samples shows the variation in the monitoring techniques being carried at them.

NON DESTRUCTIVE TECHNIQUES FOR CORROSION MONITORING

3.1 GENERAL

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

3.2 NON DESTRUCTIVE TECHNIQUE

NDT techniques are a wide group of safe analysis techniques as they don't permanently alter the structure being inspected. Various NDT techniques used for corrosion monitoring of RC structures are given below:

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 Impedance Spectroscopy (EIS)
- Embeddable Corrosion monitoring sensor
- Cover thickness measure
- Ultrasonic pulse velocity techniques

- X-ray, Gamma Radiography. measurement
- Acoustic Emission
- **Visual Inspection:** This technique is based on structural analysis of the concrete surface with the help of binoculars or directly through eyes, timely depending on the importance of structure. Hence, this technique fails to detect corrosion at an early stage [5]
- **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...
- **Open Circuit Potential (OCP) Measurement:** OCP measurement is a non-destructive test that diagnoses the corrosion risk in RC structures. OCP Measurement is based on the principle of measuring corrosion potential of steel with respect to a standard reference electrode.
- **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.
- **Concrete Resistivity Measurement:** It is a NDT technique that evaluates corrosion risk on the reinforcement based on electrical resistivity measurements.
- **Linear Polarization Resistance (LPR) Measurements:** It is a useful NDT technique that determines the instantaneous corrosion rate of reinforcing steel this method provides more detailed information as compared to simple potential survey.
- **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.
- **Electrochemical Impedance 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.

- **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.
- **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. Shows a cover meter to monitor corrosion of reinforcing steel.

Though the above discussed techniques are helpful in monitoring corrosion in RC structure but are not as efficient due respective limitation of their use hence the new Non Destructive Techniques Acoustic Emission and Ultrasonic guided wave are recommended by researchers for corrosion monitoring. Amongst all of the available Non-Destructive techniques, Ultrasonic Guided Wave and Acoustic Emission are used in this study and therefore, they are discussed in detail.

3.3 ULTRASONIC GUIDED WAVES

Elastic waves in all frequency ranges- ultrasonic, sonic and subsonic- can be classified into two groups; Body waves or bulk waves and, surface waves or guided waves (Fig3.1).

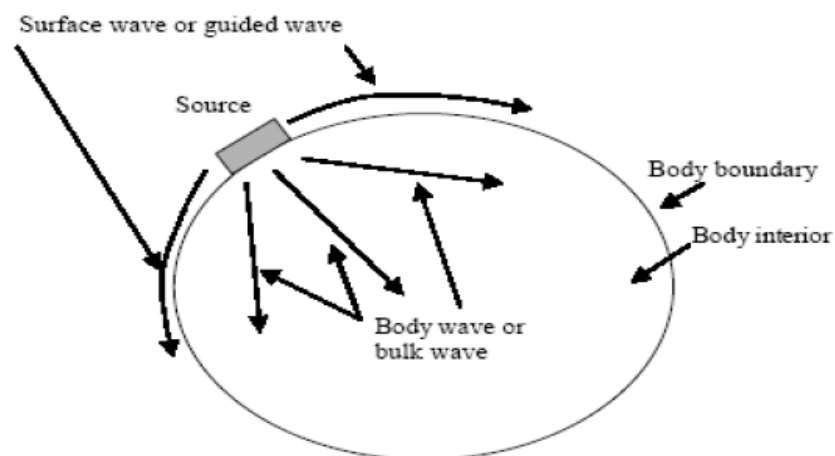


Fig.3.1: Body waves and Surface waves generated by an ultrasonic source [9]

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 material varies with its elastic properties which can be calculated by measuring the time of flight between the two points.

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.

Major 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 the structures.

3.3.1 Types of Guided Waves

There are different types of guided waves based on the geometry of the structure (wave guide) through which guided wave travels.

- Plate Wave or Lamb wave.
- Bar Wave.
- Rod Wave.
- Cylindrical Guided Wave
- Rayleigh Wave.
- Generalized Rayleigh-Lamb Wave.

They are as shown in the **Fig.3.2**

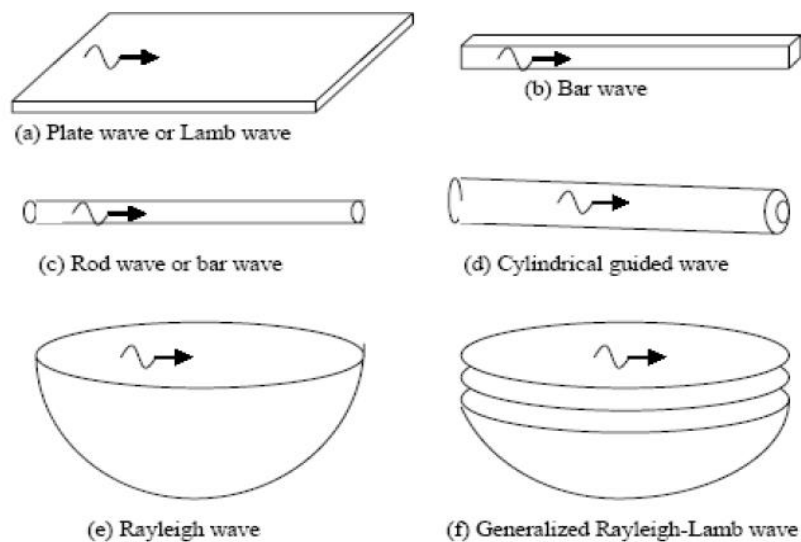


Fig3.2: Different types of guided waves [9]

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

3.3.2 Sub 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:

- **Longitudinal Mode(L)**
- **Torsional Mode(T)**
- **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.

3.3.3 Methods for Ultrasonic Testing

Most commonly used method for ultrasonic testing are:

- **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. It is shown in **Fig.3.3**.

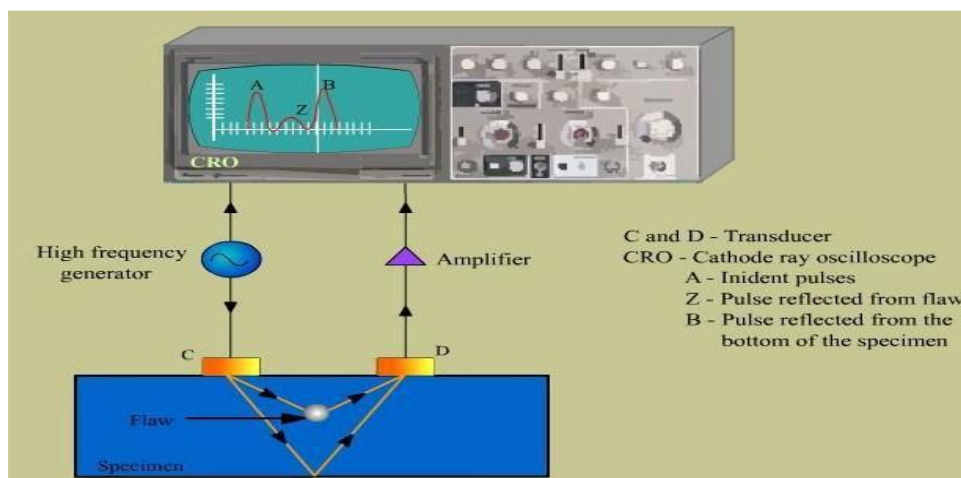


Fig.3.3: Pulse transmission method of testing

www.msheiksirajuddin.blogspot.in

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

- **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 shown in **Fig 3.4**

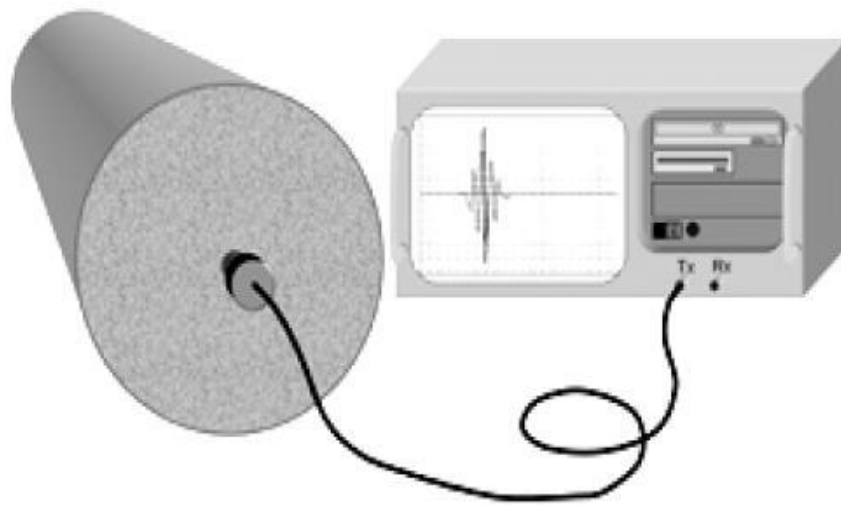


Fig.3.4: Set-up for pulse echo method [33]

In this research Ultrasonic Guided Wave is used for monitoring of corrosion and the protection offered by FRP wraps against corrosion using Pulse Echo Method.

3.4 ACOUSTIC EMISION TECHNIQUE

Acoustic emission (A.E) is one of the most promising methods of monitoring of the structure at different stages of deterioration. AE technique can be adopted to forewarn the maintenance team and to carryout repair work in a timely manner , thus saving the cost of repair and in prolonging the life of structures.

Acoustic emissions are the waves that are generated as energy from elastic or plastic deformations occuring in the material .It is defined acoustic emission as “ the class of phenomena whereby transient elastic waves are generated by rapid release of energy from localized sources within the material, or the transient elastic waves so generated “[10].

AE waves can be generated as a result of various sources dislocations, microcracking and other changes due to increase in strain. The method is very sensitive which enables it to detect damage long before its visible. AE sensors record the vibrations created by waves when they reach the materials surface. The piezoelectric crystal the detected wave to electric signal, amplify it(internally or using the external pre-amplifier), and send it to the data acquisition system. The passive ability of AE, external excitation or stimulus for data collection once sensors are placed, makes it a suitable candidate for real time monitoring and structural health monitoring of in-service structures. The method has also shown promise in assessment of damage during load tests of different structures and material including fibre reinforced polymer(FRP), steel, reinforced concrete and prestressed concrete.

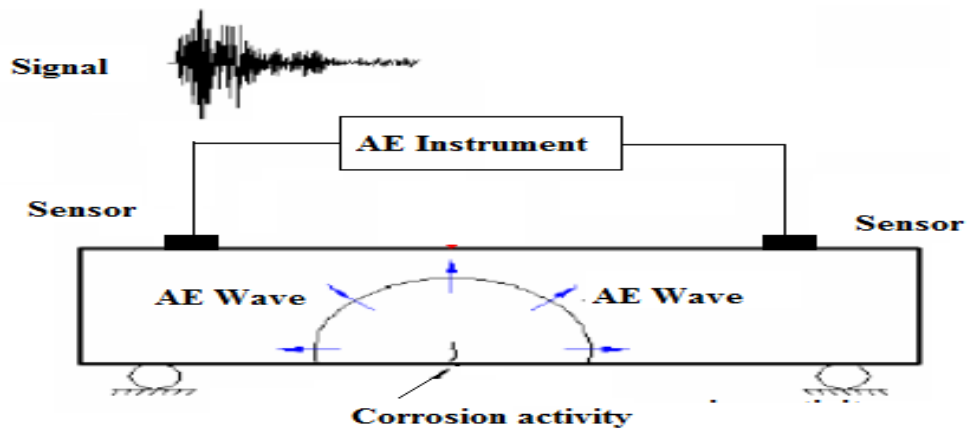


Fig.3.5: Schematic representation of AE Monitoring Process (www.tms.org)

As indicated earlier, AE waves are generated from a sudden release of energy. The strength of AE signals depends on a number of factors such as distance and orientation of the source with respect to the sensor as well as nature of transferring material. Detected AE signals are usually referred to as ‘hit’. A more detailed analysis can be conducted on the waveform of each signal to calculate a number of parameters such as amplitude, rise time, duration, signal strength, energy, counts, etc.[10] Figure 3.6 shows an AE waveform schematic with some of the parameters described.

3.4.1 The Definitions of Some Commonly Used AE Parameters are Described here

Hit: Hit is the process of detection and measurement of an AE signal on an individual sensor channel [10]

Event: Event is the rise of AE activity that will cause multiple hits on different sensors a single event can be detected on multiple sensors[10].

Amplitude: Amplitude (also known as signal amplitude) is the largest voltage peak in the AE signal waveform; customarily expressed in decibels (dB) relative to 1 μV at the preamplifier input (dB) assuming a 40 dB pre-amplification. Decibels is the unit of measurement for AE signal amplitude A, defined by $A \text{ (dB)} = 20 \log V_p$; where V_p is the peak signal voltage in μV referred to the preamplifier input [10]

Duration: Duration is defined as the time from the first threshold crossing to the end of the last threshold crossing of the AE signal from the AE threshold [10]

Rise time: Rise time is the time from an AE signal's first threshold crossing to its peak

Counts: Counts are the number of times the AE signal crosses the detection threshold [10]

Signal Strength: Signal strength is defined as the measured area of the rectified AE signal with units proportional to volt seconds (the proportionality constant is specified by the AE instrument manufacturer) [11]

$$\frac{1}{2} \int_{t_1}^{t_2} f_+(t) dt + \frac{1}{2} \left| \int_{t_1}^{t_2} f_-(t) dt \right|$$

where: is the signal strength, is the positive signal envelope function, is the negative signal envelope function, t_1 is the time at first threshold crossing, and t_2 is the time at last threshold crossing.

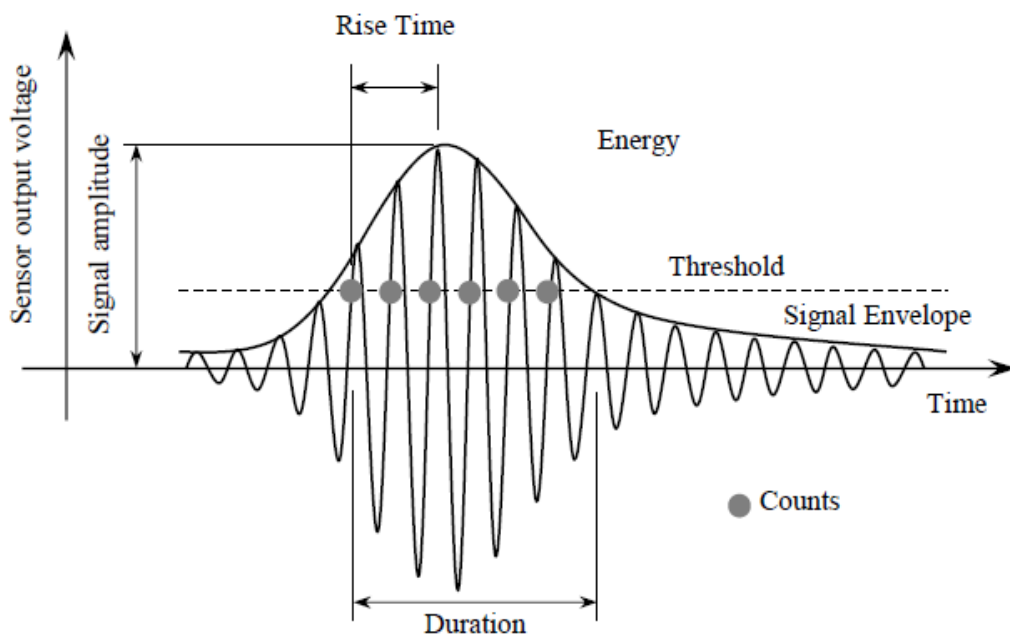


Fig.3.6: Schematic showing some parameters of an AE waveform [11]

Average Frequency: Average Frequency is the ratio between number of counts and the duration of the AE signal.

Peak Frequency: Peak frequency is the point in the power spectrum at which the peak magnitude occurs. The peak frequency is a 2 byte value reported in kHz.

RMS: The root mean square (*RMS*) is a measure of continuous varying AE voltage. IT is the rectified average value of AE signal measured in volts measured on a linear scale

RA value: RA value is the ratio of rise time and maximum amplitude in Volts to AE signal.

