`

ULTRASONIC GUIDED WAVES FOR MONITORING UNDERWATER CORROSION

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Submitted By

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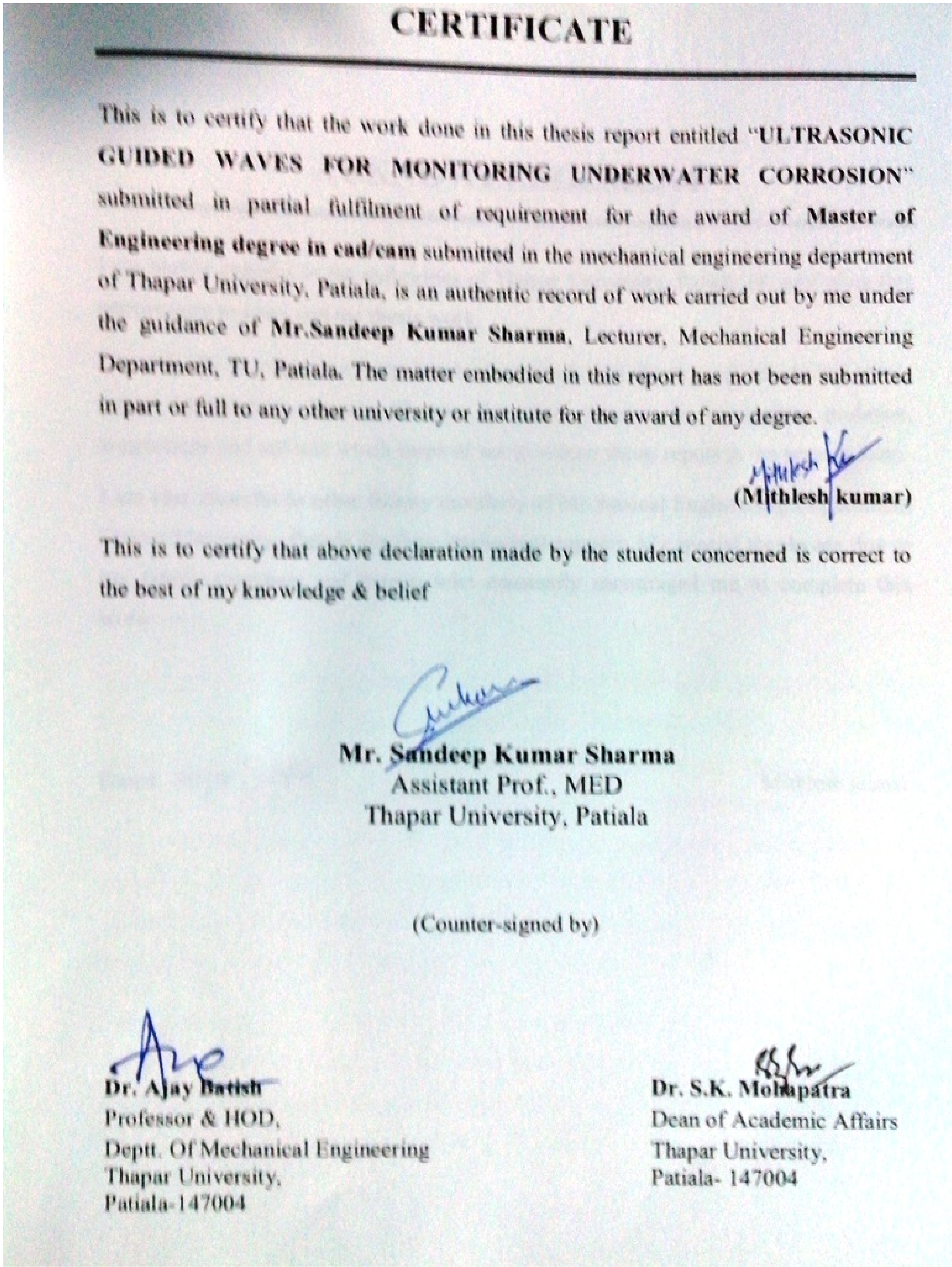

CERTIFICATE

This is to certify that the work done in this thesis report entitled "**ULTRASONIC GUIDED WAVES FOR MONITORING UNDERWATER CORROSION**" submitted in partial fulfilment of requirement for the award of **Master of Engineering degree in cad/cam** submitted in the mechanical engineering department of Thapar University, Patiala, is an authentic record of work carried out by me under the guidance of **Mr.Sandeep Kumar Sharma**, Lecturer, Mechanical Engineering Department, TU, Patiala. The matter embodied in this report has not been submitted in part or full to any other university or institute for the award of any degree.

(Mithlesh kumar)

This is to certify that above declaration made by the student concerned is correct to the best of my knowledge & belief

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Dated: Mithlesh kumar

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ABSTRACT

This thesis reports the investigation of corrosion and its progression in plate specimen simulating ship hulls in uncoated and paint coated states using ultrasonic guided waves .The effectiveness of guided waves technique for corrosion monitoring in various states of ship hull structure (as in actual conditions in ships) has been studied.

Current work proposes to use immersion transducers to generate guided elastic waves in plate geometries in first healthy state. Then guided waves are generated in steel plates undergoing corrosion damages. The signals in pitch catch orientation are send and received at particular critical angles. The variation in the signal received should lead to identify, locate and evaluate corrosion damage and determine the residual life of the structure.

However, several key technologies must be established before the guided waves could be utilized in the monitoring of health of marine structures, a reliable technique for prediction of propagation of waves through submerged damaged specimens taking into account the fluid structure interaction must be established; a number of steel plates structures in uncoated and paint coated with and without initial scratch or damage conditions must be investigated and extend of corrosion be characterized to facilitate on site application of the developed methodology. The methodology is successfully to plates undergoing corrosion in marine environment.

This thesis reports a non-contact, in-situ and non-destructive corrosion monitoring methodology for submerged plates using ultrasonic guided waves. Specific surface sensitive and core sensitive guided wave modes are utilized for monitoring plates undergoing accelerated impressed current corrosion in the presence of chlorides.

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CHAPTER 1
INTRODUCTION

1.1 MOTIVATION AND BACKGROUND

Several offshore and marine infrastructural systems contain plate-like members that are submerged and are often subjected to extreme service loads and corrosive environments. Damage discovery has been an important area of concern in the design, operation, maintenance and repair of many military, industrial and civil structures and equipment's involving plate structures, submerged in water or in air. Mild steel plates have a very wide application in industry. With the passage of time, the infrastructures involving plate assemblies deteriorate due to a variety of factors such as environmental degradation, fatigue, excessive loads and simply due to long endurance combined with intensive usage.

Researcher have suggested the use of various NDT techniques for the same like visual inspection, dye penetrant, electromagnetic testing etc. but they suffer from practical applications. There is an urgent necessity of developing a reliable, noninvasive and in-situ non-destructive testing procedure for plate structures which can detect, locate and quantify damage in submerged condition. Underwater condition of such structures often makes them isolated to many established non-destructive monitoring technologies. Marine structures are subjected to a highly corrosive environment that combines the effects of salty seawater, salt laden air, rain, dew, condensation, localized high temperature, stresses and the corrosive effects of combustion gases. Corrosion can be extensive in contained areas hidden inside the submerged areas of the structure making them very difficult to detect. A monitoring methodology can be most effective if the damage can be detected early.

Hence, there is a need for developing an online corrosion monitoring and valuation technique for submerged ship hull structures. It is proposed in this work to use ultrasonic guided waves approach for the same. Ultrasonic guided waves have been recently used by the research group in MED and CED at Thapar University Patiala for successfully monitoring damages in the form of notches, holes and material loss in the form of corrosion in steel plates immersed in water. From the ultrasonic investigations

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it was found out and that specific ultrasonic lamb waves modes having surface sensitive and core sensitive features exits. Lamb wave modes can be effectively used to identify and distinguish between surface and deep sub surface defects. Typically 0.5MHz (S_0 mode) frequency is a core sensitive mode which can pick up deep degradations in the form of sub surface notches and pits due to corrosion. Similarly S_1 mode at 1MHz frequency is a surface seeking mode which can pick up the surface degradations like surface corrosion, mass loss and surface notches.

1.2 OBJECTIVES OF PRESENT STUDY

- Experimental investigation for generation and reception of ultrasonic guided waves in plate geometries with different techniques.
- Specific guided waves identified to be used for monitoring actually corroding MS plates having different levels and extents of corrosion.
- Study to be extended to plates in actual ship hull conditions in various forms and states like in uncoated, paint coated and already dented conditions.

1.2 NON DESTRUCTIVE TECHNIQUES

Nondestructive evaluation (NDE) is a term that is often used interchangeably with NDT. However, technically, NDE is used to describe measurements that are more quantitative in nature. For example, an NDE method would not only locate a defect, but it would also be used to measure something about that defect such as its size, shape, and orientation. NDE may be used to determine material properties, such as fracture toughness, formability, and other physical characteristics. The most commonly used techniques are provided below.