3.4.2 Acoustic Emission Source Location

AE can find the source of transmitted waves. This procedure is fundamentally the same as that utilized as a part of seismology to find the epicenter of quakes. On the off chance that the speed of AE wave in the tried material is known, source location can be located the entry times of AE signs at various sensor areas. Since it requires more than one sensor, just AE events are noticeable utilizing this procedure. The calculations that perform source area are entrenched and usually embedded in the data acquisition software. AE source areas should be possible in a direct or planar or three-dimensional space taking into account the quantity of sensors utilized. AE source area is trying following the way of the material, nearness of existing breaks in the source-to-sensor way, and the measurements of the tried part may prompt false occasions as a consequence of wave reflections. Past examination demonstrated that AE source area is possible in RC or PC structures if appropriate channels were utilized

3.4.3 Advantages of Using Acoustic Emission Technique

There are numerous advantages of using the Acoustic Emission Technique (**AE**) over the conventional NDT methods. Some of them are listed below:

- High sensitivity
- Early and rapid detection of defects, flaws, cracks etc.
- Real time monitoring
- Cost reduction especially maintenance cost.
- Defective area location
- It does not require access to whole area.

Hence, Acoustic Emission (AE) technique is a powerful aid to material testing and the study of deformation, fracture and corrosion. It gives an immediate indication of the Response and behavior of a material under stress intimately connected with strength, damage and failure.

3.5 DESTRUCTIVE METHODS

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

3.5.1 Pull out Method

This method determines the bond strength between reinforcing steel and concrete subjected to corrosion. In this method, RC structures are exposed to anodic current for 24-28 days. A universal testing machine (UTM) is then used to hold these structures from the protruding portion of reinforcing steel bar (Fig. 3.7)

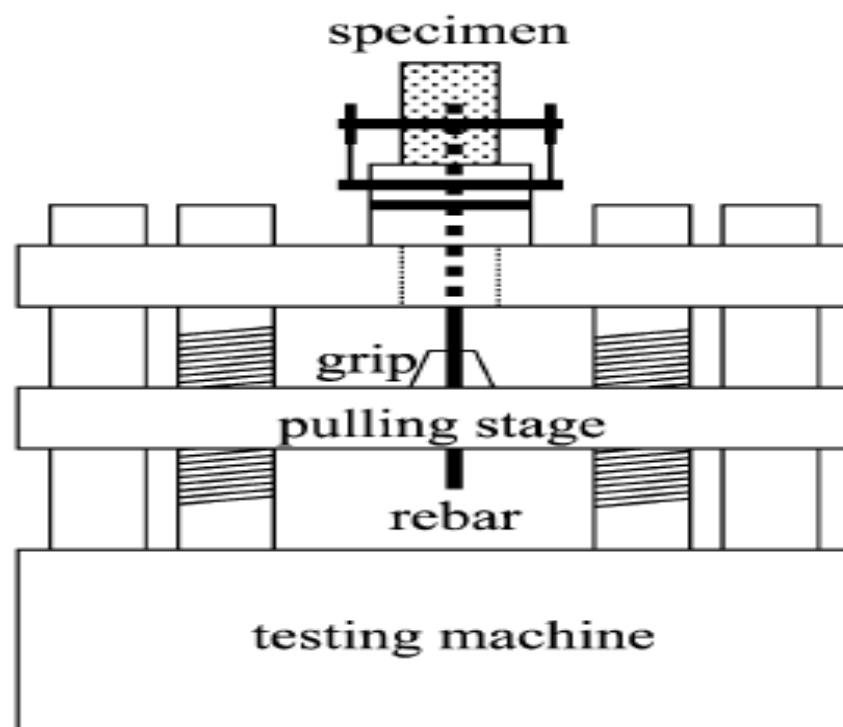


Fig. 3.7: Pull-out measurement setup [12]

The maximum pull out force is recorded. The reinforcing steel bar may break at the interface because of loss of metal at the top interface due to corrosion. Therefore, the structure is usually cut down to a certain height so as to expose the reinforcing steel bar for holding it in the grip of universal testing machine. **(Fig. 3.7)**

The pull-out tests are carried out again for these structures [7]. The bond strength can be obtained by dividing the maximum pull out force by the corresponding embedded area [12]. After carrying out the pull out tests, the concrete structures are cleaned to remove the corrosion product using chemical methods. The reinforcing steel bars are placed in 10 % solution of muriatic acid for a week. As a result, all the corrosion products and the remaining concrete is removed from the steel bar after that mass loss in the bar could also be analysed.

CHAPTER 4

LITERATURE REVIEW

4.1 ULTRASONIC GUIDED WAVES FOR CORROSION MONITORING

Pavlakovic et al. [13] investigated the behaviour of ultrasonic guided modes that show minimum attenuation while propagating along the waveguide formed by the steel bar embedded in lower impedance 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 impedance 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. The attenuation minima and energy velocity maxima correspond to points where leakage of energy into the imbedding medium is minimized. Beyond specific point, the material attenuation in the bar becomes a significant factor and attenuation at the minima increases.

Na et al. [14] investigated the feasibility for detecting and quantifying delamination at the steel-concrete interface using ultrasonic guided waves. The experiments were performed on three sets of specimens. Specimen sets 1 and 2 comprised of four cylindrical structures each with different amounts of separation (0, 25, 50, and 75 % of concrete steel interface). Specimen set 3 comprised of three concrete beam structures- specimen with different amounts of separation without stirrups, specimen with different amount of separation with stirrups and, specimen with same amount of separation at different positions with stirrups. Ultrasonic testing was conducted in through transmission mode. Two experimental set ups were devised for both relatively high and low frequency transducers and four Transmitter/ Receiver

arrangements (TRA1, TRA2, TRA3, TRA4) were designed to generate, propagate and receive guided waves through steel bars and concrete).

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

Cawley and Beard 15] Proposed a method using guided ultrasonic waves for inspection of corrosion and fracture in the case of grouted steel tendons and rock bolt. Two types of reinforcing tendons were constructed- single wire (5 or 7 mm in diameter) and 15 mm seven wire strands. On structures free end analysis through 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 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.

Mahmoud et al. [16] investigated the use of ultrasonic waves for non-destructive structural health monitoring of CFRP bonded concrete specimens subjected to water immersion ageing at controlled temperatures of 25-60 degree Celsius. The feasibility of using non-destructive ultrasonic technique as an alternative to destructive technique was analysed. Narrow-band transducers with center frequency of 110 kHz were used to generate and receive surface waves at the external face of CFRP. Results indicated a decrease in the measured ultrasonic parameters due to ageing over time. A simultaneous destructive study was carried out on mode-11 fracture loading of CFRP concrete samples subjected to some ageing conditions and temperature and a parameter G_F , fracture energy was obtained. A correlation analysis was performed at each ageing temperature, between the non-destructive parameters ($P_{avg}, P_{max} (P/F)_{max}$) and destructive parameter (G_F), as the results indicate a good correlation between the ultrasonic parameters and fracture energy at all temperatures.

Sharma and Mukherjee [17] studied the use of longitudinal guided ultrasonic waves to monitor notch and bond weakening 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 [18] 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-se. 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 techniques

Sharma and Mukherjee[19] 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 ultrasonic 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.

Sharma et al. [20] studied the behaviour of reinforced concrete structure that are corroded and rehabilitated by FRP. The NDT used for monitoring is Ultrasonic Guided Wave before and after wrapping Concrete Cylinders embedded with reinforced bars are subjected to impressed current corrosion in chloride environment After specific days of exposure to corrosive environment the cylinders are repaired by wrapping with GFRP and CFRP sheets. Anodic current was further continued for specified times. Specific core and surface seeking guided wave modes were used to ultrasonically measure the resistance offered by FRP wraps to corrosion. The ultrasonic measurements were correlated with destructive parameters of pull-out strength and mass loss. It was observed that guided waves were able to discern the corrosion protection done by the FRP. It is observed that Glass FRP gives better resistance than Carbon FRP. The specimens were subjected to accelerated anodic current corrosion at constant current. Before wrapping the specimens, all the samples exhibited similar rate of corrosion and first crack appeared in two days in all samples. The cell voltages required for maintaining a constant anodic current was also monitored as a metric for corrosion rate. It is observed that wrapping the concrete cylinders with FRP dramatically increases the cell voltages by about 300% indicating increased resistance to corrosion. Also GFRP wrapped samples exhibited

higher electrical resistance than CFRP samples and hence, glass fibres impedes corrosion better than carbon fibres.

The efficacy of specific guided wave modes to monitor corrosion progression and then its inhibition by FRP wraps is demonstrated in this investigation. By monitoring surface seeking and core seeking ultrasonic guided waves it was established that PE technique is suitable to assess corrosion in FRP wrapped samples. It was marked by fall in surface seeking signal as against the rise of the signals due to delamination of the bar from the surrounding concrete in control samples. Core seeking mode signal which measures the deterioration of the bar due to pitting and area loss at later stages of corrosion indicates a very slow and marginal fall after wrapping as against a huge and drastic fall in signal with control samples. It indicates that protection by FRP wraps greatly reduces the rate of corrosion. There is a correlation between the observed phenomena and the PE signals. Using the two modes of the signal it was possible to discern the pitting corrosion from surface corrosion.

4.2 ACOUSTIC EMISSION USE FOR CORROSION MONITORING

Yoon et al. [21] studied damage in corroded Reinforced concrete using the Acoustic emission. He conducted a series of normal strength concrete beams tests using four-point flexural loading. The beams were 100 mm wide, 150 mm deep and 1150 mm long. Several different types of beams were tested to simulate different sources of damage.

Three plain unreinforced beams and three notched plain unreinforced beams were used to obtain the initial response of distributed micro crack development and localized crack propagation, respectively. The reinforced specimens allow the determination of the characteristic AE response of a reinforced concrete element from several sources such as Micro cracking, Localized crack Propagation, Flexural cracking, Shear cracking and De bonding. In addition, three reinforced beams were corroded to three levels of distress using anodic current that was applied after 28 days of standard moist curing. The response of the unreinforced beams is divided into two regions to describe the presence of distributed micro cracking throughout the beam in region and localized crack development in the other region. The load cycle showed a fine line plotted in. On the whole, in each load cycle the AE activity decreased as the load was held constantly or

unloaded. In early stages of loading, there is a large difference between the no. of AE events as shown in a large no. of AE events were generated in the un corroded specimens whereas fewer AE events were observed in the corroded specimen; in the reinforced beams the higher the degree of corrosion, the lower the AE activity. Thus, the majority of micro cracking and longitudinal cracking along the reinforced beam has already dissipated by damage process due to corrosion.

Tomoda et al. [22] studied corrosion monitoring in reinforced concrete by acoustic emission. In the accelerated corrosion test, two types of mixture were employed. Three specimens were prepared for each W/C ratio, and the chloride contents were measured after accelerated corrosion. For W/C = 45%, core samples were taken at 4 days, 10 days, and 12 days elapsed, while for W/C = 55% at 4 days, 8 days, and 10 days elapsed. These periods are determined from a comparison between AE activities. And half-cell potentials. High AE activities are observed at two stages of 3 days and 7 days elapsed. For non-destructive evaluation of corrosion, the half-cell potential measurement is normally carried out. It was observed tensile cracks running vertically to the surface are mostly visible from outside. In contrast, shear cracks are not explicitly associated with the extension of surface-breaking cracks. In crack trace tensile and shear cracks are fully mixed up. Results obtained are summarized, as follow:

- In the accelerated corrosion tests, AE occurrence is monitored continuously. Investigating ingress of chloride ions, a relationship with chloride concentration and AE activity is obtained. Right after the chloride contents become higher than 0.3 kg/m³, a high AE activity period is observed. Subsequently, at the stage where the chloride contents become higher than 1.2 kg/m³, another high AE activity period is observed.
- Two stages of high AE activities are observed in the accelerated corrosion test, which remarkably correspond to the two stages in the deterioration process due to salt attack.
- The corrosion probability by the half-cell potential reaches over 90% after the appearance of these two stages. It confirms that AE monitoring could provide earlier warning of corrosion than the half-cell potential measurement.

Ohtsu and Tomoda [23] the corrosion process in Reinforced concrete identified by Acoustic emission. RC slabs tested were of dimensions 300mm × 300mm × 100mm. Reinforcing steel bars of 13 mm diameter are embedded with 15 mm cover thickness for longitudinal arrangement. An accelerated corrosion test and cyclic wet -dry test were conducted. Half-cell potentials at the surface of the specimen were measured by portable corrosion-meter. In the accelerated corrosion test, the measurement was conducted twice a day, right after discontinuing the current. Chloride concentrations were measured at several stages the b-value becomes large at the 1st period and then the b-values keep fairly low. This result implies generation of small shear cracks at the first period. He concluded,

- That during the 1st period of high AE activities, the RA values become high, the average frequencies are low and the b-value is large. This implies that small shear cracks are actively generated as AE sources. Approaching to the 2nd period, the RA values become low, the average frequencies are getting higher and the b-values are small. The fact reasonably suggests that fairly large tensile cracks are generated due to expansion of corrosive product.
- Compared with AE results, it is found that the onset of corrosion starts, when the chloride concentration exceeds the lower -bound threshold.
- Removing rebars from the specimen, it is confirmed that rebars could corrode after chloride concentration reaches over the specified threshold, and AE activities after 100 days result from concrete cracking due to expansion of corrosive products in rebars.

Ohtsu et al. [24] studied the Acoustic emission Techniques for rebar corrosion in Reinforced corrosion. Two deformed steel-bars (rebars) of 13 mm nominal diameter were embedded with 20 mm cover -thickness. A In is observed, the total number of AE hits observed during the test is plotted by a solid curve. The 1st AE activity around at 14 days elapsed is clearly observed, while the 2nd activity is found at 60 day around in the NaCl portion.

The curve of AE activity in the NaCl portion is in remarkable agreement with the typical corrosion loss of the phenomenological model. The AE activity could be generated by concrete cracking due to expansion of corrosion products. It was suggested that AE activity can be observed in concrete specimen. Comparing AE activity with half-cell

potentials, it is found that with the increase in the number of AE hits, the potentials shift to more negative values. Here, two kinds of potentials are plotted. One is the potentials measured at the surface and the other is those by the embedded sensor. The embedded sensor shows more negative potentials. Still, the decreasing trends are similar. In the NaCl portion, at the 2nd period of high AE activity around 60 days elapsed, the potentials reach to more negative than -350 mV.

It is found that chloride concentration becomes higher than 0.3 kg/m^3 around at the 1st high AE activity, and it reaches higher than 1.2 kg/m^3 , resulting in the 2nd high AE activity in the NaCl portion. In the water portion, the 1st high AE activity is observed prior to the stage, where chloride concentration becomes over 0.3 kg/m^3 . Comparing AE activities in with the typical curve of corrosion loss for steel in sea water immersion, it could be summarized that two high AE activities reasonably correspond to two periods of the onset of corrosion and the nucleation of cracking. Corresponding to high AE activities twice, two active periods of AE events are observed in the NaCl portion. In contrast, only activity at the 2nd period is emphasized in the water portion. By employing the flaw location procedure, AE events were located. Then, it was found AE events located at the 1st period in the NaCl portion were only found around locations of AE sensors. So, AE wave-forms were examined. AE events detected at the 1st period were of so small amplitudes. Consequently, AE source locations at the 2nd period of high AE activity. It is realized that AE sources are reasonably located around rebar locations. This implies that corrosion activity due to concrete cracking, which is generated by expansion of corrosion products in rebar, is readily detected and located by AE technique.

Prateepasen et al [25] implemented AE recognition for severity prediction section that AE was used to detect the corrosion source and the observed frequency range can also be used for analysis successfully increases signal to noise ratio AE source got from pitting, uniform corrosion was detected using theories and analysis of corrosion mechanism frequency above 125KHz were used to separate bubble breakage from metal corrosion the AE hit rate with time factor was used to detect the corrosion rate the AE hit rate with the time factor was used to detect the corrosion rate both total Ae signal and each AE source was related to corrosion rate.