• Visual and Optical Testing:

Visual inspection involves using an inspector's eyes to look for defects. The inspector may also use special tools such as magnifying glasses or mirrors gain access and more closely inspect the subject area.

• **Electromagnetic Testing (ET) or Eddy Current Testing:**

Eddy currents are generated in conductive material by an induced alternating magnetic field and they flow in circles at just below the surface of the material. Interruptions in the flow of eddy currents, caused by imperfections, dimensional changes, or changes in the materials conductive and permeability properties can be detected with the proper equipment.

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• **Penetrant Testing:**

Test specimens are coated with visible or fluorescent dye solution. Excess dye is then wiped out from the surface, and a developer is applied. The developer acts as blotter, drawing trapped penetrate out of imperfections open to the surface. With visible dyes, vivid color contrasts between the penetrant and developer make “bleed out" easy to see.

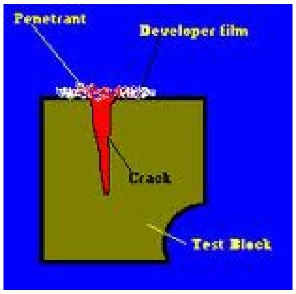

Fig 1.1 Penetrant Testing

• **Magnetic Particle Testing (MT)**

In this method a magnetic field in a ferromagnetic material is induced and then dusting the surface with iron particles (either dry or suspended in liquid) is done. Surface and near-surface imperfections distort the magnetic field and concentrate iron particles near imperfections, previewing a visual indication of the flaw.

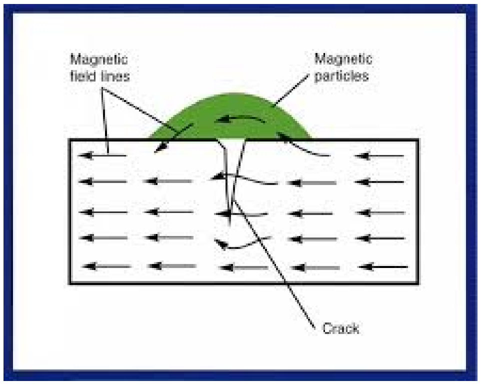

Fig 1.2 Magnetic partial Testing

• **X-Ray Fluorescence (XRF):**

X-ray fluorescence is one of the methods for NDT. The equipment contains radioactive sources or a low voltage x-ray generator, which sends out radiation. The exposed material then sends temporarily element specific radiation back, generating energy. As every element has its own atomic structure, this reflection will generate a different energy level for every element. This energy is measured and detected, thus identifying the alloy elements.

• **Radiography (RT):**

Radiography involves the use of penetrating gamma or X radiation to examine parts and products for imperfections. An X-ray generator or radioactive isotope is used as a source of radiation. The resulting shadowgraph shows the dimensional features of the part. Possible imperfections are indicated as density changes on the film in the same manner as medical X-ray shows broken bones.

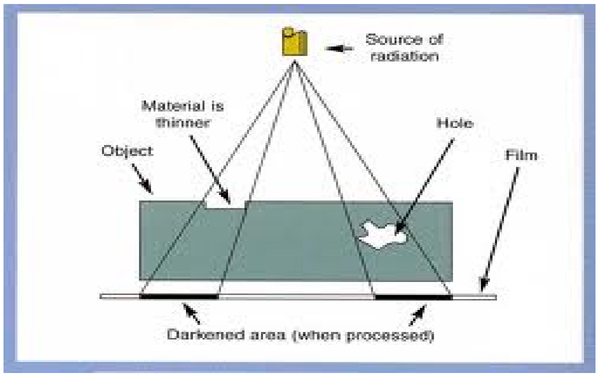

Fig 1.3 Radiography Testing

• **Leak Testing (LT):** Several techniques are used to detect and locate leaks in pressure containment parts, pressure vessels, and structures. Leaks can be detected by using electronic listening devices, pressure gauge measurements, liquid and gas Penetrant techniques, and/or a simple soap-bubble test.

•**Infrared Thermography:**

It is a fast NDT inspection method which does not influence the process and maps the temperature differences of any object in a range from -50ºC to 1500ºC. Instead of detecting the temperature point by point, thermo graphic camera is able to detect.

• **Ultrasonic Testing (UT):**

Ultrasonic testing use transmission of high-frequency sound waves into a material to detect imperfections or to locate changes in material properties. The most commonly used ultrasonic testing technique is pulse echo, wherein sound is introduced into a test object and reflections (echoes) are returned to a receiver from internal imperfections or from the part's geometrical surfaces.

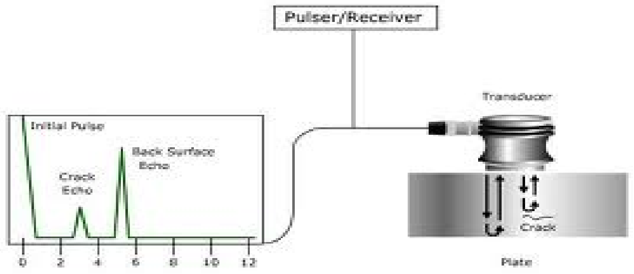

Fig 1.4 Ultrasonic Testing

• **Acoustic Emission Testing (AE):** When a solid material is stressed, imperfections within the material emit short bursts of acoustic energy called "emissions." as in ultrasonic testing; acoustic emissions can be detected by special receivers. Emission sources can be evaluated through the study of their intensity, rate, and location.

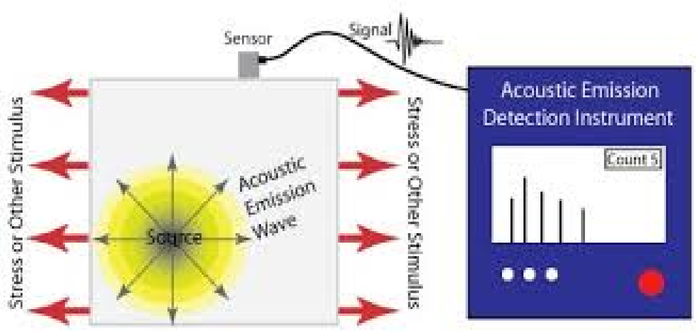

Fig 1.5 Acoustic Emission Testing

• **Electromagnetic Acoustic Transducers (EMATs):**

They generate and detect ultrasonic waves via electromagnetic coupling between the EMAT and the metal samples. They operate via the Lorentz force or magneto elastic mechanisms or both simultaneously.

1.3 ULTRASONIC TESTING

Ultrasonic non-destructive testing introduces high frequency (greater than 20 kHz) sound waves into a test object to obtain information about the object without altering or damaging it. It is used for detection of damage in structures. This is one of the best nondestructive testing methods where ultrasonic wave is send into the structure to find the location and magnitude of the defect. Ultrasonic wave

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propagation varies with change in the medium in which the wave propagates. Ultrasonic waves are simply organized mechanical vibrations travelling through a medium, which may be in any state of matter. These waves travel through a given medium at a specific speed or velocity, in a predictable direction, and when they encounter a boundary with a different medium they will be reflected or transmitted according to simple rules. This is the principle of physics that underlies ultrasonic flaw detection. Some of the generally used terms to define the ultrasonic waves are

- **Frequency (υ):** All sound waves oscillate at a specific frequency, or number of vibrations or cycles per second, which we experience as pitch in the familiar range of audible sound. Human hearing extends to a maximum frequency of about 20,000 cycles per second (20 KHz), while the majority of ultrasonic flaw detection applications utilize frequencies between 500 KHz to 10 MHz At frequencies in the Megahertz range, sound energy does not travel efficiently through air or other gasses, but it travels freely through most liquids and common engineering materials.

- **Wave Speed:** The speed of a sound wave varies depending on the medium through which it is travelling, affected by the medium’s density and elastic properties. Different types of sound waves will travel at different velocities.

- **Wavelength (λ)**: It is the distance between any two corresponding points in the wave cycle as it travels through a medium. Wavelength is related to frequency and velocity by the simple equation.

$$\lambda = c/\upsilon \qquad \text{..... (1.1)}$$

Where,

λ = wavelength,

c = sound velocity,

υ = frequency

In ultrasonic flaw detection, the generally accepted lower limit of detection for a small flaw is one-half wavelength, and anything smaller than that will be invisible. In ultrasonic thickness gauging, the theoretical minimum measurable thickness is one wavelength.

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• **Acoustic impedance (Z):** Sound travels through materials under the influence of sound pressure. Because molecules or atoms of a solid are bound elastically to one another, the excess pressure results in a wave propagating through the solid. The Acoustic impedance (Z) of a material is defined as the product of its density (ρ) and acoustic speed in medium.

$Z=\rho/c$ …… (1.2)

Acoustic impedance is important in determining acoustic transmission and reflection at the boundary of two materials having different acoustic impedances.

1.3.1 TYPES OF ULTRASONIC WAVES FOR NDT

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.

- **Body waves**

Body waves travel through the bulk material while surface waves propagate along the surface. Sound waves travel as a bulk wave in any elastic material where the sound does not interact with the edges of material therefore acting as infinite extent of material. The velocity of sound in materials varies with its elastic properties which can be calculated by measuring the time of flight between the two points as shown in **Fig 1.6**

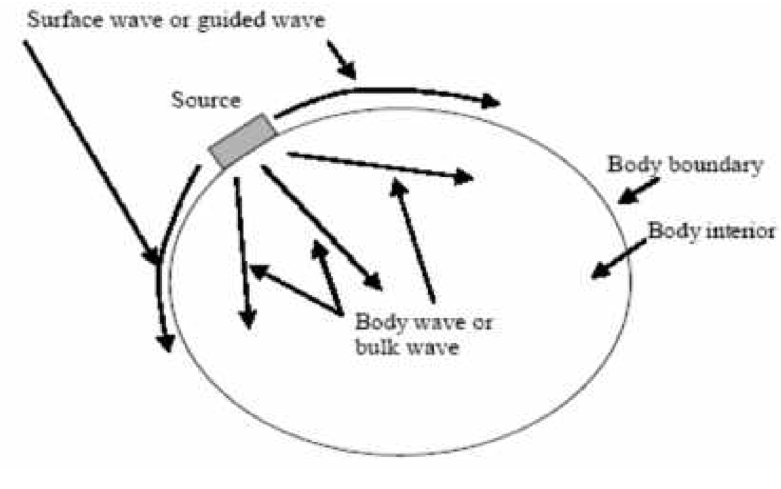

Fig 1.6 Body waves and Surface waves generated by an ultrasonic source [kundu,2004]

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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.

- **Guided waves**

When ultrasonic wave is constrained within the boundaries and is guided by the geometry of the structure, it becomes a guided wave that has the ability to travel long distances with minimum loss of energy. The structure that guides the wave is termed as ‘waveguide’. Surface waves are often called guided waves because of the geometry of the boundary which guides them. The basic requirement for an ultrasonic wave to be a guided wave is that the thickness of the waveguide must be comparable to the operating wavelength (**Fig. 1.7**). However, if the thickness of the material is much greater than the operating wavelength, then bulk waves and surface waves exist (**Fig.1.8**)

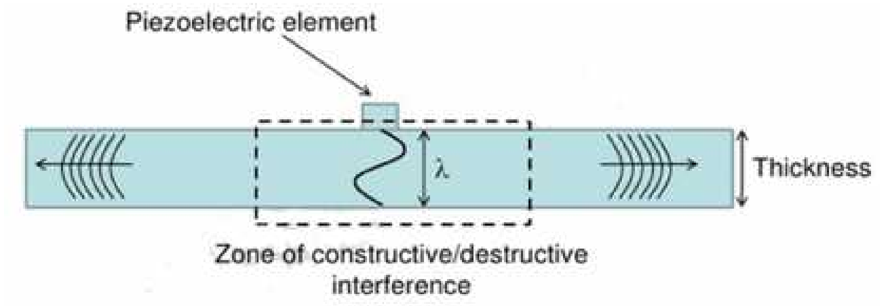

Fig.1.7 Propagation of guided waves through a structure (*www.wins-ndt.com*)

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

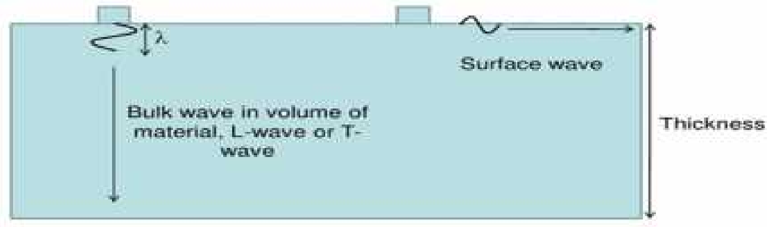

Fig.1.8 Wave Propagation when thickness of material >> wavelength

(*www.wins-ndt.com*)

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

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

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

1.3.2 TYPES OF GUIDED WAVES

There are different types of guided waves based on the geometry of the structure (waveguide) through which guided wave travels (**Fig. 1.9)**

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

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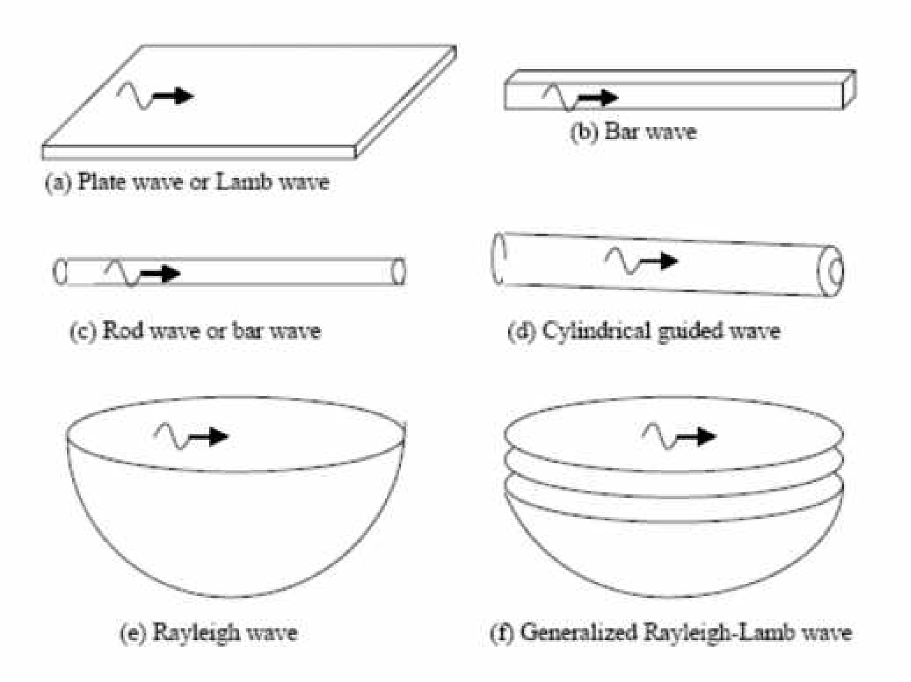

Fig. 1.9 Different types of guided waves [kundu,2004]

If the structure of the waveguide is a homogenous half space, then the guided wave propagating along the surface of the half space is called Rayleigh wave, named after its inventor.

Waves propagating through a plate like structure with two parallel stress free boundaries are known as Lamb waves.

Elastic waves propagating through a hollow cylindrical or pipe structure are called cylindrical guided waves. When the guided waves propagate through a solid rod or bar, they are known as bar waves. In this experiment we used lamb waves.

1.3.3 LAMB WAVES

These are similar to surface waves except they can only be generated in specimen which is a few wavelengths thick. Lamb waves are the most commonly used plate waves in NDT. They are complex vibration waves that propagate parallel to the test surface throughout the thickness of the material. Propagation of Lamb waves depends on the density and the elastic material properties of a component. They are also highly influenced by the test frequency and material thickness. Lamb waves are generated at an incident angle in which the parallel component of the velocity of the wave in the source is equal to the velocity of the wave in the test material.

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Lamb waves can travel several meters in steel and so are useful to scan plate, wire, and tubes. With these waves a number of modes of particle vibration are possible, but the two most common are symmetrical and asymmetrical as shown in Fig. **1.10(a)** & **(b).** The complex motion of the particles is similar to the elliptical orbits for surface waves. Symmetrical Lamb waves move in a symmetrical fashion about the median plane of the plate. This is sometimes called the extensional mode because the wave is "stretching and compressing" the plate in the wave motion direction.