Kawasaki et al. [26] studied the corrosion mechanisms in Reinforced concrete by acoustic emission. In the paper, AE activities under a cyclic wet and dry test are investigated and these results are investigated by an electron probe microscope (EPMA). In order to investigate the Kinematical information of AE sources and nucleation of micro-cracks inside concrete, AE sources due to rebar corrosion in reinforced concrete are identified by Sigma analysis (Simplified Green's functions for Moment tensor Analysis). In addition, characteristics of AE signals are investigated by using AE parameter analysis and Ib-value analysis.

Cumulative AE hits are compared with half-cell potentials in. The half-cell potentials start to decrease after 28 days. Then, the potentials keep negative and less than -350 mV in Stage 2. Thus, the increase in AE activity could be associated with the decrease trend of the half-cell potentials. After Stage 1, corresponding to continuous increase in AE activity, corrosion-induced cracks in concrete is to be nucleated due to expansion of corrosion products in rebar. The corrosion could be started from the start. However, the half-cell potentials cannot detect the small corrosion. On the other hand, AE can detect very tiny corrosion phenomenon. Furthermore, fluctuations of Ib-values in Stage 2 are even bigger than those of Stage 1. These results imply that cracks were repeatedly generated as the onset of corrosion and the corrosion-induced cracks in concrete.

Two Stages in the corrosion process are confirmed, in relation to the onset of corrosion in rebar and the nucleation of corrosion-induced cracks in concrete. At the onset of corrosion, the decrease of the RA value and the increase of the average frequency are observed. At the same time, the decrease of the Ib-value is confirmed. It implies that the onset of corrosion could be identified by AE parameter analysis. Particular AE activity is found at Stage 2, corresponding to Phase 3 and Phase 4 in the phenomenological model. Due to corrosion-induced cracks, many of AE hits are observed. At Stage 2, the increase of the RA value and the decrease of the average frequency are observed. Then, the fluctuations of Ib-values in the Stage 2 are even bigger than those of Stage 1. This implies that Ib-value is effective to detect both the onset of corrosion and the corrosion-induced crack. At Stage 1, AE events were located in the specimen while no cracks were observed by the stereo-microscope. It implies that AE phenomena occurred due to corrosion initiation as the shear and the mixed-mode cracks. At Stage 2, micro-cracks were observed at the cross-section by the stereo-microscope.

Mangual et al. [27] studied the degradation of steel in prestressed concrete bridges using AE technique. Along with Half Cell Potential the damage in strands was observed by the variation of current. HCP was also used to assess the probability of initiation of corrosion and was compared with AE results and the above hypothesis was proven right. The variation in current and result of HCP was compared to A and the credibility of technique was proven. Source location based on AE data enabled the accuracy of detection of corrosion. Intensity analysis was able to differentiate the early stage corrosion compared to electrochemical and mass loss. The magnitude of slope in cumulative signal strength versus time curve was able to portray the Depassivation process and the onset of corrosion as corroded by Half Cell Potential.

Patil et al. [28] also used the non-destructive testing technique AE with the relative study of result from electrochemical analysis. Comparative study of AE with the other two techniques was done for monitoring of corrosion of reinforced concrete element and a perfect correlation between the techniques was obtained. The results show two stages of corrosion and it ensures that cumulative signal strength is a reliable parameter of AE technique to monitor corrosion. Half Cell Potential Variation in initial stages shows very low permeability of corrosion in initial stages but somehow HCP of all specimens drop down quickly indicating active corrosion almost at same point. The decrease in potential shows high probability of active corrosion. Somehow the corrosion resistance is increased due to movement of chloride ion herein concrete under the influence of electric field of impressed current. Although HCP is a good parameter to check the initiation of corrosion but afterwards it doesn't give a good idea of the later stages. Electrochemical polarisation scan were done of all samples, variation of corrosion density with respect to time was also compared with variation of cumulative signal strength with respect to time. It indicates four stages with two sudden rises. Hence the reliability of AE Cumulative signal strength parameter so as to evaluate chloride induced corrosion.

Weng et al. [29] studied the early corrosion process in Pre Stressed concrete piles using AE and is sensitive to formation and growth of micro nuclear cracks both in steel concrete which may develop upon Depassivation of reinforcement and build-up of corrosion by products. Five specimens were undergone wet and dry salt water tidal action for one year and was monitored continuously using AE sensors side by side. Electrochemical recordings were taken regularly. No apparent behaviour in prestressed and

no prestressed piles with respect to corrosion was observed. The analysis of AE signal strength and cumulative signal strength can aid in detection of steel Depassivation and early corrosion. It was conducted that IA and AE were effective for discriminating between corroding and non-corroding samples. The number of significant hits to calculate the historic index and severely shall suitably defined to offset under staining corrosion damage previously proposed IA base for corrosion assessment were refined for the case of steel Depassivation and early corrosion.

4.3 CLOSING REMARKS

This chapter presents the literature review on the use of ultrasonic guided wave technique and acoustic emission technique for monitoring the corrosion process in RC structures. Both these techniques were found to be very efficient in the corrosion monitoring of the structures. In this study, both these techniques are used for monitoring the RC cylinder specimen subjected to accelerated induced corrosion.

CHAPTER5

EXPERIMENTAL DETAIL AND METHODOLOGY

5.1 GENERAL

The focus of this study is to check the reliability of ultrasonic Guided Wave and Acoustic emission technique to analyse the behaviour of passively protected RC cylindrical specimen during various stages of corrosion. Wrapping of these specimen are done by FRP as a protection from corrosion and the results are compared with the destructive tests Pull out Test and Mass loss carried out on the same samples and check the efficiency of FRP protection on RC specimen from corrosion.

5.2 TEST PROGRAM

The detailed step by step by step procedure followed in the research is explained below and shown in Fig 5.1

1. Finding out the basic material properties of mainly cement, fine aggregates, coarse aggregates and Steel Bar properties as per Indian Standard.
2. RC cylinder specimen having dimensions 150mm diameter 300mm height with 600mm reinforcement of 25 mm diameter casted in a way such that half of it is inside the specimen and the other 300 mm is projected out of M20 grade concrete **Fig 5.2** and **Fig 5.3**
3. A constant Voltage of 10 V was maintained for a time period of 28 days inducing accelerated corrosion in specimen under study (RC Cylinders)
4. Acoustic Emission (AET) and Ultrasonic Guided wave (UGW) technique was used to monitor the RC cylinder specimen under study and induced corrosion.
5. CFRP GFRP were used to laminate the RC cylindrical specimen under study after an interval of Three six nine and twelve days of corrosion to protect against corrosion in future.

6. Monitoring of CFRP GFRP wrapped specimen after respective days of corrosion using UGW and AET to determine efficiency of these NDT techniques to monitor protection offered by wraps
7. Destructive Tests such as Pull out and mass loss test was carried out on the RC cylinder specimen under study.

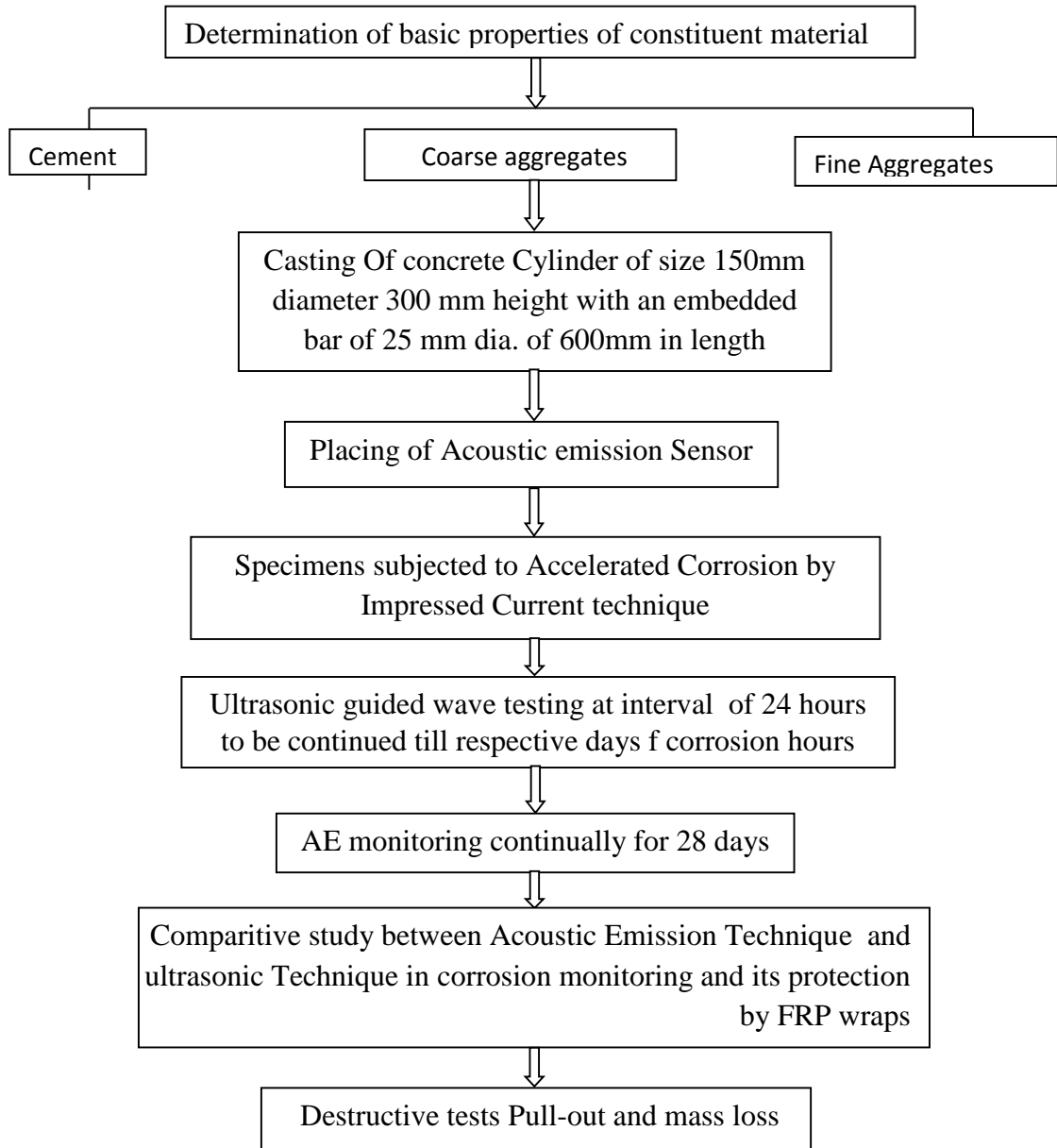


Fig 5.1: Methodology Followed

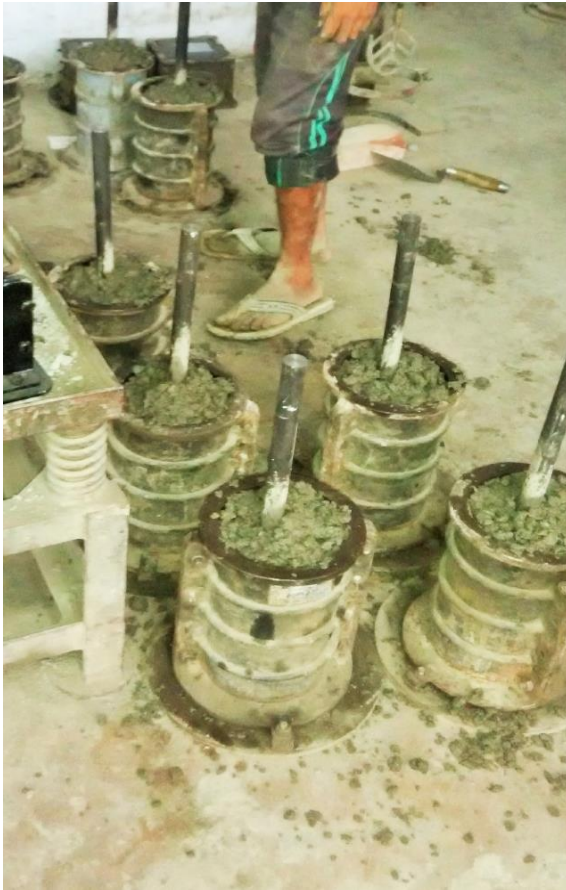


Fig 5.2 Specimen being Casted



Fig 5.3 Cylindrical Specimen after corrosion

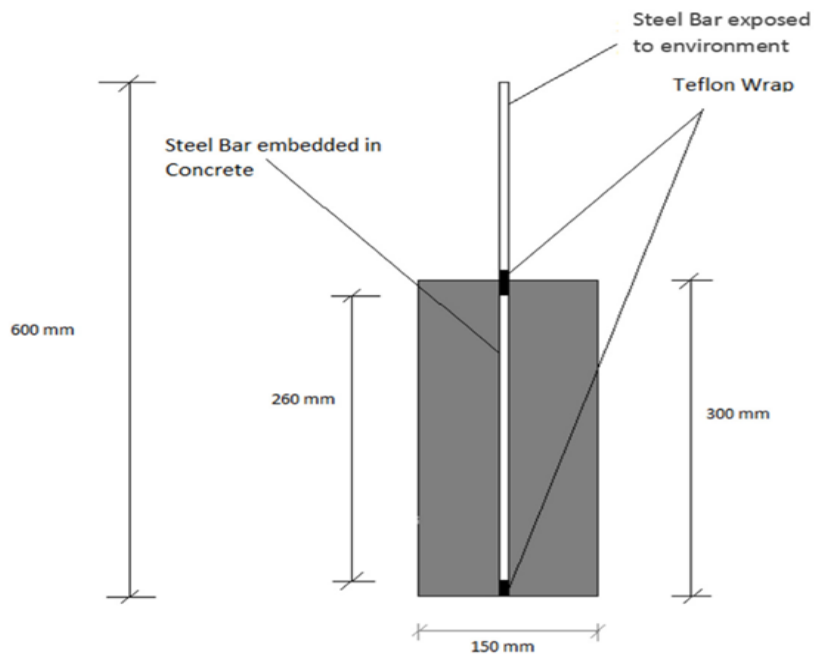


Fig 5.4 Schematic of Specimen [20]

Table 5.1: Test Matrix for Specimens

Wrap Material	Exposure in days	Protection	Nomenclature
Unwrapped samples	28	No	C-1
	28	No	C-2
Wrapped with Glass fibre	3	Passive	GPP-3 S1
	3	Passive	GPP-3 S2
	6	Passive	GPP-6 S1
	6	Passive	GPP-6 S2
	9	Passive	GPP-9 S1
	9	Passive	GPP-9 S2
	12	Passive	GPP-12 S1
	12	Passive	CPP-12 S2
Wrapped with carbon fibre	3	Passive	CPP-3 S1
	3	Passive	CPP-3 S2
	6	Passive	CPP-6 S1
	6	Passive	CPP-6 S2
	9	Passive	CPP-9 S1
	9	Passive	CPP-9 S2
	12	Passive	CPP-12 S1
	12	Passive	CPP-12 S2

5.3 MATERIALS USED

For casting cylinder cement, fine aggregates, coarse aggregates, water was used and 25 mm mild steel bar was embedded in it. The specifications and properties of these materials are as under:

5.3.1 Cement

Ordinary Portland cement of 43 grade (O.P.C 43) was investigated. The cement was of uniform colour i.e. grey with a light greenish shade and was free from any hard lumps. Summary of various test conducted on cement is given in table. All these tests were carried out in accordance with the procedure laid down [31]

5.3.2 Fine Aggregates:

The fine aggregates used for the experimental work was locally procured and conformed to grading zone III. Sieve analysis was carried out in the laboratory [32]. Fine aggregates were first sieved through 4.75mm sieve to remove aggregates greater than 4.75 mm in size and were then washed to remove the dust. The physical properties and sieve analysis of fine aggregates are shown in the table 5.2 and 5.3 respectively.

Table 5.2: 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	–
Compressive strength			
S. No.	Time (Days)	Values N/mm ²	
1	3	13.8	
2	7	25.42	
3	28	28.33	

Table 5.3: Physical properties of cement

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 5.4: 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
				<i>FM =</i>	<i>2.62</i>

5.3.3 Coarse Aggregates

Crushed stone aggregates of size 20mm were used throughout the experimental study. The aggregates were washed to remove the dust and dirt and were dried to surface dry condition. The aggregates were tested as per IS 383-1970. The results of various tests conducted on coarse aggregates are given in **Table 5.5** and **Table 5.6** shows the sieve analysis results.