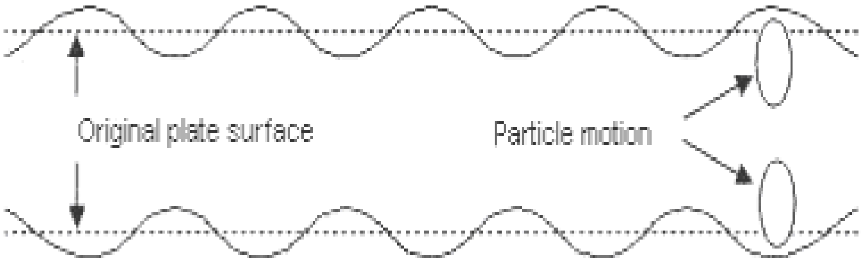

Fig. 1.10 (a) Lamb Wave Symmetric mode(S mode)

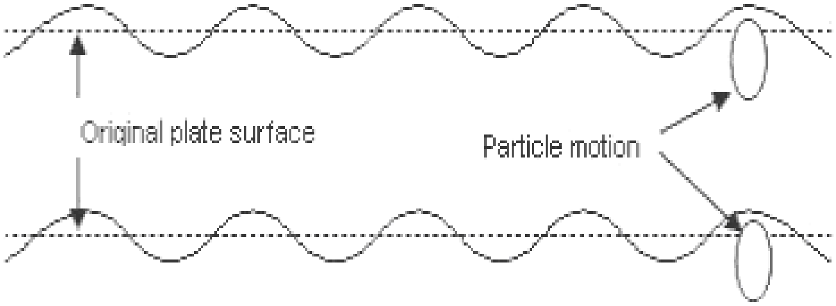

Fig. 1.10 (b) Lamb Wave Anti-symmetric Mode (A mode) (www.nde-ed.org)

1.3.4 LIMITATIONS OF GUIDED WAVES

There are few limitations associated with guided waves which are:

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

1.3.5 METHODS FOR ULTRASONIC TESTING

Most commonly used methods for ultrasonic testing are:

(a) Pulse Transmission method

(b) Pulse Echo method

(c) Pitch catch

(a) Pulse Transmission method

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

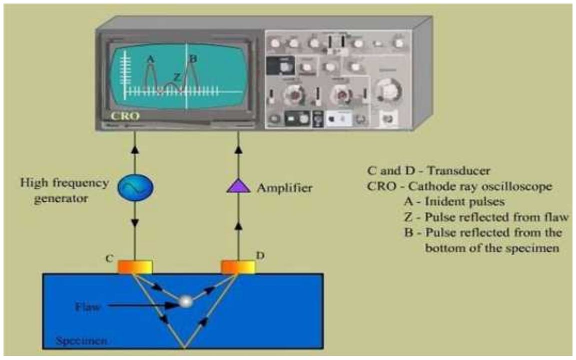

Fig. 1.11 Pulse Transmission method of testing

(*www.msheiksirajuddeen.blogspot.in*)

(b) Pulse Echo Method

In the pulse-echo method, a piezoelectric transducer with its longitudinal axis located perpendicular to and mounted on or near the surface of the test material is used to transmit and receive ultrasonic energy, as shown in **Fig. 1.12**. The ultrasonic waves are reflected by the opposite face of the material or by discontinuities, layers, voids, or inclusions in the material, and received by the same transducer, where the reflected energy is converted into an electrical signal as shown in the Figure. The electrical signal is computer processed for display on a video monitor or TV screen. The display can show the relative thickness of the material, depth into the material where flaws are located, and (with proper scanning hardware and software), where the flaws are located in the X-Y plane.

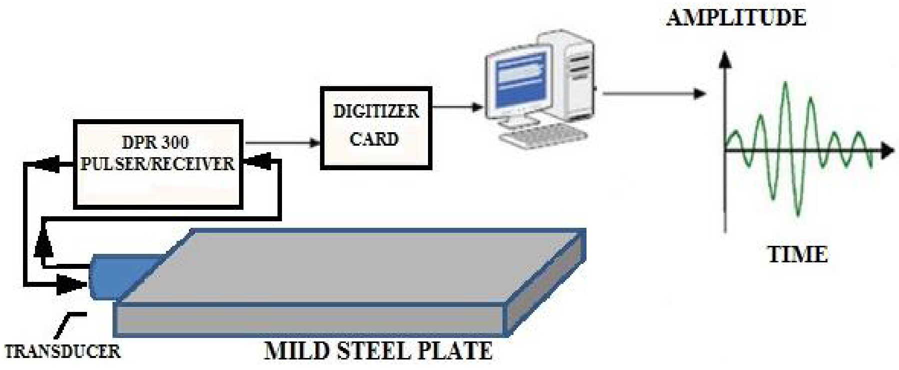

Fig. 1.12 Pulse Echo Method (www.nde-ed.org)

(c) Pitch Catch Method

An ultrasonic testing technique involving the use of two separate probes one probe being used to transmit the ultrasonic energy into the body and the other being positioned so as to receive the reflected energy from a discontinuity. In variations of the technique, more than two probes may be used. Also called double probe technique. We used this method of ultrasonic testing in our experiment. In this method a water based gel has proven to be most practical coupling agent. Ultrasonic transmitters and receivers encased in a water jet nozzle have been used to provide continuous coupling during testing of large areas by continuously injecting a plane of water between the sensor and the material being tested.

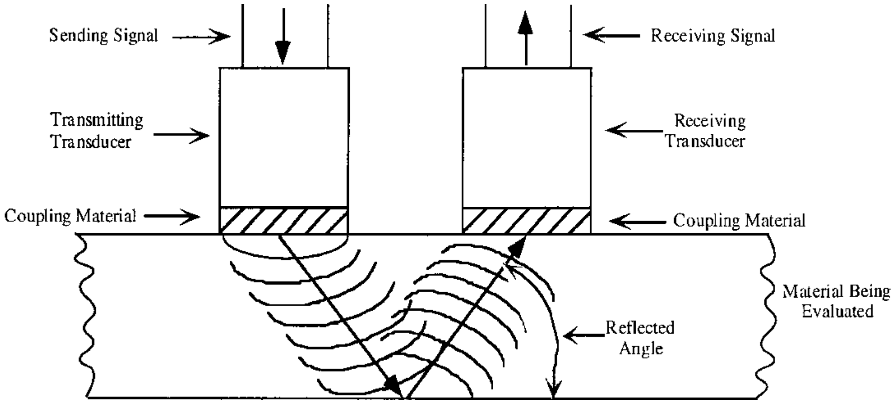

Fig 1.13 Pitch-Catch Method of Ultrasonic Testing (www.nasa.gov)

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1.4 CLOSURE

This chapter gives a background of Structural health monitoring using nondestructive techniques. Important factors that are to be considered for effective nondestructive testing have also been discussed. A brief description of various NDT techniques is presented.

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CHAPTER 2

LITERATURE REVIEW

Ultrasonic is a very efficient way of detecting defects in NDT. So these can be very efficiently used to detect defects in plated structures. This chapter presents a review of literature on utilization of ultrasonic guided waves for damage detection in plated structures. This gives an idea of study carried out in this area up to this stage.

2.1 REWIEW OF LATEST WORK DONE

Kundu et al. (1997) Discussed methods of detecting kissing bond in the plate structure was discussed. When the crack surfaces stay in very close contact with each other than the bond between the two surfaces of the crack is called a ‘kissing bond’. When the crack surfaces are smooth then kissing bonds cannot transmit shear stress very well but can carry compressive normal stress, these bonds are called ‘slip bonds’. These bonds remain invisible to the conventional P-wave based C-scan or A-scan techniques. In this paper it was shown that the kissing bonds can be effectively detected by some leaky Lamb mode.

Theoretical and experimental results were presented to show that using the Lamb waves is an effective way of detecting kissing bonds. Conventional ultrasonic techniques could detect internal cracks and inclusion type defects in homogeneous as well as layered materials. But the conventional ultrasonic scanning was not very efficient for detecting cracks which are located normal to the specimen surface. Back scattering technique and acoustic microscopy technique can detect such vertical cracks when they are located near the specimen surface. However, these techniques failed when the cracks were not very close to the surface.

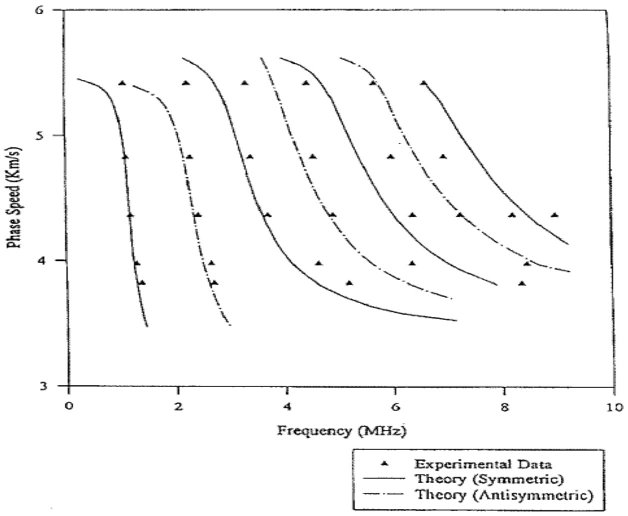

Fig 2.1: Comparison of theoretically calculated and experimentally observed Lamb wave dispersion curves for double layered specimen (Kundu, 1997)

Ghosh et al. (1997) investigated the wave propagation in large plates and its use in internal defect detection had been studied. Both symmetric and anti-symmetric modes had maximum flow rate at the central plane of the plate. Energy approach is efficient for vertical defects but it's not efficient in case of horizontal defects. So for this it was important to compute stress distribution inside the plate. If a particular component of stress was affected by a defect then the lamb wave sensitive to that defect was required. Internal variation of other stress components which are not affected by defect were not of interest since both defective and non-defective specimen would produce same levels for those stress components. The experimental values of V (f) curve are plotted on theoretical dispersion curve. Comparison between specimen with defect and without defect was compared and percentage change in the mode signal was found at the point of defect. Finally they found that lamb waves were more sensitive to the horizontal defects.

Kundu et al. (1998) has studied the lamb wave propagation in large plates and its use in internal defect detection. The lamb wave modes which are most efficient for detecting different types of defects are identified. Stress fields inside the plate for different modes of lamb waves are computed. From these stress plots, the most efficient mode for detecting the particular types of defect can be identified.

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Rose et al. (2000) carried out an experimental investigation to establish a technical concept for detection of defects in thin steel plates. The goal was to find the most efficient testing parameters, in context to relationship between excitation frequency of tone burst and various incident angles.

Rose et al. (2000) In order to establish a technical concept for the detection of defects in thin steel plates, an experimental investigation was carried out for the artificial defects in 2.4mm thick steel plates by using guided wave technique. The goal was to find the most efficient testing parameters paying attention to the relationship between the excitation frequencies by tone burst system and various incident angles. For the case of S_0 mode impingement, amplitudes of reflected signals were proportional to sizes of defects. A_0 mode was also sensitive to the same defects but proportional relation was not observed. Tone burst signals were used to control the center frequency and frequency bandwidth of excited signals. The dispersion curves of Lamb wave modes could be obtained by solving wave equation with boundary conditions. In this case, the phase velocity was continuously controlled by variable angle shoe so that the phased velocity tuning could be performed by incident angle tuning.

Shin and Song et al. (2000) Lamb wave mode conversions were experimentally studied to utilize the mode conversion characteristics for the nondestructive testing. Aluminum plates with various depths of EDM notches were used for the experiments. The numerical results of Lamb wave dispersion in the plate were given. Short time Fourier transforms was employed to obtain the dispersive patterns of the group velocity of the received signals, which represented experimental results of Lamb wave dispersion. Then, the mode identifications were performed by the comparison of the dispersive patterns obtained by numerically and experimentally. For the excitation and reception of the Lamb waves, angle beam transducers with tone burst signals were used. Mode conversion was observed in both pitch-catch and pulse-echo techniques. Mode conversions occurred in forms of phased velocity shift and frequency shift. It showed the possibility of defect detection by using Lamb wave pitch-catch techniques. In addition, by analyzing the characteristics of mode conversion, it might have been be possible to size defects with Lamb waves.

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Younho et at. (2000) In this paper, utilization of hybrid boundary element modeling for specific Lamb wave mode incidence situations with special energy distributions along the structural cross section was proposed for estimating reflection and transmission from various scatterers, such as a step discontinuity and tapered parts of a waveguide, etc. Interaction of individual Lamb wave modes with scatterers that represent arbitrary thickness variation along the direction of guided wave propagation was investigated by calculating the scattered fields for varying incident modes, frequency, and scatterer shape. The mode conversion phenomenon through step discontinuity in a plate was also experimentally explored. The theoretical predictions of reflection and transmission by boundary element methods and the utility of dispersion curves were compared with experiments for specific modes. Results in this paper could be used to improve inspection sensitivity and penetration power for a variety of practical NDE applications, notably those in which thickness variation was found. In addition, the feasibility of inspecting sections located behind a waveguide thickness variation region and subsequent mode control was also been discussed. The integrated approach including hybrid BEM simulations for physically based data on the guided wave mode conversion phenomenon and corresponding experiments with redundancy based on the appropriate angle tuning and self-calibration could help to extract rich features from the guided wave mode conversion phenomenon for more optimized and quantitative guided wave applications.

Kundu et al. (2001) has investigated the difficulties in detection of internal defects in mirror symmetric composite plates using lamb wave modes. In a symmetrically layered composite plate stress, displacement magnitudes and energy distribution profiles for all lamb modes are symmetric about central plane of the plate. As a result, ability of lamb mode to detect a defect in corresponding layer of mirror symmetry. Hence form lamb wave image generated, it is difficult to distinguish between the defects in two layers of mirror symmetry. The authors discuss to solve the problem by fine tuning of frequency used and striking angle of incident beam.

Rose et al (2002) studied that the major difference between bulk wave propagation and guided wave propagation is that a boundary is required for guided wave propagation. As

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a result of a boundary along a thin plate or interface, variety of different waves is reflected and mode converting inside a structure and superimposes with areas of constructive and destructive interference that finally leads to the guided wave packets that can travel in the structure. As a result of refraction at the interface, a variety of different waves can propagate in the structure.

Worden et al. (2002) States that a practical complication of Lamb wave inspection mainly lies in the propagation characteristics of the elastic waves. The propagation is typically characterized by the product of the wave frequency and the sample thickness, or frequency-thickness product (FT). For a low value of this parameter (typically less than 1MHz-mm in aluminum media), only the fundamental symmetric, S_0, and anti-symmetric, A_0, modes can propagate. As the FT product increases, so does the number of allowed modes. However, these higher modes have widely different phase velocities and often experience considerable phase-velocity dispersion as a function of the FT value. Note that damage diagnosis is much simplified if a known single mode of the Lamb waves is generated over anon dispersive region of the FT product.

Lindenb et al (2003) describes about the online monitoring of fatigue cracks using ultrasonic waves. Most of the currently available non-destructive testing methods are off-line, i.e. the operational loading and the inspection are considered as two distinct stages. In this article, an experimental methodology based on ultrasonic surface waves is developed to continuously inspect a structure during its operation. The proposed method uses spectral information of transmitted surface waves at several working points of the operational load. Simple statistical indicators of the transmitted wave energy during loading are introduced in order to be able to monitor the structural health on-line. As a validation experiment, a propagating fatigue crack in a sinusoidal loaded beam is considered.

Fromme at el (2004) the scattering of the first anti- symmetric Lamb wave mode A_0 at obstacles in plate-like structures was studied in this dissertation. The propagation in an isotropic, homogeneous plate, the scattering at a circular hole, and the scattering at a hole with a defect were investigated experimentally and theoretically. Guided flexural

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waves had the advantage of propagating over large distances in plates, thus allowing the fast and efficient detection of defects in large structures. This method holds promise for the nondestructive testing of aircraft Airplane fuselage and wings often consist of aluminum face sheets, connected with fasteners or containing holes, which are sources of stress concentration and crack formation at their boundaries. When the guided wave hits such a discontinuity, a typical scattered displacement field is obtained. A change in the scattered field indicates the development of a fatigue crack, and thus the growth of such cracks can be monitored. In the experiments, the A_0 mode was excited selectively by means of a piezoelectric transducer with a well-defined time signal. The used frequency range was below the cut-off frequencies of the higher wave modes in the plate. The scattered field was measured on a grid around the hole with a heterodyne laser-interferometer Using fast Fourier transformation, the amplitude and phase values of the scattered field were extracted from the measured time series. The introduction of a small imperfection, like a notch, at the boundary of the cavity changed the measured scattered field significantly. The first anti- symmetric Lamb wave mode A0 physically represented a flexural wave propagating along the structure. It can be described well using approximate theories. Therefore no three-dimensional theory needed to be implemented, and a fast calculation was achieved

Demma et al (2004) in this thesis the author investigated the effect of geometrical discontinuities in plates and pipes on the propagation of guided waves. The discontinuities studied are both defects in the structure and features of the structure. Firstly the scattering of the SH_0 mode from discontinuities in the geometry of a plate were presented. Both Finite Element and modal decomposition methods have been used to study the reflection and transmission characteristics from a thickness step in a plate, very good agreement being obtained. A method to approximate the reflection from rectangular notches by superimposing the reflection from a step down (start of the notch) and a step up (end of the notch) was proposed. The limits of this method in approximating crack-like defects were discussed. The second part of this thesis reports an experimental and numerical (Finite Element method) study of the reflection of the T(0,1) mode from defects in pipes. Both crack-like defects with zero axial extent and notches with varying

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axial extents were considered in this study. An interpretation of the crack-like reflection coefficients in terms of the wave number-defect size product was proposed.

Fromme et al. (2004) In this paper the method of detecting defects in steel plate was discussed. Fromme et al. designed a guided wave array consisting of a ring of 32 piezoelectric transducer elements, equally spaced on a diameter of 70 mm. Each transducer element consisted of a PZT disc (diameter 5 mm, thickness 2 mm) and a backing mass. The array was permanently bonded to the structure using conductive epoxy glue. The individual transducer elements had been optimized to act as a good approximation to point sources and receivers for the transmission and reception of the first anti -symmetric Lamb wave mode A_0.