Table 5.5: 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 5.6 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 =
				<i>FM</i> =	6.95

FM of 20 mm coarse aggregates= $(195.73+500)/100=6.95$

5.3.5 Concrete Mix

Concrete mix is prepared using 43 grade O.P.C, fine aggregates (Medium sized river sand) and crushed stone coarse aggregates with a nominal size of 20mm. The mix is designed as per the Indian standard guidelines. Mixed design was calculated as 1:1.49:2.48. The water cement ratio is 0.45 and compressive strength of concrete after 28 days is 28.5 MPa.

5.4 TEST PROCEDURE

5.4.1 General

It is an established fact that corrosion takes place only when the chloride concentration at the rebar value reaches the critical value. The ultrasonic guided waves were used to identify the extent to which corrosion has occurred or to identify the mechanism of corrosion in the R.C. Cylinder by measuring the ultrasonic signals while the bar is subjected to corrosion in the chloride environment. Acoustic Emission monitoring was also done continuously for 28 days and finally both the techniques were compared in their efficiency of corrosion monitoring in the R.C Cylinder.

5.4.2 Preparation and Preconditioning of Steel Bars

Steel bars are cut to the desired length of 600 mm. Each bar is then wire brushed to remove any surface scale. These are then cleaned by soaking them in analytical reagent hexane and allowed to dry in the air. Before embedding these bars in the concrete, these cylinders were also monitored ultrasonically to check their quality.

5.4.3 Preparation of Specimens

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

- **Water:** Fresh and clean tap water is used for casting slabs in the present study. The water is relatively free organic matter, silt, oil, sugar, chloride and acidic material as per Indian standard.
- **Steel reinforcement:** Mild steel bars of 25 mm diameter and 600 mm length are used as reinforcement. Half of the steel rod (300 mm) is embedded in the concrete and half remains exposed to environment, in order to make electrical connections and conduct pull-out test later on. **Table 5.7** shows the properties of reinforcing bars used for casting of RC cylindrical structures.

Table 5.7: Properties of reinforcing bars used for casting specimens

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

- **Fibre Reinforced Polymer:** The FRP materials used are CFRP (Carbon Fibre Reinforced Polymer) and GFRP (Glass Fibre Reinforced Polymer) as shown in Fig. 5.4 and Fig. 5.5 below:



Fig. 5.5: CFRP laminate



Fig. 5.6: GFRP laminate

The various properties of CFRP and GFRP laminates are given in **Table 5.8**

Table 5.8: Properties of CFRP and GFRP [20]

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

- **Adhesives:** concrete is bonded with FRP sheets using adhesive named compatible epoxy system (MBrace) as shown in **Fig 5.6**. MBrace fibre sheet is saturated with this blue pigmented resin to form in-situ FRP composite. It is made by mixing hardener in the ratio 100:40 and base saturant. Mixing of saturant and hardener is mixed thoroughly for five minutes until components are thoroughly dispersed. Epoxy is made conductive by adding graphite powder. Properties of the epoxy are discussed in **Table 5.9**.

Table 5.9: Properties of saturant

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



Fig. 5.7: MC Brace Adhesive used for bonding FRP with concrete

5.5 INDUCING CORROSION IN CONCRETE

The main objective of inducing corrosion to the reinforcing bar is to simulate the corrosion to damaged concrete. The commonly used methods of inducing corrosion in reinforced concrete specimens can be called as Salt spray, Chloride diffusion and impressed current method. Previous studies have revealed that the test specimens that were kept in a salt spray chamber for more 100 days or more did not show any visible signs of corrosion. Since there are always time constraint. So, the method is not suitable. This method was not taken into account because it did not simulate the present condition of interest.

Corrosion is also induced by immersing the specimen into NaCl and drying alternately. However, impressing anodic current is the quickest method of inducing corrosion. In this method, NaCl solution is provided to the specimens and direct current is passed through them making the reinforcement bar as an anode and another metal which is nobler than reinforcing bar in electro-chemical series as cathode.

The cylindrical specimens were immersed in a bucket with 3.5 % NaCl solution to keep them fully saturated. Anode was the rebar. A stainless steel (SS) mesh is rolled around the circumference by stainless steel mesh in order to assure electrical continuity, it was tied together with metal ties and is used as cathode (**Fig. 5.7**).

The constant voltage of 10 mV is impressed in order to accelerate corrosion. The DC power supply (Aplab) was used as a voltage source. The rebar is arranged such that positive terminal is connected to the external DC source and negative terminal is connected to SS mesh. It is important to maintain a constant voltage between the two electrodes. Constant Potential drop is maintained by the help of an external power supplying Fig **5.10**

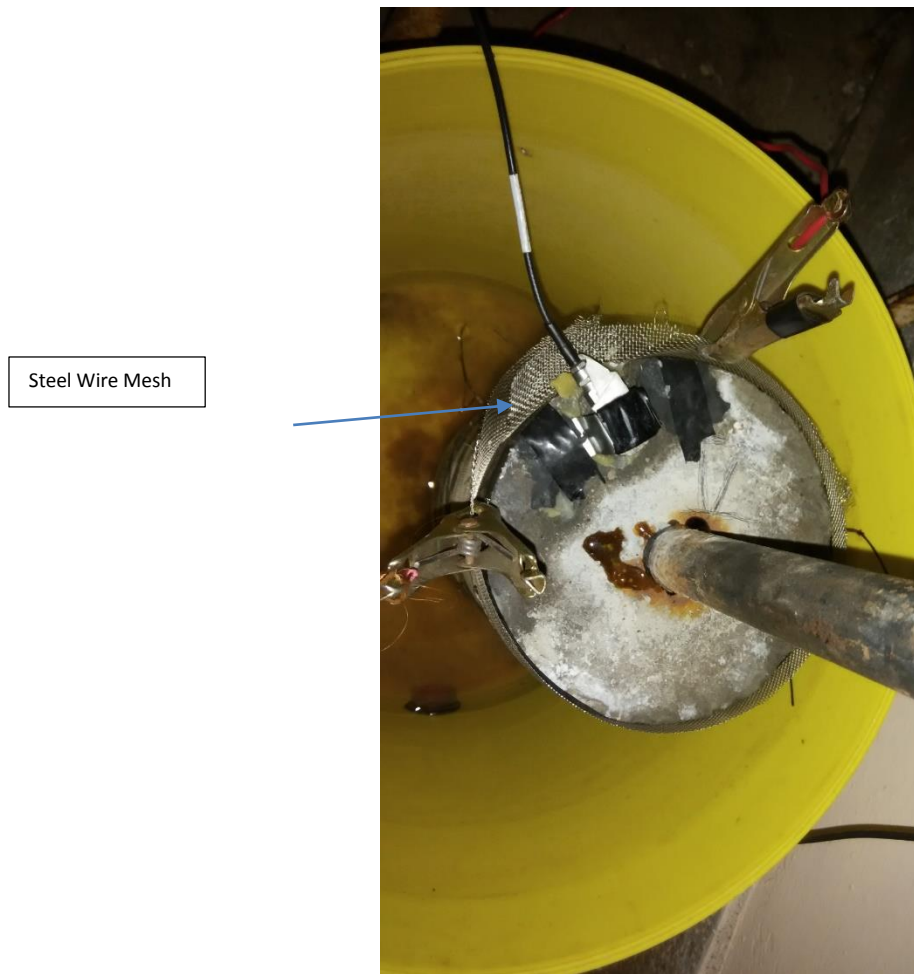


Fig. 5.8: Specimen wrapped with stainless steel

5.6 PROTECTION AGAINST CORROSION BY FRP WRAPS

Two fibre materials commonly used for rehabilitation of structures in India are Glass and Carbon. Because of the better electrical conductivity of carbon fibre, only CFRP has generally been used for active protection. A comparison has been made between glass and carbon fibre sheets regarding the active and passive protection offered by both. Unidirectional sheets of fibres are made. Glass fibre sheets are generally thicker than the carbon fibre sheets. In this investigation CFRP and GFRP sheets and compatible epoxy adhesive are used.

Method of applying wraps: The samples are dried in air prior to the application of FRP wraps. During application of the wraps, manufacturer's specifications are followed. A mixture of epoxy resin and hardener is prepared in the ratio of 100:40. This mixture is being used for wrapping the carbon fibre sheets into

concrete. One specimen out of four was kept unwrapped. Specimens were wrapped with one layer of either GFRP or CFRP sheet with fibre along the circumferential direction of the cylinder (**fig. 5.9**). The cylinder was entirely covered. Overlap of 25mm was provided at the ends of the sheets.

The remaining specimens are used for active protection. To facilitate uniform distribution of direct current throughout the specimen for effective active protection, CFRP wrapped test specimens are provided with additionally adhesive bonded 25 mm to 30 mm wide, vertically oriented carbon sheet. Modified epoxy adhesive was used as conductive.



(a)



(b)

Fig. 5.9: Specimens wrapped with (a) GFRP (b) CFRP



Fig 5.10 DC Power Supply (AplabLD6405)

5.7 DESTRUCTIVE TESTS

- **Pull-out test:** All the specimens were subjected to pull out test. The pull out test is carried out on specimen at 3, 6, 9, 12, and 28 days which are have been protected by FRP interval and compared with 28 days corroded sample and healthy specimen. From demoulding day to test day the specimen were completely exposed to salt mist. Test was carried out by securing the cylinder in a universal testing machine and the grip was attached on to the protruding portion of the reinforcing bar.
- **Mass-loss:** Mass loss was calculated after the pull out test had been conducted. To calculate the mass loss, the steel bars were cleaned up. To remove the corrosion products steel bars were immersed in the acidic solution. The acidic solution was prepared using 50% solution of hydrochloric acid to which hexamethylene tertramine was added with a concentration of 3.5 g per litre. Steel bars were immersed in this solution for about 10-15 min, depending upon the extent of corrosion, and then taken out to measure the weight. To ensure that all the corrosion products were completely removed, the process was repeated 4-5 times so as to stabilize weight of the steel bars. To determine the mass loss, the final weight of the steel bars were compared to the original weights.

5.8 ULTRASONIC GUIDED WAVE INVESTIGATION

5.8.1 Method of Testing

Pulse-echo (PE) testing method was adopted for ultrasonic guided wave investigation. In the pulse-echo method, ultrasonic energy was transmitted and received by a piezoelectric transducer. Its longitudinal axis is located perpendicular to and mounted on or near the surface of the test material (Fig.5.11). The ultrasonic waves get reflected by the opposite face of the material, by discontinuities, voids, layers, or inclusions in the material. Waves are received by the same transducer and the reflected energy is converted into an electrical signal using the transducer. The electrical signal is processed by computer and then displayed on a video monitor or TV screen. The displayed content shows the relative thickness of the material, depth into the material where flaws are located, and (with proper scanning hardware and software), location of flaws in X-Y plane.

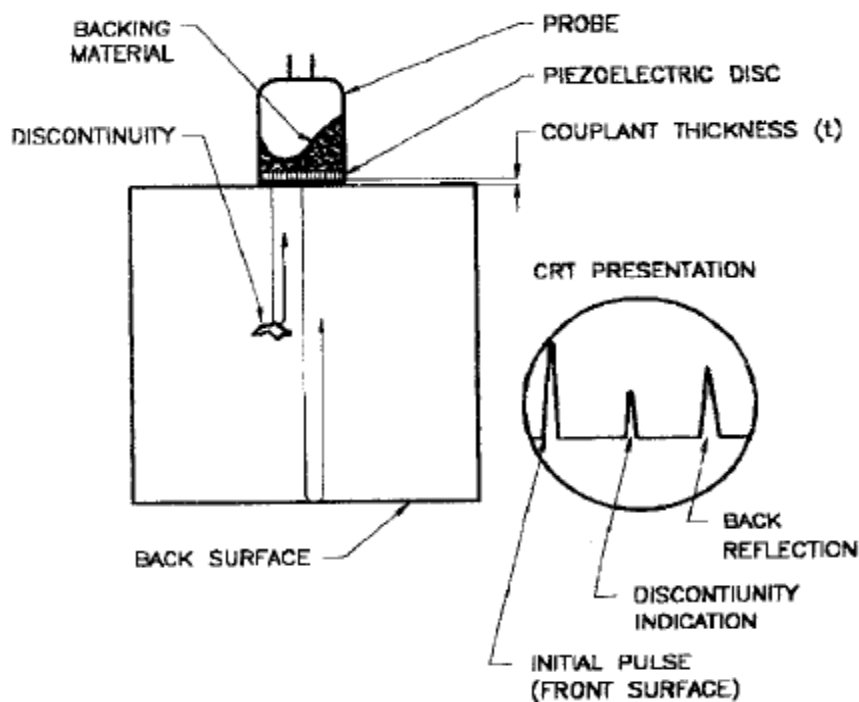


Fig5.11. Pulse Echo method for Testing [30]

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

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

$$D = Vt \text{ ----- (5.1)}$$

Where, D = Distance of defect from transducer end,

V = Velocity of wave

t = Time of Flight.

Now in this case the distance travelled by the wave would be equal to double the length of the bar that would be 1200 mm and the speed of wave would be the speed of sound, i.e., 5 km/s.

Therefore the time at which the peak has to be noticed would be 0.00021 or 200µs. The set up used in the present study is sketched up in Fig 5.12. The ultrasonic test set in this study uses DPR 300 pulse receiver system (Fig. 5.13) and Karl Deutch contact transducers (Fig. 5.14)

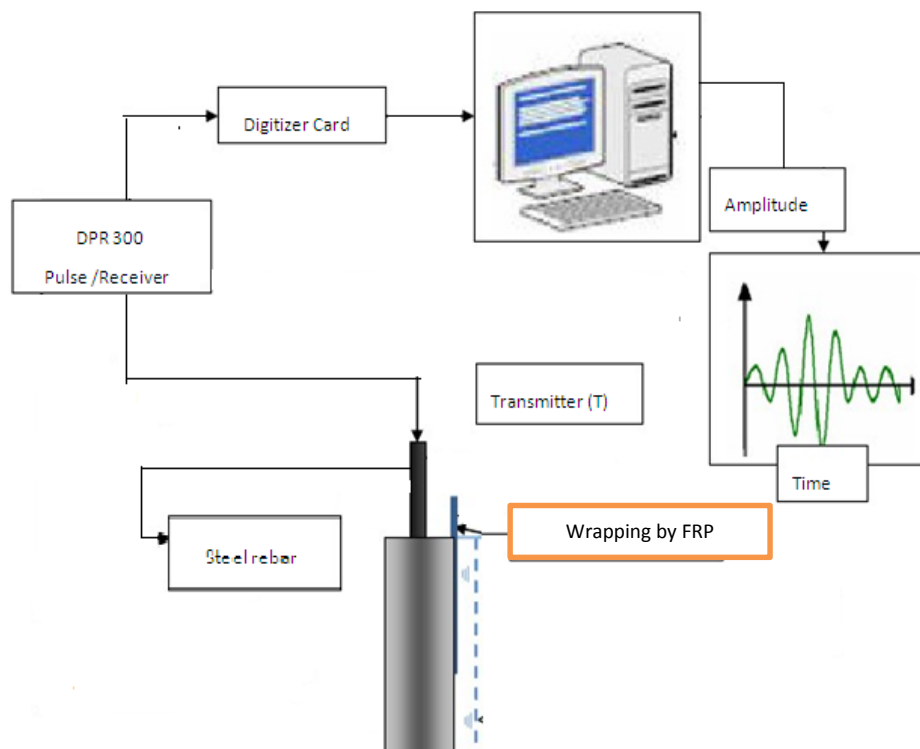


Fig. 5.12: Set up for P-E Ultrasonic investigations [20]



Fig. 5.13: Contact type transducers (Karl deutch)



Fig. 5.14: Pulse Receiver (DPR 300)

5.8.2 Selection of Excitation mode and Frequency

The selection of a suitable test mode and frequency is done after analyzing the dispersion curves using the software Disperse. It was Studied modes that have lowest signal attenuation and at the same time are easily distinguishable are selected[31]. Generally, modes at low attenuation are used to maximize the inspection range and at the same time to minimize the effects of dispersion and also minimize the interference of other modes in the received signal

5.9 ACOUSTIC EMISSION TECHNIQUE

The phenomenon of acoustic emission is defined as the propagation of elastic waves due to release of localized internal energy, such as micro-fracture in elastic material. Structural deformation processes such as plastic deformation, crack expansion and other kinds of material degradation are the sources of the AE activity. Detection, amplification, filtering and analyzing the signal are some of the important issues in AE technology. AE monitoring system typically consists of sensors, preamplifiers and AE acquisition and analysis system.