The circular array design was introduced to achieve the same performance in all directions. In order to ascertain the sensitivity of the array monitoring measurements, the predicted and measured reflection amplitude of the various structural features and defects was compared. The measured reflections at model defects like circular through holes were compared to theoretical predictions and good agreement was found.

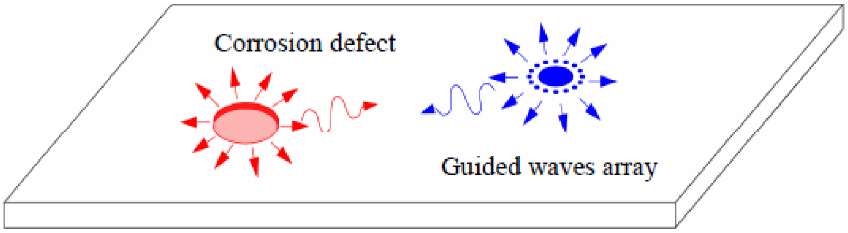

Figure 2.2: Schematic of guided ultrasonic wave monitoring of large plate like structures (Fromme, 2004)

Therefore an approximate indication of the severity of a defect could be obtained from the amplitude of the reflected signal. Defects simulating typical thickness reductions due to corrosion were machined into the plate. Good agreement between the measured reflections at circular flat bottom holes and Finite Element predictions was found. Simulated corrosion pitting and a rough ground defect could be well detected within the dynamic range of the array measurement.

Oppenheim et al. (2006) In this paper the authors examined the detection of fatigue cracks in a specimen that exhibited the complications of multiple welded joints. They induced a fatigue crack in a particular location and recorded Lamb wave reflections during the development of the fatigue crack and also later after mechanical enlargement of the fatigue crack. In this paper we explore the detection of crack generation and growth using Lamb wave transducers was explored. Two wired transducers were located on each side of the girder. In principle one could detect a crack by using a single transducer as both an emitter and a receiver, or alternatively by using a transducer pair in a pitch-catch configuration. However, in this experimental work use of additional transducers to obtain insight into the robustness of the crack detection was done. The transducers were near to but not extremely close to the anticipated crack location, making crack detection more challenging. It would be necessary to distinguish crack-induced reflections from other reflections from the various joints and the flange and stiffener ends. The enlarged cracks were clearly apparent from the reflected Lamb waves while the smaller fatigue-induced cracks were not unambiguously detected. These results were robust with respect to changes in the pulse center frequency and also were clearly observed for all transducer pairs. Detection of small fatigue cracks, the usage of Rayleigh-like waves was investigated. In the frequency-thickness range of interest Rayleigh-like waves in plates, which could be interpreted as the superposition of the fundamental Lamb modes A_0 and S_0, transfer energy between both surfaces with a characteristic distance called the beat length. A simple analytical model and Finite Difference (FD) calculations were used to describe the reflection of the Rayleigh-like wave at small surface defects. Experimentally the Rayleigh-like waves can be excited using standard wedge transducers and measured using either standard pulse-echo equipment or laser interferometry. Good sensitivity for the detection of small defects

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on both plate surfaces had been found. Full three-dimensional simulation of the scattering of the Rayleigh wave at the fastener hole and crack has been implemented using the FD method. The comparison of the results showed a good correlation to the observed signals.

Srivastava et al (2009) This dissertation presented the use of ultrasonic guided waves for the structural health monitoring of plates, rods, and waveguides with complex cross-sections like multilayered composite laminates, 7-wire steel strands, and rails. Modeling of guided waves by a Semi Analytical Finite Element (SAFE) model was presented. This model assumed constant cross- section along the direction of propagation. Therefore, while SAFE can efficiently compute dispersion characteristics of complicated waveguides, it cannot be used to study scattering due to local irregularities. A Global Local (GL) model, which combined SAFE and FE, was presented. This model was used to study scattering and mode-conversion effects of local defects in Aluminum plates and composite laminates. It has been shown that the nonlinear features of guided waves were often more sensitive to small defects than the linear features. This included generation laws for plate and rod modes at nonlinear higher harmonics which underline the analogous behavior of nonlinear bulk waves and nonlinear waves in plates and rods. Finally, SAFE simulations of nonlinear waves in rail were presented.

Sharma and Mukhergee (2014) this paper reports a non-contact, in-situ and non-destructive corrosion monitoring methodology for submerged plates using ultrasonic guided waves. Specific surface sensitive and core sensitive guided wave modes are utilized for monitoring plates undergoing accelerated impressed current corrosion in the presence of chlorides. A combination of the selected guided wave modes could effectively discern various corrosion mechanisms occurring in plates. Along with the ultrasonic signals, mass loss, stress–strain behavior and tensile strength of the plates at different stages of corrosion have been monitored.

Plates at different stages of corrosion were also ultrasonically monitored to explore the ability of ultrasonic to predict the level of deterioration of the plates. It was performed successfully by studying correlations between ultrasonic voltages and destructive

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parameters of mass loss and tensile strength. Thus, a mapping between the physical conditions of the plate with the voltage ratios is attempted in the form of algebraic equations. These should facilitate evaluation of fitness of plated structures for their intended purpose in immersed conditions. However, the relationships presented here are not generalized and are based on limited early results. More tests in varying conditions are necessary for arriving at a more general calibration.

2.2 CLOSURE

The chapter reviews the latest research works done in the field of defect detection in plates using ultrasonic testing techniques. Different type of defects to be detected and techniques that are implemented in this field are discussed in this chapter.

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CHAPTER 3
EXPERIMENTAL DETAILS & METHODS

3.1 BACKGROUND

Ultrasonic guided waves have been recently used by the research group in MED and CED at Thapar University Patiala for successfully monitoring damages in the form of notches, holes and material loss in the form of corrosion in steel plates immersed in water. From the ultrasonic investigations it was found out and that specific ultrasonic lamb waves modes having surface sensitive and core sensitive features exits. Lamb wave modes can be effectively used to identify and distinguish between surface and deep sub surface defects. Typically 0.5MHz (S_0 mode) frequency is a core sensitive mode which can pick up deep degradations in the form of sub surface notches and pits due to corrosion. Similarly S_1 mode at 1MHz frequency is a surface seeking mode which can pick up the near surface degradations like onset corrosion, mass loss and surface notches defect etc.

Present defects study is a detailed investigation of the pilot study carried out to monitor progression of corrosion in submerged plates under various conditions. Hence for the present study 4mm steel plates submerged in water will be monitored for corrosion progression using core sensitive and surface sensitive modes. The angle of incidence of both probes in these successive modes will be 17.4° and 14.7° respectively.

3.2 GENERATION OF GUIDED WAVES IN PLATES

3.2.1 General

Guided waves are waves whose propagation characters depend on structural geometries, such as plates, rods, pipes, etc. These waves are generated by impinging the plate obliquely with a piezoelectric transducer or by directly using transducer in contact with plate. In plates these ultrasonic waves propagate in two ways:

- Longitudinal ultrasonic wave (L): displacement of particles is parallel with the energy transport direction.

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- Shear ultrasonic wave (S): displacement occurs in the direction perpendicular to energy transport.

Shear wave, can further propagate in two modes **(Fig. 3.1)**.

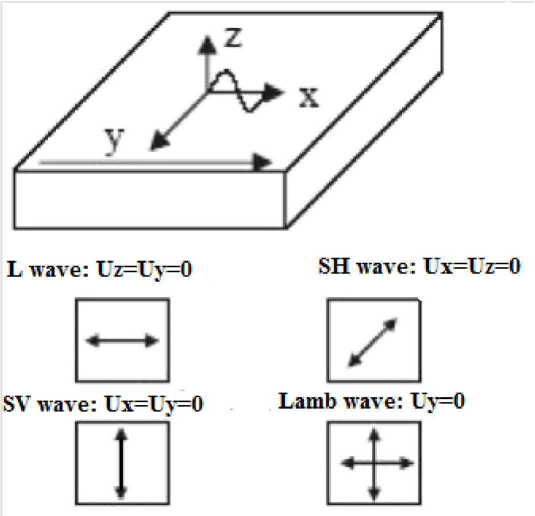


Fig 3.1 Various Modes of Shear Waves (Rose, 1992)

To use Lamb waves for defect detection in plated structures, knowledge of the Lamb modes is must for detecting the defects at specific depth.

3.2.2 Dispersion effect in plates

This phenomenon of the wave speed dependence on the frequency is called dispersion phenomenon and these waves are called dispersive waves. Lamb wave speed is not only dispersive but also multi-valued. At a given frequency multiple values of the wave speed are obtained for these waves. Different wave speeds correspond to different modes of the propagating Lamb wave. Such multiple modes do not exist for the bulk wave propagation. Fig 3.2 shows dispersion curves through a 4mm MS plates completely submerged in water.

For example, in the **Fig 3.2**, at the particular frequency e.g. 1MHz, the dispersion curve shows the existence of four modes (S_0, A_1, S_1 and S_2, where S_1 and S_2 are overlapped) propagating through the plate, of which S_0, S_1 and S_2 are symmetric modes and A_1 is anti-symmetric mode At the given frequency, the velocity of mode S_0 is 3 km/s, mode S_1, S_2 is 6km/s and A1 is 5.5 Km/s.

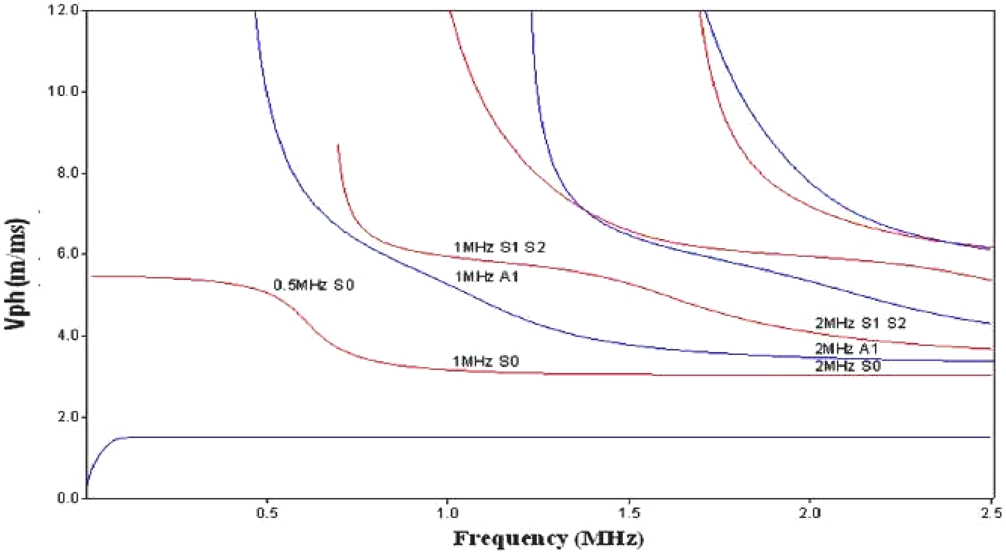


Fig 3.2 Dispersion curves for Lamb wave propagation in a 4 mm steel plate, immersed in water(Kundu,1997)

The particular mode at 1MHz frequency can be obtained by varying the striking angle, calculated by Snell's law e.g. for S_1 mode, the phase velocity is 6km/s, so the striking angle (A_1) for S_1 mode at 1MHz is calculated as follows by Snell's law:

Let the angle required is A_1

$$\frac{\text{Sin A}}{C_1} = \frac{\text{Sin90}}{C_2}$$

C_1 is velocity of lamb wave in water (1.5 km/sec).

C_2 is phase velocity of lamb wave in Steel (6 km/sec)

$A_1 = \sin^{-1} C1/C2$

$A_1 = \sin^{-1} 1.5/6$

$A_1 = 14.7°$

So at an angle of 14.7° (of both transmitter and receiver) hence keeping the probe at 14.7° at 1MHz will generate S_1 mode.

Hence, the dispersion curves of Lamb wave modes could be obtained by solving wave equation with boundary conditions. In case of ultrasonic testing in air, the transducer is in contact with the specimen along with the couplant but it is touched in perpendicular direction to the surface to be tested. So in this case it becomes difficult to identify the mode of the ultrasonic wave. But non-contact testing gives an advantage by determining speed of a particular mode from the DISPERSE software, we can roughly estimate mode at a given time for a given frequency. So dispersion curves are important tool for estimating various characteristics and modes of given ultrasonic wave.

3.3 EXPERIMENTAL DETAILS

3.3.1 Set up and Specimen Details

Experimental set up consists of a conventional UT system consisting of P-R, digitizer card, data acquisition ,immersion probes for sending and receiving signals. The setup is shown in **Fig 3.3**

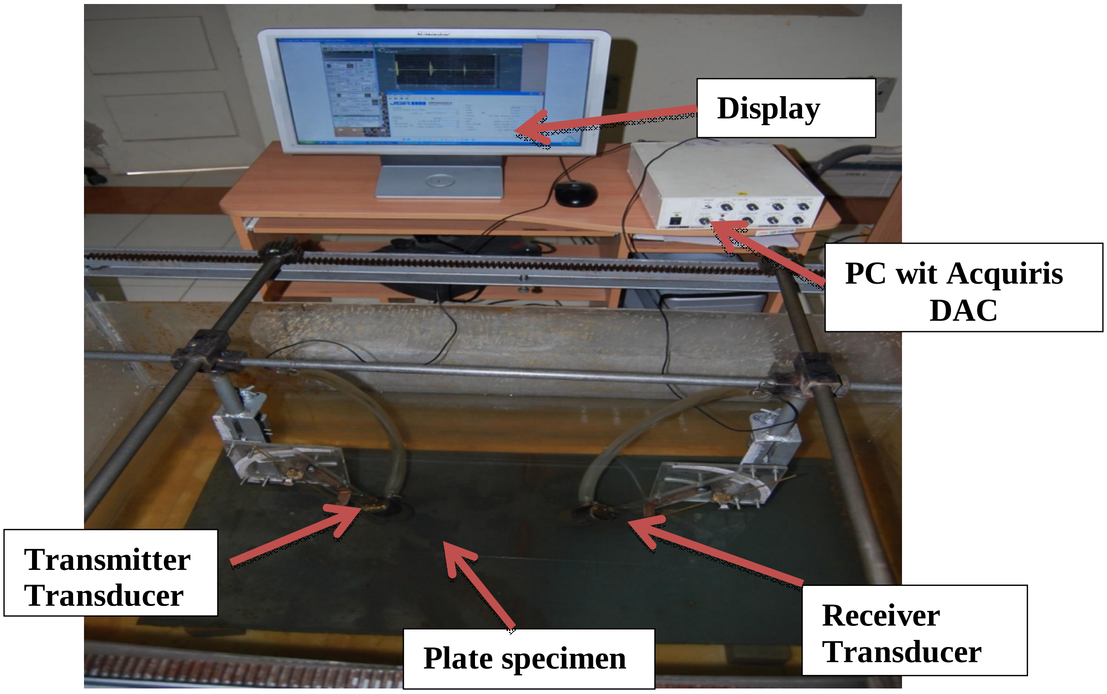


Fig.3.3. Experimental Set up

The experimental study consists of utilizing ultrasonic guided waves for monitoring corrosion in steel plates of 4mm thickness. The plate is submerged in an acrylic tank of dimensions (1500mm×1000mm×900mm) filled with water .Plates specimen are placed on the wooden blocks .The probes are mounted on the holder. The probes are placed in Pitch Catch configuration **Fig 3.4** .The angle of the probe will be kept at 17.4° for 1MHz and 14.7° for 0.5MHz transducers according to the modes as shown in **Fig 3.4** .The probes are excited with the help of pulser receiver (PR) (DPR 100 Model, Make Karl Deutsch) .The signals first travel through water, then travel through the submerged plates and is finally received by receiver probe

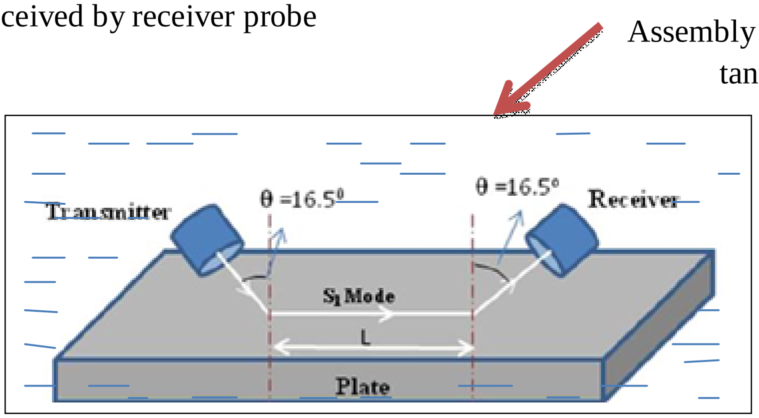
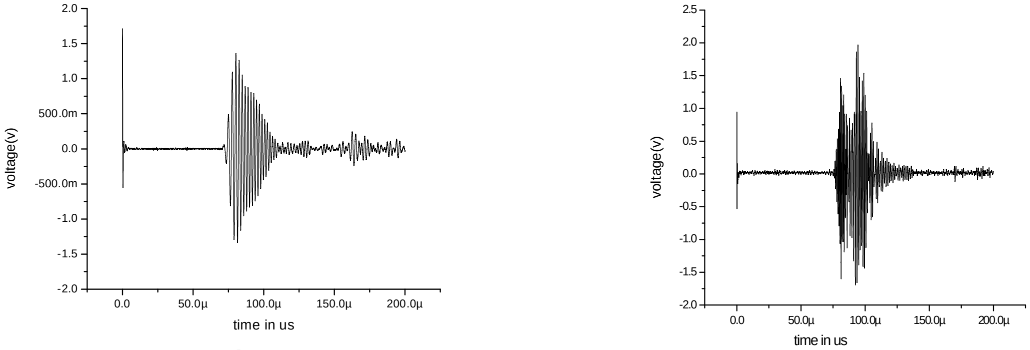