In our study the corrosion process was accelerated by the impressed current technique. The research aims to identify the onset of corrosion by means of AE in RC specimens. The schematic representation of AE set up is as shown in the **Fig.5.15:**

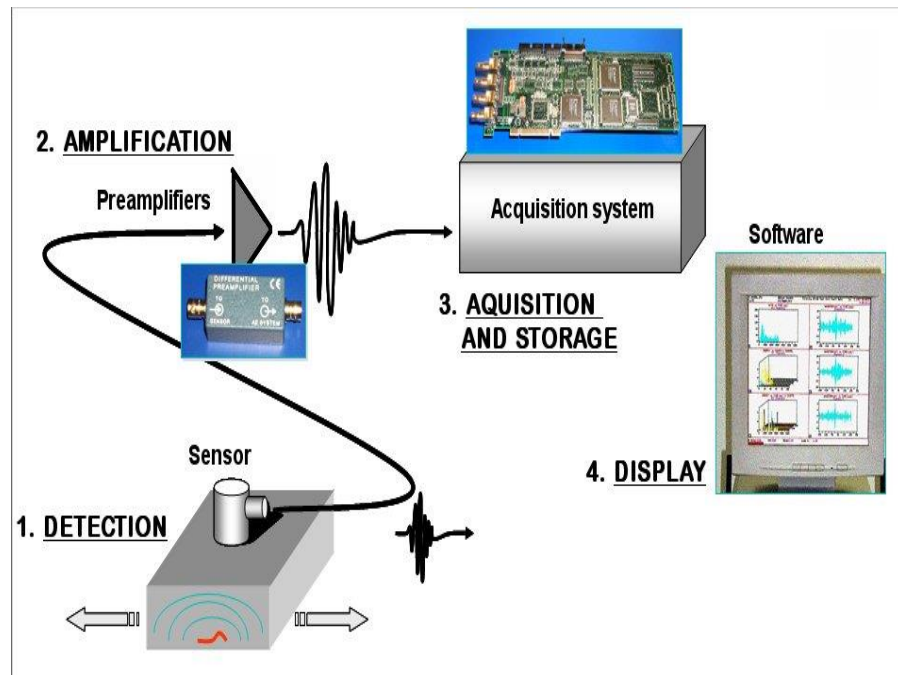


Fig.5.15: Schematic representation of the AE monitoring

AE data acquisition system used for experimentation was Micro II digital AE system provided by PAC (Physical Acoustics Corporation) **MISTRAS GROUP** which is shown in the **Fig.5.16**.



Fig.5.16: Data acquisition set up used for the study

Sensors are placed on the surface of the structure to record acoustic emission signals. Sensors are available in wide range of shapes and sizes as shown in the **Fig.5.17**.



Fig.5.17: Acoustic Emission Sensors generally used

Acoustic Emission sensors which were used for monitoring the corrosion in the present study are shown in the **Fig.5.18**.



Fig.5.18: R3a Sensors for AE Acquisition used in the study.

The specifications of the sensors used in the present study are shown in the **Table 5.7**.



Fig.5.19: Pre-amplifier used in the study

Table5.10: Specifications of the sensors

Operating frequency range	35-100 KHz.
Resonant frequency	150 KHz
Physical Dimensions	19mm dia.× 22.4mm height
Weight	31 grams
Case Materials	Stainless Steel

Good coupling of the sensors to the test specimen is necessary for the effective transmission of AE signals. Sensors are attached on the surfaces using magnetic holders, glues, even rubber bands and tapes. A layer of couplant such as vacuum grease, ultrasonic gel, and oil is applied between the two surfaces. Operating frequency range is important during sensor selection. The common frequency range for AE testing in civil infrastructure is 100-300 kHz.

Experiment was carried out on a RC cylinder specimen of 150mm X300mm along with a bar of 600mm long and 25mm diameter embedded in concrete such that 150mm length is exposed to the environments from both sides. The acquisition system has 8 channels and is expandable up to 32 channels. However, we used four R3 α sensors (resonant at 30 KHz) and preamplifiers with a gain set at 40 db and frequency range of 20-1200 KHz.

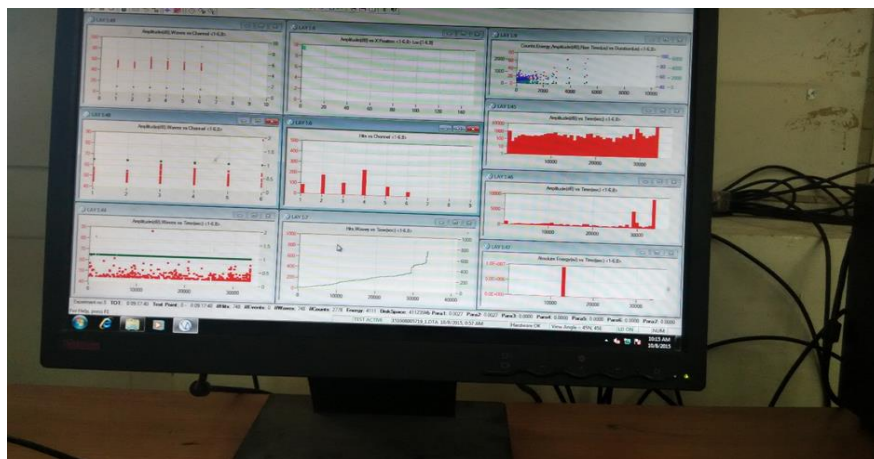


Fig 5.20 AE Win Software Interface Recording

Two sensors were mounted on the front face of the RC cylinder specimen and two sensors were mounted on the bottom face of the cylinder specimen. The position of the sensors is shown in the **Fig.5.21** and **Fig.5.22**

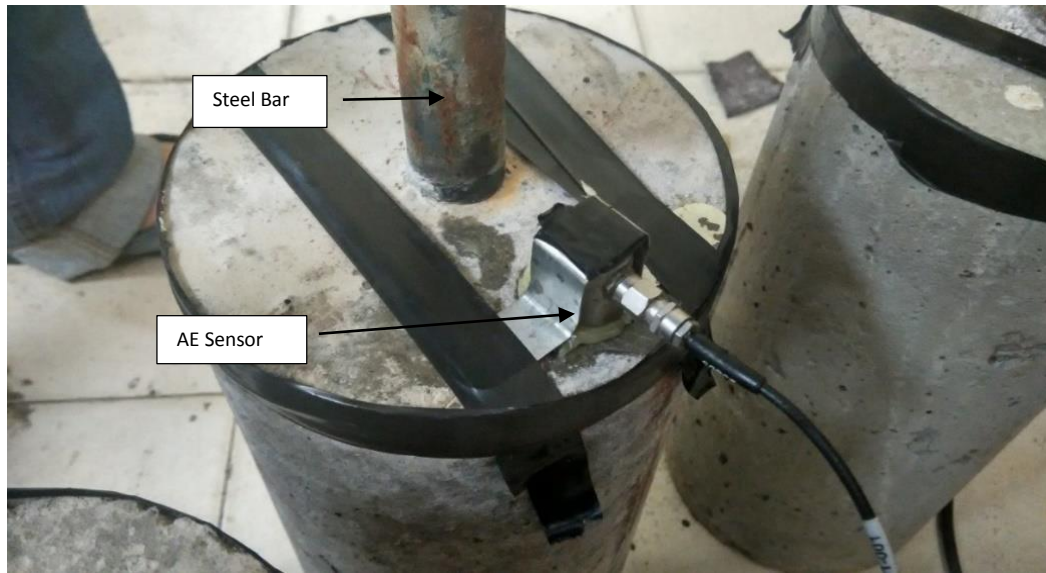


Fig.5.21: Location of sensors on the Top face of the cylinder



Fig.5.22: Actual sensors mounted on the cylinder

A band pass filter of 20-400 KHz was set in the software control of the data acquisition system. A threshold value was set at 45 db for experimental purpose. The experimental set up used in the study is shown in the **Fig.5.22**.

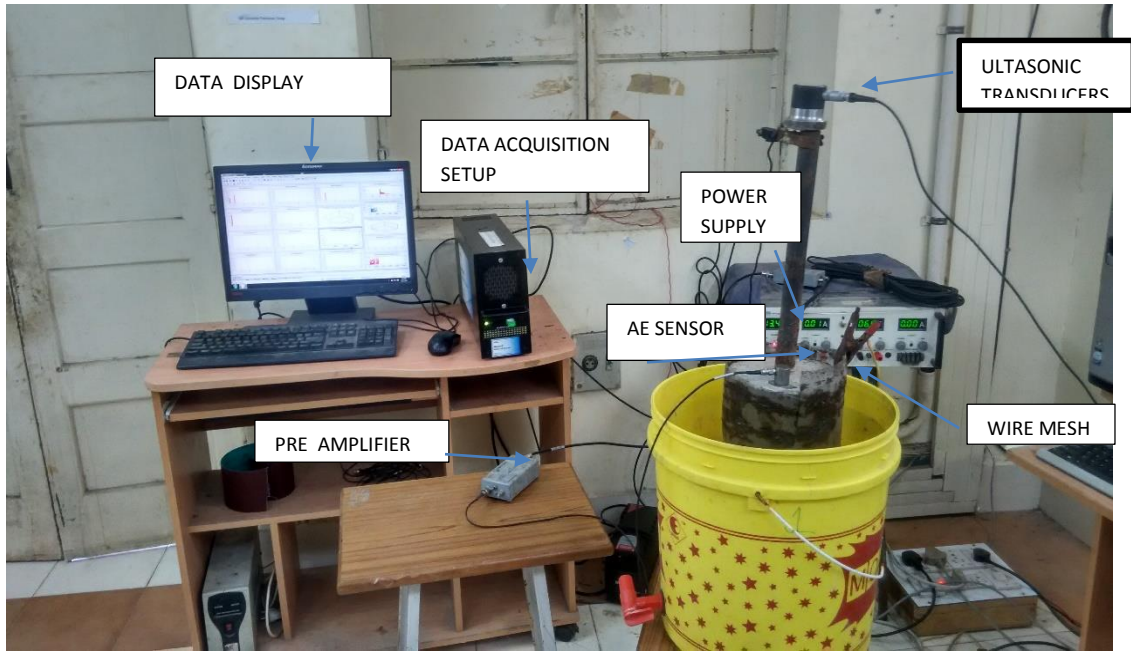


Fig.5.23: Experimental set up used in the study.

Hence, it is clear from the above figure that any acoustic activity occurring in the specimen is detected by the sensors. These signals are amplified by the pre-amplifiers before entering the data acquisition system. The data acquisition set (Micro II Digital AE system) which processes the data and finally displays the data on the monitor screen.

AE signals were generated by breaking 0.5mm pencil leads at selected locations on the plate and in each position pencil lead break tests were done thrice. (Fig.5.24)



Fig.5.24: Pencil lead

The AE signals were generated by breaking 0.5mm pencil leads on the selected locations on the surface of the RC cylinder specimen and in each position pencil lead break test were done twice. This was done to make sure that sensors are mounted properly on the RC cylinder specimen and they are able to detect the reflections though their amplitude would be smaller than the crack related signal.

5.10 CLOSING REMARKS

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

6.1 GENERAL

There are a number of techniques that can be used to carry out the assessment of a structure suffering from corrosion of the reinforcement. However, in order to determine the rate of deterioration of the structure; it is useful to monitor the condition change with time. It was carried out using the latest technique of ultrasonic guided waves and acoustic emission. Ultrasonic guided waves and Acoustic Emission which are used to monitor initiation and progression of Acoustic Emission due to corrosion in RC cylinders before and after protection. Efficacy of guided waves to monitor effectiveness of passive protection in RC structures is investigated in the study. Destructive tests of mass loss and pull out tests were also carried out to relate the physical condition of the RC cylinder during corrosion

6.2 GUIDEDB WAVE INVESTIGATION

6.2.1 Control Samples Undergoing Corrosion (Ultrasonic Guided Wave Measurement :

Ultrasonic guided wave technique was used to monitor the corrosion in RC Cylinder using $L(0, 1)$ and $L(0, 7)$ at 0.1 MHz and 1Mhz respectively. The embedded reinforcement in concrete were excited at one end. The bar acting as a waveguide assisted its propagation. The waves leaked into the concrete and thus attenuate before coming back where it was received by the transducer. The exciting signal consisted of a compressive spike pulse. The received signal was further studied and processed for interpretations.

Fig. 6.1, 6.2 PE signatures taken over progression days of corrosion using $L(0,1)$ and $L(0,7)$ mode for Control samples C1 using .1Mhz ,1Mhz respectively and Similarly Fig 6.3 and 6.4 show the PE trend for Control Sample C2.

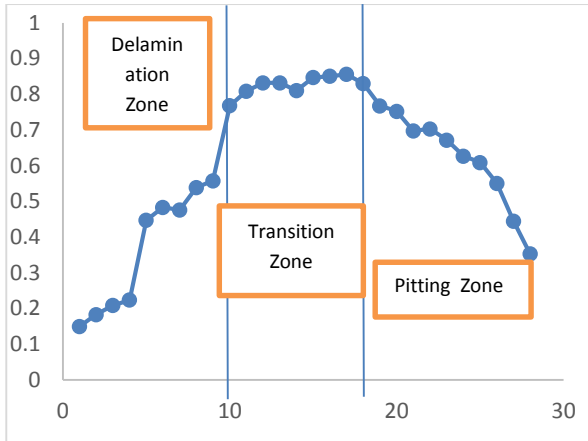


Fig.6.1: P-E trends for C1- sample using L (0, 1) at .1 MHz transducer

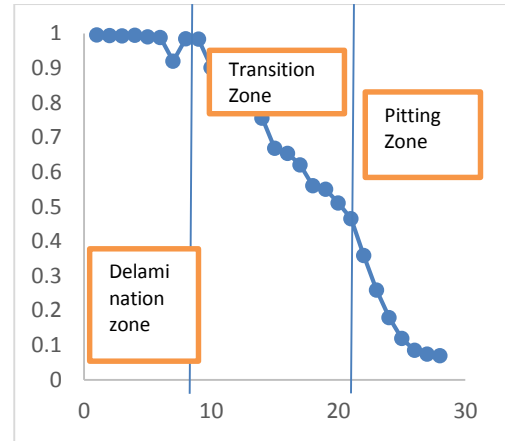


Fig.6.2: P-E trends for C1- sample using L (0, 7) at 1 MHz transducer

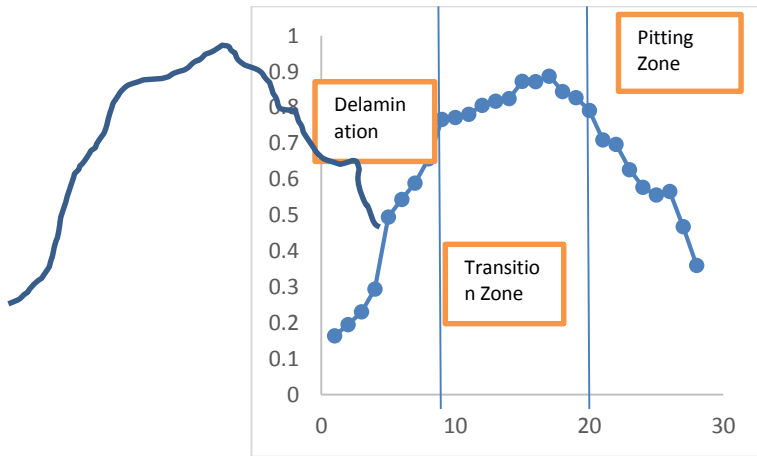


Fig.6.3: P-E trends for C2- sample using L (0, 1) , .1 MHz transducer

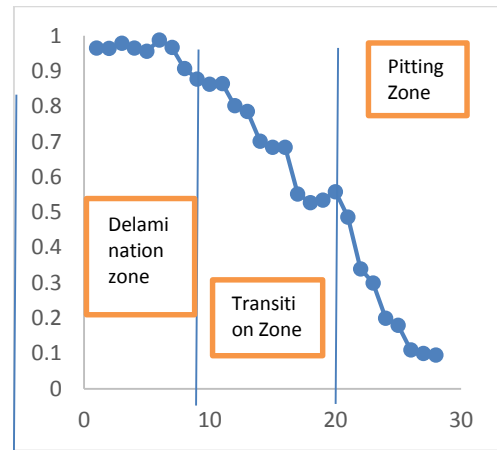


Fig.6.4: P-E trends for C2- sample using L (0, 7) ,1 MHz transducer

From P-E investigations of control samples, following observations are made using selected node:

- **L(0,1) at 0.1 MHz**

From **Fig. 6.1, 6.3** it can be seen that the voltage amplitude of the reflected signal increases rapidly with the progression of corrosion in initial 10 days which marks the delamination of the rebar due to corrosion. Initially, the reinforcing bar has a good bond with the surrounding concrete which causes reduction signal leakage. 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 causing reduction of signal leakage, as the corrosion progresses, the delamination keeps on increasing which creates a barrier around the rebar. Now the signal keeps on increasing with the increase of corrosion. This is well depicted by the signal rise as shown in the graphs. This is marked as delamination zone in the graph further after this from 10 to 20 days using this mode doesn't vary much and is named as transition Zone. From 20 to 25 days there is rapid fall in the signal and this region is termed as pitting zone as the fall in the signal is rapid.

- **L(0,7) at 1 MHz**

From **Fig 6.2, 6.4** it can be seen that initially the reflected pulse strength is very high but as corrosion progresses, the reflected signal starts falling. The reflected signal keeps on falling till it vanishes. Initially when the corrosion starts, (0 to 10 days) it first delaminates the bar completely from the surrounding concrete which is not picked up by this mode. As corrosion progresses further, it starts penetrating into the bar and is marked by the local loss of area in the form of pitting and crevices of the bar which are detected by this mode. The reduction in the area of the bar due to corrosion causes fall in the amplitude of the signal and the reflected pulse. Hence pitting is marked by the core seeking mode..L(0,7) mode which is centre seeking mode. The intermediate 10 to 20 days is marked as the transition phase and after that till 28 days is marked by pitting zone which is very well picked up by this mode.

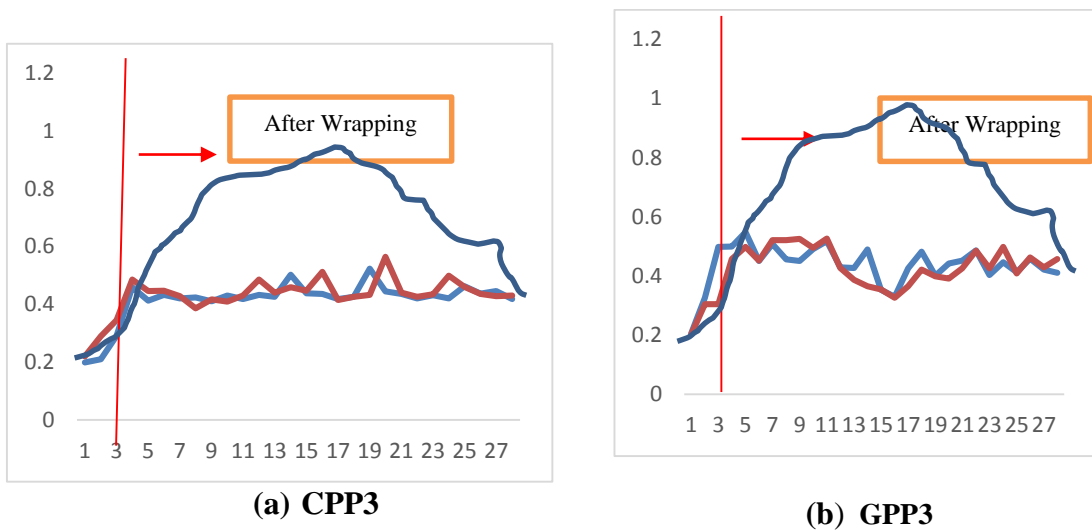
Hence the accelerated corrosion process is picked up by Guided wave consisting of three phases Delamination Zone, Transition Zone, Pitting Zone

6.2.2 Protected Samples Undergoing Corrosion (Ultrasonic Guided Wave Measurement)

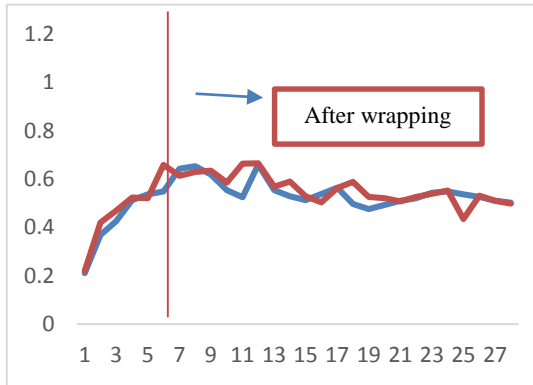
Fig. 6.5, 6.7, 6.9 and **6.11** shows P-E Trends for passively protected cylindrical samples protected by CFRP monitored with 0.1 MHz transducer it can be seen that the voltage amplitude of the reflected signal increases rapidly with the progression of corrosion in initial 10 days which marks the delamination of the

rebar due to corrosion. Initially, the reinforcing bar has a good bond with the surrounding concrete causes reduction signal leakage but as soon as the specimen are passively wrapped the signal does not falls considerably and there is not much variation now from the time passive protection is done to the specimen as the wrapping of CFRP to corroded specimen impedes the corrosion process and there is variation from the genral trend that should have been followed by signals of a specimen under corrosion.

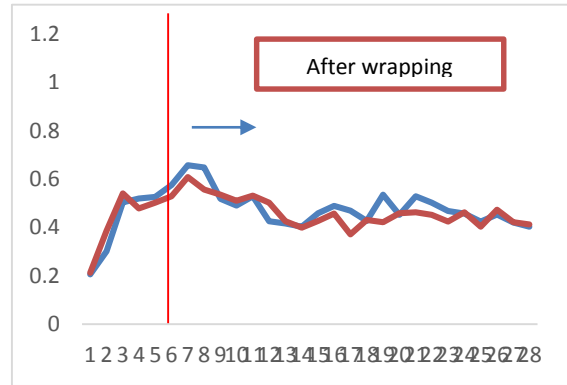
Fig. 6.6 , 6.8 6.10 and 6.12 show P-E Trends for passively protected cylindrical samples protected by GFRP and monitored with 0.1 MHz transducer Further in this report the relative difference in the results is discussed and the trend on signal rise and fall are co related with the phases of corrosion of control samples .



**P-E Trends for passively protected samples after 3 days of corrosion
(a) CFRP and (b) GFRP**



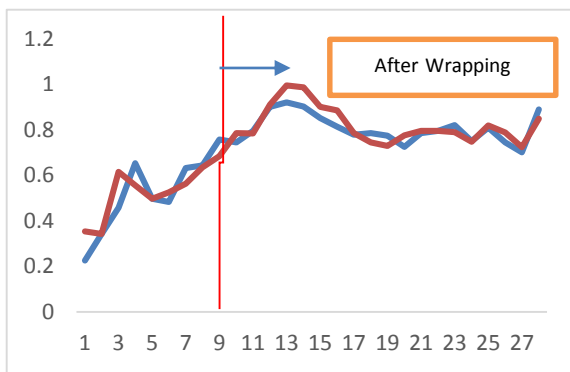
a)CPP6



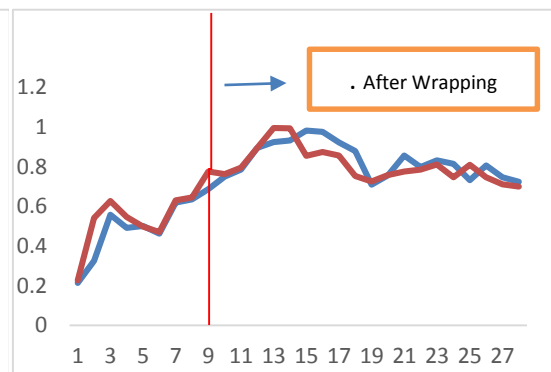
(b)GPP6

P-E Trends for passively protected samples after 6 days of corrosion

(a) CFRP and (b) GFRP



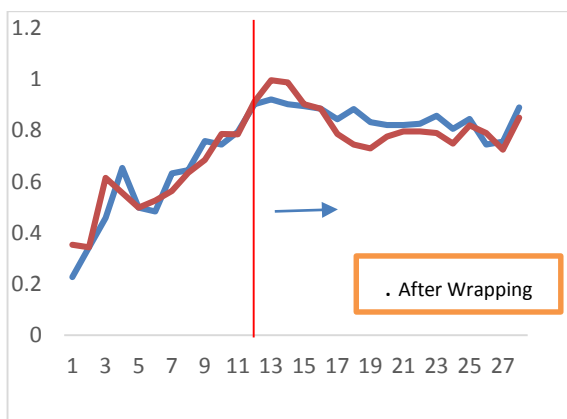
(a)CPP9



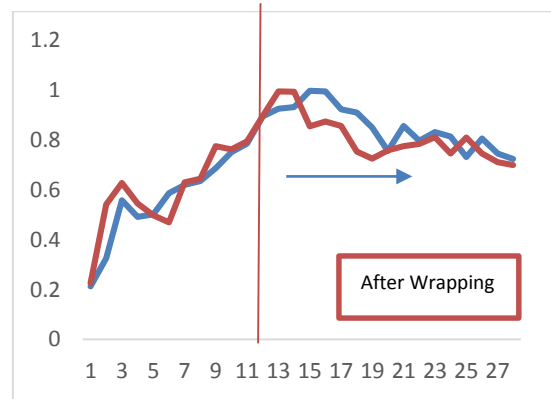
(b) GPP9

P-E Trends for passively protected samples after 9 days of corrosion

(a) CFRP and (b) GFRP



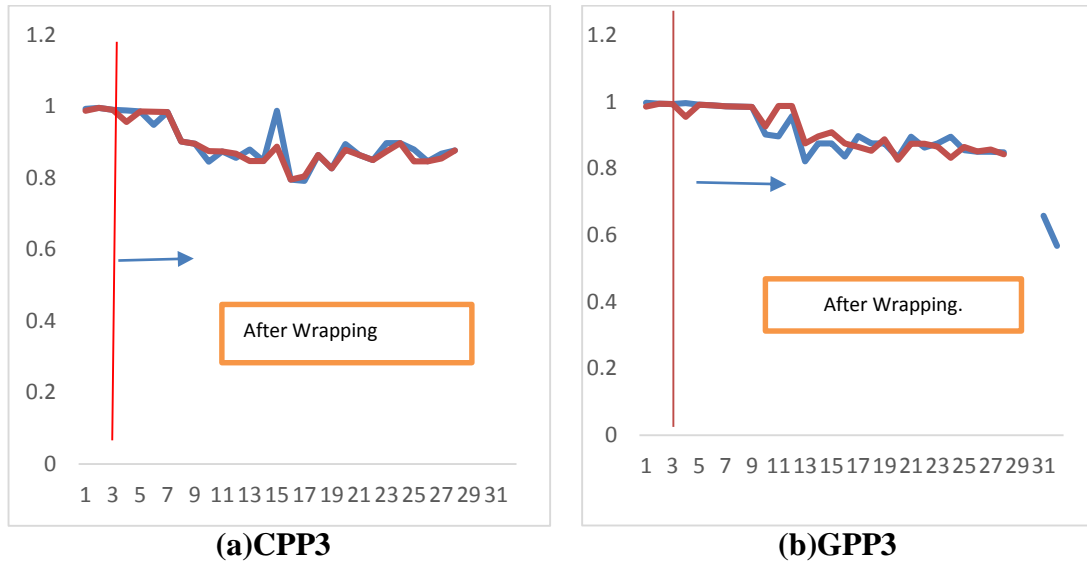
(a)CPP12



(b)GPP12

Fig. 6.8: P-E Trends for passively protected samples after 12 days of corrosion (a) CFRP and (b) GFRP

Pulse Echo trends for passively protected Cylinders at L(0,7) mode at 1 Mhz



P-E Trends for passively protected samples after 3days of corrosion

L(0,7) mode at 1 Mhz (a) CFRP and (b) GFRP

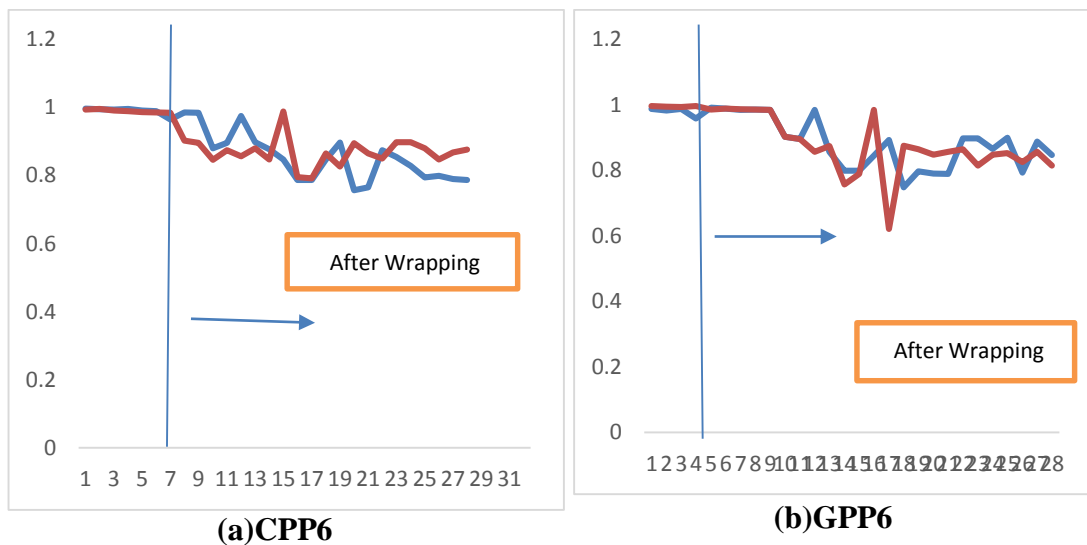


Fig. 6.10: P-E Trends for passively protected samples after 6 days of corrosion L(0,7) mode at 1 MHz (a) CFRP and (b) GFRP

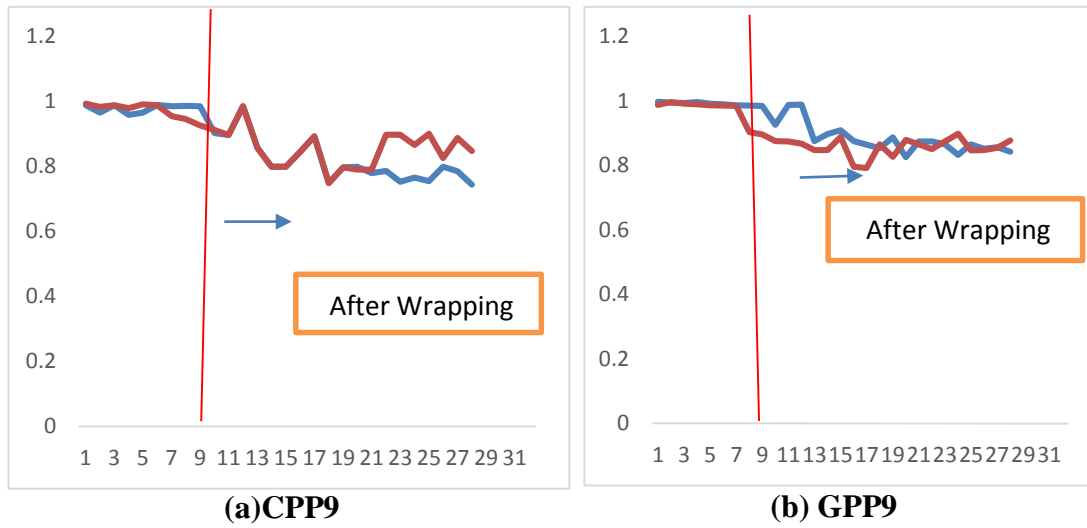


Fig. 6.11: P-E Trends for passively protected samples at L(0,7) mode at 1 MHz after 9 days of corrosion (a) CFRP and (b) GFRP

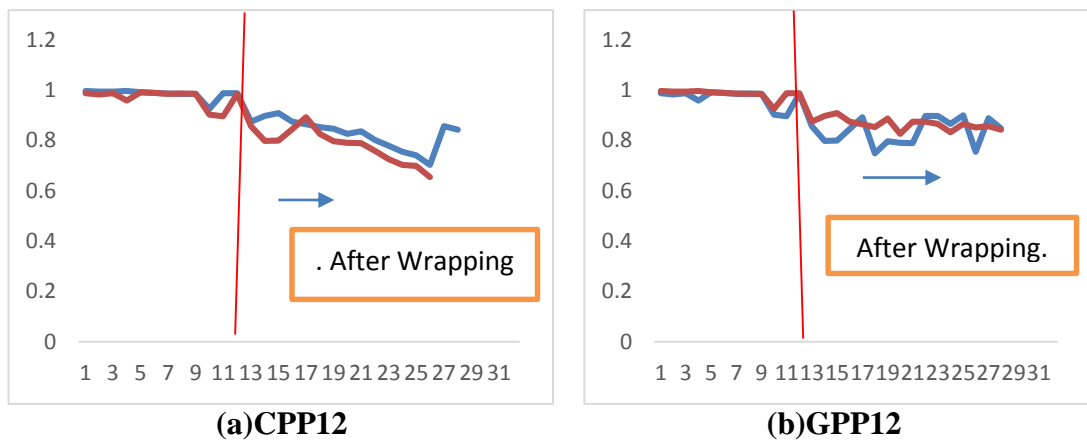


Fig. 6.12: P-E Trends for passively protected samples at L(0,7) mode at 1 MHz after 12 days of corrosion (a) CFRP and (b) GFRP

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

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

From the graphs shown in **Figures 6.5, 6.6, 6.7, 6.8** following observations are made:

1. The peak to peak voltage amplitude starts rising with the progression of corrosion till the days upto which the corrosion is carried out i.e., 3 days, 6 days , 9 Days and 12 days, pointing towards the delamination due to corrosion with increased exposure. This causes less leakage into concrete and signal strength rises. It is similar to the trends observed with the control samples
2. After providing passive protection with GFRP in GPP3, GPP6 ,GPP9 and GPP12 samples, the signal instead of rising starts becoming constant first and then starts falling. It points towards confining effect of wrapping on concrete, hence impeding corrosion which is shown by fall in signal strength. Hence, the guided waves are not only effective in picking up corrosion but are also able to detect effect of corrosion protection by fall in signal using surface seeking modes.
3. After providing passive protection with CFRP in CPP3, CPP6 CPP9 and CPP 12 samples, using the surface seeking mode, same behaviour of signal as it was in case of GFRP is seen.
4. Important observation regarding the comparison of GFRP and CFRP is seen the specimen which The signal becomes constant for a while and then starts falling after protection and the further corrosion progress almost negligibly .In the case of GFRP it is observed that the signal fall is .comparatively less than specimen that are protected by CFRP. . This shows that GFRP gives better passive protection than the CFRP.

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

From the graphs shown in **Fig 6.9 , 6.10 , 6.11, 6.12** following observations are made:

1. As in case of control samples, upto corrosion in 3, 6, 9 and 12 days in CPP and GPP samples, the signal remain constant as in the case of control samples upto the respective exposure period starts falling due to pitting effect of chloride corrosion causing the attenuation of signal After the primary 10 to 12 days .

2. But after protection using both GFRP and CFRP, after 3, 6, 9, 12 days instead of falling as in transition and pitting zone using core seeking mode samples till approximately 10 to 12 days in delamination dominates zero in this mode does not work the signal stops falling but almost becomes constant pointing towards the confinement of concrete with FRP wraps, slowing down the progression of corrosion in protected samples.
3. Both passive protection systems using GFRP and CFRP showed similar trends but the signal did not fall in the case of CFRP wrapping when compared to GFRP is more wrapping pointing towards that GFRP gives better results GFRP .
4. Moreover, the signal starts rising instead of falling in case of CPP and GPP samples after 3, 6, 9 and 12 days. This is a very remarkable observation showing the effectiveness of corrosion impediment by wrapping.

6.3 ACOUSTIC EMISSION MONITORING

Acoustic emission has been recently used for corrosion monitoring in RC structures. According to the phenomenological model of steel corrosion in marine environments (Fig. 6.13), loss of mass can be divided into four phases [34].

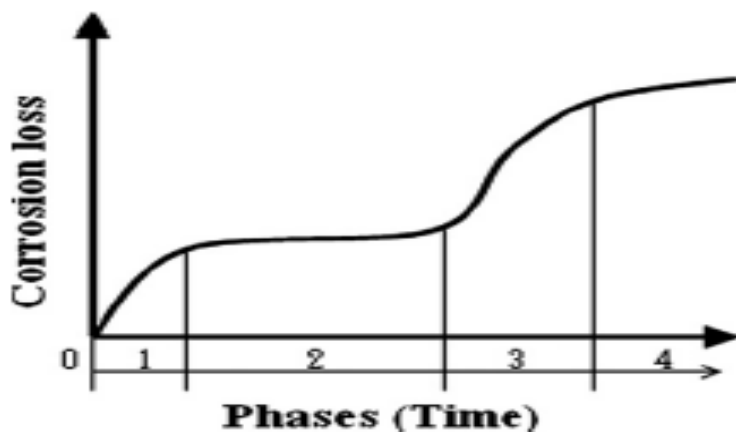


Fig. 6.13 Typical corrosion loss of steel in marine conditions [31]

- The **FIRST PHASE** corresponds to the initiation of corrosion. It can be said that the alkalinity of the system reduces to a great extent. This results in the breaking of the passive layer and therefore the initiation of corrosion.

- The **SECOND PHASE**: Once the corrosion is initiated, the development of rust on the reinforcing bar takes place. This further blocks the flow of oxygen and hence, the loss of mass decreases. This is called an s phase 2 and can also be termed as the calm phase.
- The **THIRD PHASE**: As the corrosion penetrates inside and their expansion of corrosion products occur, the mass loss increases readily. This phase is termed as phase 3.
- The **FOURTH PHASE**: And After phase, the corrosion progresses at a uniform speed. This phase is called as phase 4. The phenomenological model clearly indicates the two transition stages, i.e. the initiation of corrosion and the growth of cracks. Therefore, since the phenomenon of corrosion is able to generate the corrosion-induced cracks in concrete, the importance of AE technique is for monitoring can be capitalised to understand the initiation progression and cracking process in concrete due to corrosion.

However, in this study, acoustic emission monitoring was done continuously for a period of 28 days. A single sensor (R3a) was mounted on the surface of the RC cylinder, subjected to accelerated corrosion. AE monitoring was stopped every day when the UGW readings had to be taken.

6.3.1 Monitoring AE observation of Control samples

Fig.6.15 shows the acoustic emission recorded for control samples(C-1 and C-2), subjected to corrosion for a period of 28 days. A very important parameter “AE hits” has been used and plotted against time, in order to study the process of corrosion in RC structures. From the Fig. 1& 2, it can be clearly seen that cumulative AE hit plot is very much congruous to the phenomenological model. During the first eight days of accelerated corrosion, there is an increase in the number of AE hits. This increase can be very well linked with the Phase 1 of the corrosion model that points towards the onset of corrosion and thereby increase in the internal stress causing the recording of AE hits. From 8-17 days of accelerated corrosion, the increase in AE hits decreases to a great extent which further relates with the phase 2 of the corrosion model. This is essentially because of the development of rust on steel thereby impeding the corrosion for some time. From 17-22 days, a sharp rise in the recording of AE hits has

been observed. This suggests the nucleation of corrosion induced cracks in concrete which relates well with the phase 3 of the corrosion model. From 22-28 days of accelerated corrosion, not much AE activity has been recorded. This is because of two reasons one is that all major cracking has occurred and secondly, with the development of cracks, there is a great attenuation of signal reaching the AE sensor. It correlates with Phase 4 of the corrosion model.

6.3. 2 Monitoring AE observation of Control samples

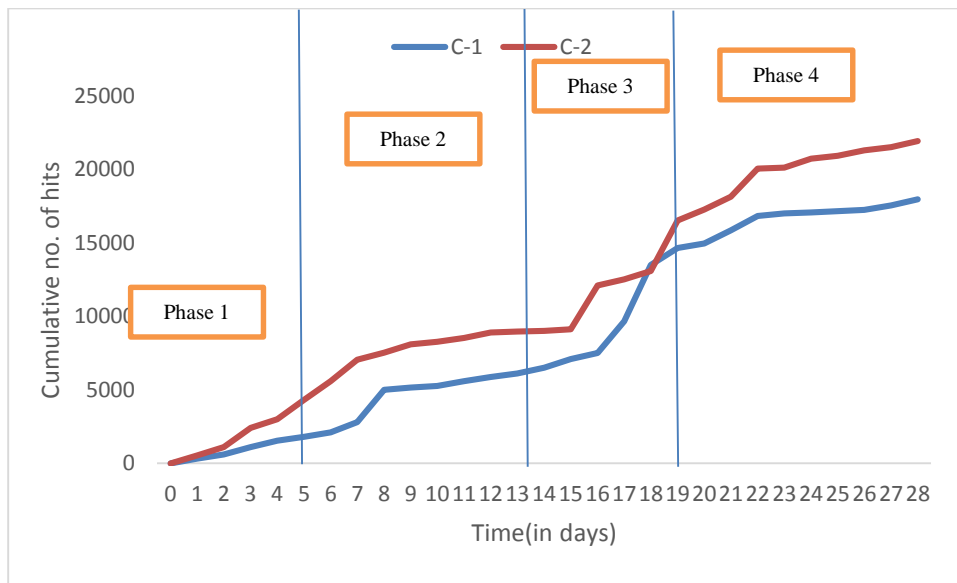
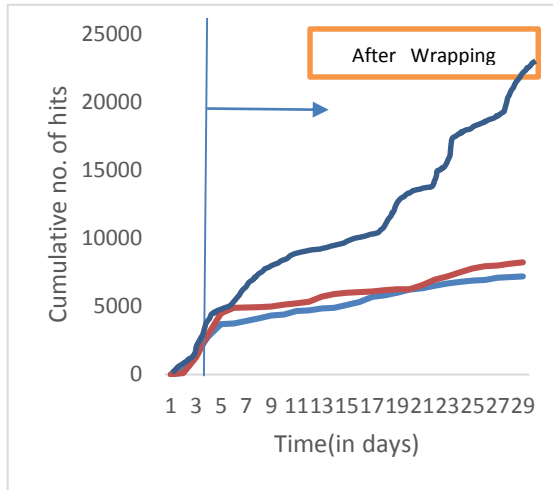


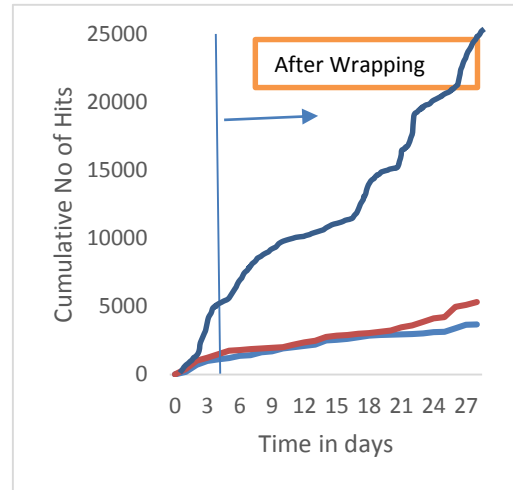
Fig 6.14 Cumulative AE vs Time for control specimen

Hence in control samples subjected to 28 days of accelerated corrosion induced degradation in concrete in RC cylinder leading to initiation progression and cracking of concrete is well picked up by concrete AET. The following section reports AE hits recorded after wrapping of cylinder with GFRP and CFRP wraps for corrosion impediment.

Fig.6.15 shows that the protection provided after 3 days of accelerated corrosion has proven to be very successful. There is very small marginal increase in the no. of AE hits after the protection is provided. It can also be observed that though the corrosion has initiated in initial 3 days, which is visible from the initial rise and hits recorded. But the passive protection has successfully been able to block the entry of oxygen and therefore impeding the corrosion process.



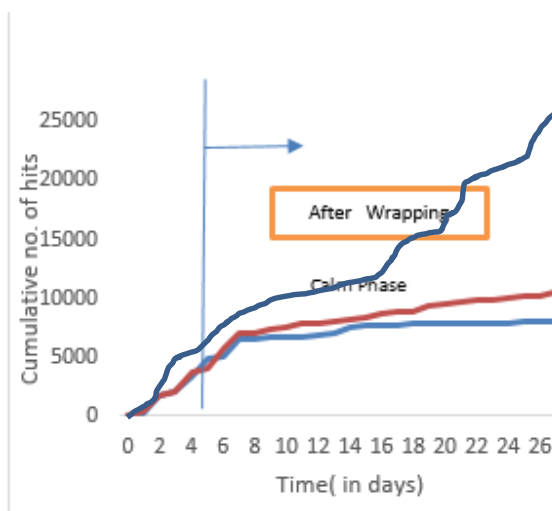
a) CPP3



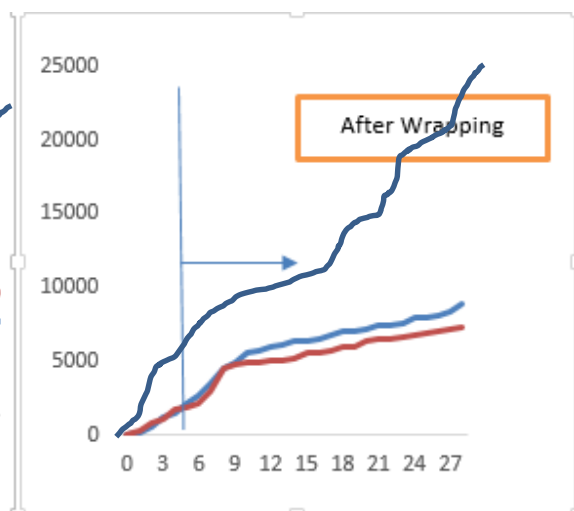
b) GPP3

Fig. 6.15 shows the AE hits recorded Of CPP3 and GPP 3 after 3 days of accelerated corrosion and passively protected from corrosion

None of the phases could be identified from the graphs as it was reported in case of the control specimens. Although the partial initiation of **PHASE1** can be seen, there is no culmination of **PHASE 1**. GFRP and CFRP if compared with each other on the basis of number Acoustic Emission reported in wrapped sample than control samples points towards the efficiency of protection by FRP wraps by corrosion protection by AET .The result indicates the effectiveness of AET for not only monitoring initiation of corrosion but also impediment by wrapping



a)CPP6



b)GPP6

Fig. 6.16 Shows the No. of hits versus time for passively protected specimens after 6 days using both GFRP and CFRP.

Fig.6.16 shows the recorded AE hits plotted against time for RC cylindrical specimens, passively protected after 6 days of accelerated corrosion. It can clearly be observed that the passive protection has been able to impede the corrosion. Only **PHASE 1** is predominant and no other phase is detected. This implies that corrosion was only initiated but due to the blockade of further oxygen by the passive protection wraps of GFRP and CFRP around the concrete, the corrosion process stops immediately.

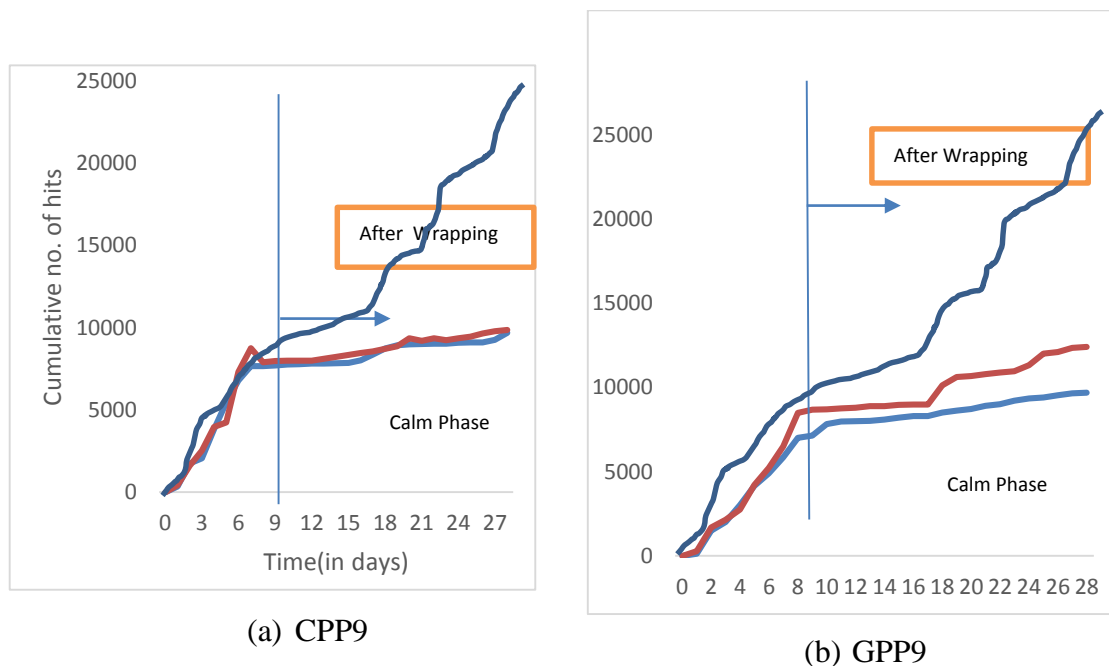


Fig. 6.17 Cumulative no. of hits versus time for passively protected specimens after 9 days using both GFRP and CFRP.

Wrapping after 9 days : Fig 6.17 shows the plot of recorded AE hits with time for RC cylindrical specimens passively protected against corrosion after 9 days of accelerated corrosion. The graph clearly indicates that the **PHASE 1** has completed. This implies that corrosion has initiated. And there is also beginning of **PHASE 2** which is the calm phase. But afterwards, there is very little number of AE hits that are being recorded implying that corrosion progress has been completely stopped.

Fig.6.18 shows the plot of recorded AE hits with time for RC cylindrical samples, passively protected after 12 days of accelerated corrosion. The **PHASE 1** has been clearly identified indicating the onset of corrosion and the beginning of **PHASE 2**. However, it

can be very clearly seen but the corrosion process in PHASE 3 is not observed which involves major cracking due to the nucleation of induced cracking that the protection is not as successful as it was in the case of 3, 6, 9 and 12 days.

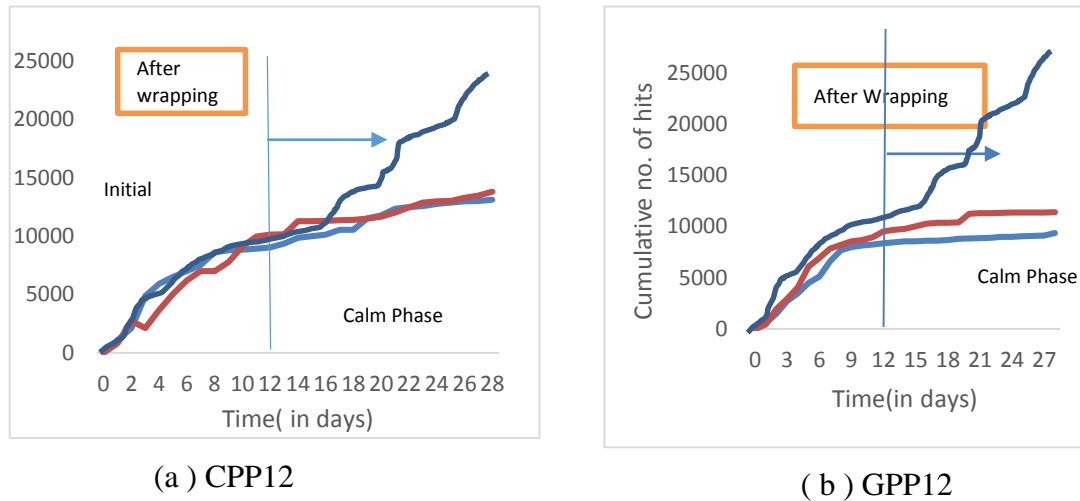


Fig. 6.18 Cumulative no. of hits versus time for passively protected specimens after 12 days using both GFRP and CFRP.

Though the corrosion progress has been stopped and there are no signs of **PHASE 3** and **PHASE 4** which involve the major cracking due to the nucleation corrosion induced cracking. Actually unprotected samples it can be said that calm phase continues after wrapping hence impeding corrosion.

From AE monitoring of CFRP and GFRP protected specimens providing passive protection using R3a sensor mounted on the surface of the cylinder, following observations are made:

- The AE activity stops immediately after the protection is applied for GFRP as well as CFRP protection.
- GFRP wraps has given better results as can be clearly seen that almost no rise in AE hits has been recorded after the protection in comparison to CRP there is small increase in the no hits observed .
- After comparing the results with the control specimens, It can also be concluded that other than **PHASE 1**, no other phase could be identified in case of specimens wrapped after 3 and 6 days of accelerated corrosion,

In sample wrapped after 9 days of **PHASE 2** are seen in case of the sample wrapped after 9 days of corrosion and complete **PHASE 2** can be observed from the sample wrapped after 12 days of accelerated corrosion.

- It can also be identified that AE hits are being recorded right from the time of initiation of experiment. This further implies that AE has the capability of recording corrosion as it starts inside concrete.

Hence AET not only picked up initiation and progression of corrosion as in phenomenal model but also remarkable related to the corrosion protection offered by FRP wraps in both CFRP and GFRP samples It is indicated by phases Which are picked by AE .

6.4 DESTRUCTIVE TEST MEASUREMENTS

6.4.1 Pull-out test: Destructive pull-out test is performed when the specimen has been subjected to exposure of corrosion for respective days and protected both passively and actively. This was done by securing the cylinder in a Universal Testing Machine (UTM) and attaching the grip to the protruding portion of reinforcement bar as shown in Fig. 6.19.



Fig. 6.19: Pull-out test set-up

Table 6.3: Pull Out Strength measurements Control and GFRP Protected Samples

Sample	Pull Out Strength (MPa)
Control Specimen	6.3
GPP-3	10.2
GPP-6	10.91
GPP-9	9.1
GPP-12	8.15

Table 6.4: Pull Out Strength measurements Healthy and CFRP Protected

Sample	Pull Out Strength (MPa)
Healthy	12.3
CPP-3	8.35
CPP-6	8.6
CPP-9	8.2
CPP-12	7.95

From **Table 6.3**, it can be said that as the number of days of corrosion exposure increases, pull out strength decreases. This is due to the formation of rust products that delaminate or debond the bar from surrounding concrete. Hence, the bars are pulled out from the concrete very easily and the pull out strength reduces.

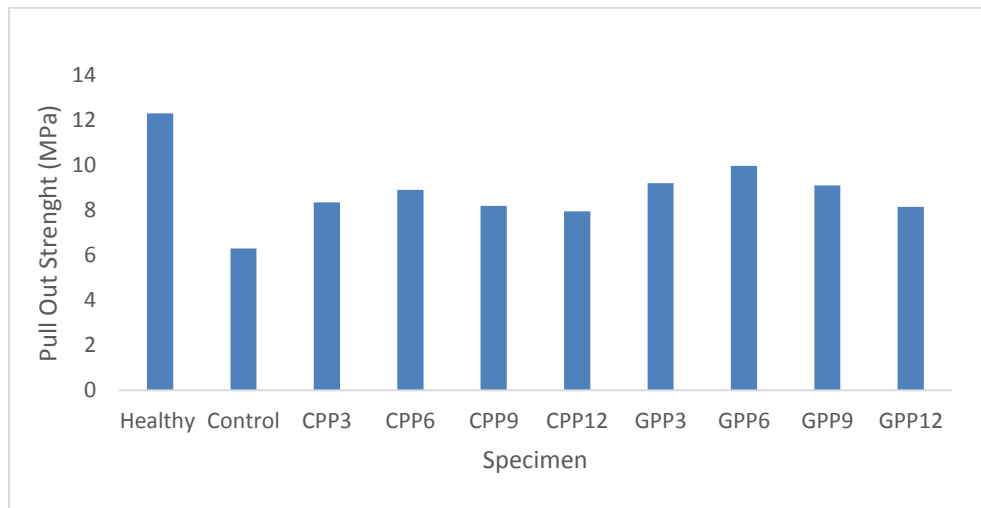


Figure 6.20: Pull Out Strength VS Days of Corrosion

From the graph shown in Fig 6.20 Plotted from data of Table 6.3, following conclusions can be drawn:

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

- There is a huge difference in the values of control specimen that was corroded for 28 days to the healthy specimen which proves that the bond between the reinforcement and the concrete reduces with the progress in corrosion.
- Further the pull out strength of GFRP protected samples to that of CFRP samples is higher showing that GFRP gives better confinement and resistance to corrosion. The pull out strength on general increases from 3day FRP protected sample to 6 day protected sample as the corrosion by products fill the void around the bar and some how increases the bonding but with further increase in corrosion with time these by-products gets drained out from concrete.

6.4.2 Mass Loss

After carrying out the pull-out test, the corroded bars were cleaned of all corrosion products and weighed to determine their mass loss. **Table 6.4** shows the variation in mass loss for different samples.

Table 6.3: % Mass loss measurements Control and GFRP Protected Samples

Sample No.	% Mass loss
Control Specimen	7.25
GPP-3	2.87
CPP-6	3.645
CPP-9	4.37
CPP-12	5.40

Table 6.4: % Mass loss measurements Control and CFRP Protected

Sample No.	% Mass loss
Healthy	0.1
GPP-3	3.1
GPP-6	4.4
GPP-9	5.15
GPP-12	6.14

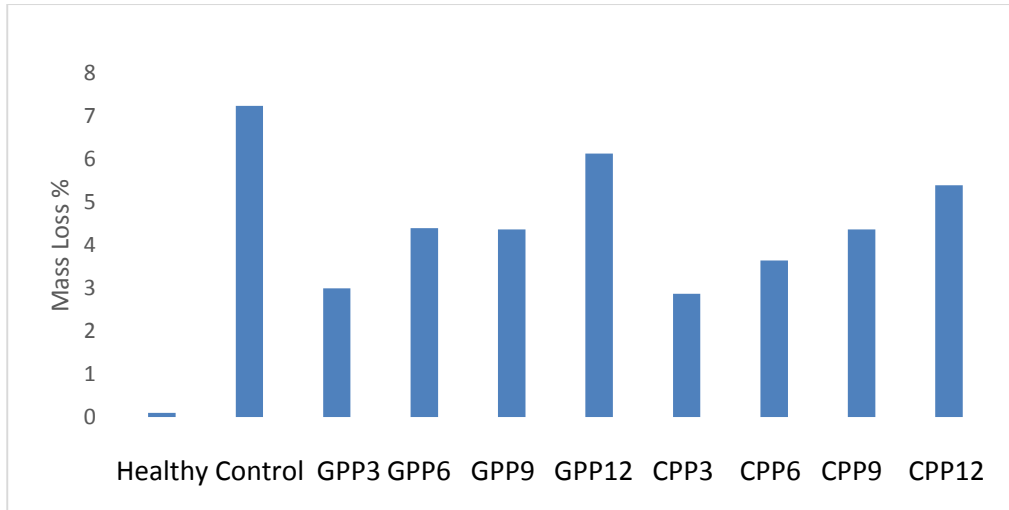


Figure 6.21: Mass Loss VS Days of Corrosion

Analysis:

From **Table 6.4** following conclusions can be drawn:

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

From the destructive test performed following major conclusions were drawn

Table 6.4 and 6.3 shows variations of mass loss with pull out strength for all specimens. From the graph, we can say that pull out strength varies inversely with the mass loss i.e. corrosion reduces bond strength. The

rate of loss of pull-out strength in GPP and CPP specimens is lowest. This implies that even with the same level of corrosion, the passively protected specimens exhibit a better bond with concrete. As a result of corrosion, the bars exert a bursting pressure on the concrete. In the absence of FRP wrap, tensile stresses develop in the concrete that result in its cracking and spalling. Eventually, concrete goes in compression. This result in loss of bond strength.

6.5 CLOSING REMARKS

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

CHAPTER 7 CONCLUSIONS

Following conclusions can be obtained from ultrasonic guided wave monitoring and acoustic emission monitoring of RC Cylinder specimen subjected to accelerated corrosion using impressed current technique done in this research work.

- Ultrasonic guided waves and Acoustic emission technique has proven to be very effective in monitoring the corrosion in RC structures and also been able to pick up the behaviour when protected with FRP.
- By monitoring with ultrasonic guided waves and Acoustic emission technique, it can be established that passive protection using CFRP and GFRP proves to be a very effective method of protection.
- Both Ultrasonic Guided waves and Acoustic emission technique have been very much able to pick up the behaviour of RC specimens when subjected to Passive Protection. They also provide wonderful results that can be used to compare the passive protection provided by different FRP

(Carbon and Glass). In this experiment, GFRP proves to give better protection than CFRP passively.

- The surface seeking modes and the core seeking modes are very much able to explain the behaviour of RC specimens subjected to corrosion and also when subjected to protection. This further helps in examining the extent of delamination and pitting as a result of corrosion.
- Although both techniques i.e. the ultrasonic guided waves and acoustic emission technique have been successfully able to monitor the corrosion and the efficacy of protection provided to RC specimens. But it has been very clear that Acoustic emission is very effective to predict the onset of corrosion in RC structures. Whereas in case of Ultrasonic guided waves, L (0, 7) mode almost seems ineffective in the beginning and L (0, 1) gives lesser variation during the same period.
- Both the modes L (0, 1) and L (0, 7) has shown greater variations in the later part of the experiment and the plot of AE hits becomes flat. This does imply that AE is very helpful while cracking is going on and UGW gives promising results even when major cracking has occurred.
- It is also observed that the surface bonded FRP wrapping protects the steel in concrete and reduces the corrosion to a great extent. The protected samples exhibited lower mass loss than the controlled samples.
- It can also be concluded that a judicious combination of both the ultrasonic guided waves as well as the Acoustic emission techniques can provide better results as UGW predicts the damage in RC by monitoring the steel bar. While, AE sensors are mounted on the concrete and they directly give the damage that occurs in concrete. The combination of two methods enables us to monitor the degradation in steel and concrete simultaneously and instead of prediction of damage, it provides us better results
- The Cumulative AE Hit no didn't rise more than three thousand in case of 3 days protection, ten thousand cumulative in case of protection at nine days ,seven thousand cumulative in case of protection at six days and fifteen thousand in case of twelve days.

7.1 FUTURE SCOPE OF WORK

The present study emphasized on the two non-destructive techniques (ultrasonic guided waves technique and Acoustic Emission Technique) for the monitoring of corrosion in RC cylinders. Combination of Acoustic Emission Technique and Ultrasonic Guided Wave Technique has proven to be very effective in the corrosion monitoring process as far as this study is concerned.

Lot of work in the area needs to be done before the acoustic emission technique as well ultrasonic guided wave technique can be adopted as corrosion monitoring technique.

- More number of samples justifying the technique especially acoustic emission technique needs to be investigated and studied before Acoustic Emission Technique is established for corrosion monitoring in RC structures.
- Effect of placement/ attachment of sensors on the cylinders on the AE signals need to be assessed.
- Mechanism of corrosion cracking needs to be studied numerically and related to cracks parameters vis-a-vis corrosion.

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