Assembly in water tank

Fig. 3.4 Pitch Catch arrangement of probes for signals

To ensure equidistant placement of the probes at a convenient location from the specimen in terms of time of flight is kept as 40 µs in the entire experimental investigation. When the signal travels to the other end it is then received with the help of data acquisition card (DAC, Aquiris Make). The signal received on the CPU is in the form of v-t curves. The recived signals in the healthy plate obtained for 0.5MHz at S_0 mode and 1MHz at S_1 mode probes as shown in **Fig 3.5**



(a) S_0 mode at 0.5MHz

(b) S_1 mode at 1MHz

Fig 3.5 Pulse transmission signatures for healthy plate

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3.3.2 Components of setup used

(a) JSR Ultrasonic DPR 300 Pulser/Receiver System

DPR300 pulser produces a high voltage electrical excitation pulse (up to 475 Volt) and applies this pulse to the instrument's T/R connector. An ultrasonic transducer connected to the T/R connector via a length of 50 Ω coaxial cable has been then employed to convert the electrical energy of the excitation pulse into an ultrasonic pulse that has been propagated into a test material or medium.

With the DPR300 configured for pulse-echo mode operation, acoustic echoes reflected from interfaces or defects within the test material are converted by the transducer into electrical signals that are presented to the T/R connector of the DPR300. The low-noise DPR300 receiver amplifies these electrical signals, and the signals then pass through adjustable high pass and low pass filters. The DPR300 receiver gain has been adjustable between -13 dB and 66 dB, and there are six high pass and six low pass filter settings for band-limiting the receiver frequency response. The amplified and filtered signals are available on the instrument's Receiver Output connector.

The DPR300 may also be used in transmission mode operation wherein a separate receiving transducer has been used to detect acoustic pulses that have propagated through a test material or medium. **Fig. 3.6** gives the details of the inside layout of the JSR pulse generator. The sub-units of the JSR pulse-receiver are as given below:

(b) PRF Oscillator & Pulser Trigger

The internal PRF oscillator generates repetitive trigger pulses for the pulser subsystem under the control of the PRF control. Pulser Trigger control selects between the internal PRF oscillator and an external source applied to the Trig/Sync connector as trigger sources for the DPR 300 Pulser.

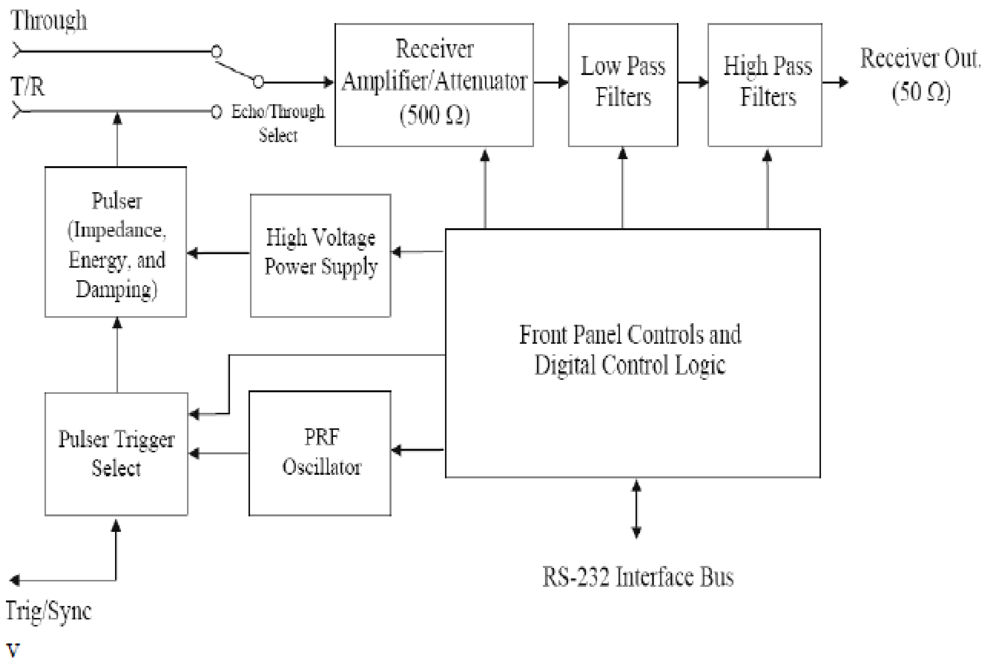

Fig 3.6.Layout of JSR Pulse Generator

(c) Data acquisition card (DAC)

Model DC438 Dual-channel, 12-bit, 100 MHz, 200 MS/s, 4 M point acquisition memory cards was used to capture the waveform. Waveforms are transferred directly into the digitizer large acquisition memories so that complex signals can be stored over very long time periods. Large memories are essential for maintaining fast sampling rates and therefore timing resolution. **Table 1.1** shows the configuration of digitizer card

Table 1.1 Configuration of Digitizer Card

Model DC438	
Bandwidth (-3 dB)	DC to 100 MHz
Full Scale Range (FSR)	250 mV, 500 mV, 1 V, 2 V, 5 V and 10 V
Impedance	50 ohm ± 1% @ DC
Connector	BNC, gold-plated
Channels	Two
Coupling	DC
Maximum Input Voltage	±10 V DC (2 W) or 10 V RMS at 50 ohm

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Bandwidth Limit Filter	35 MHz 2-pole Bessel filter (DC438)
Minimum Amplitude	1 V pk-pk
Impedance	50 ohm

3.4 CORROSION STUDY AND METHODLOGY

3.4.1 Introduction

Basic aim of the study is to investigate the progression of corrosion in MS plate in submerged state using the selected modes. Marine environments cause corrosion on metal surfaces exposed for extended periods. Uniform corrosion usually occurs in stagnant or low-flow seawater at a rate of approximately 5-10 microns per year. Corrosion is a sever process it takes several year to take place. Marine structures are subjected to a highly corrosive environment that combines the effects of saline seawater, salt laden air, rain, dew, condensation, localized high temperature, stresses and the corrosive effects of combustion gases. Corrosion can be extensive in localized areas hidden inside the submerged areas of the structure making them very difficult to detect. In extreme situations, such age-related deteriorations can cause catastrophic failures including total losses. In order to avoid severe loss, real-time health monitoring is very important. In marine structure generally two types of corrosion occurs:

- **Uniform Corrosion**

This type of corrosion develops as pits of very small diameter, in the order of a micrometre, and results in a uniform and continuous decrease in thickness over the entire surface area of the metal as shown in **Fig 3.7**

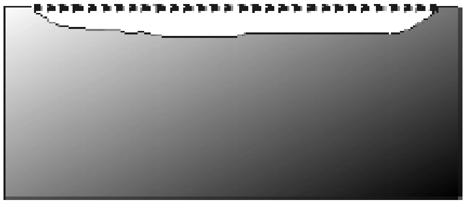

Fig 3.7 Uniform Corrosion (www. corrosion-doctors.or)

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- **Pitting Corrosion**

This localised form of corrosion is characterised by the formation of irregularly shaped cavities on the surface of the metal. Their diameter and depth depend on several parameters related to the metal, the medium and service conditions. Aluminium is prone to pitting corrosion in media with a pH close to neutral, which basically covers all natural environments such as surface water, seawater, and moist air.

Pitting is considered to be more dangerous than uniform corrosion damage because it is more difficult to detect, predict and design against. Corrosion products often cover the pits. As shown in **Fig 3.8** small, narrow pit with minimal overall metal loss can lead to the failure of an entire engineering system.

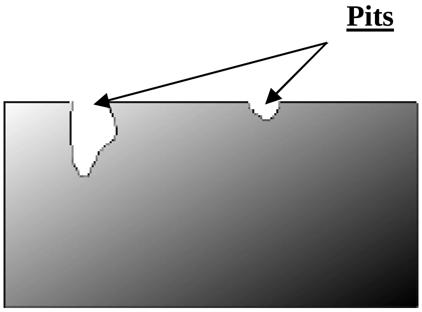

Fig 3.8 Pitting Corrosion (www. www. corrosion-doctors.org)

3.4.2 Methodology of accelerated corrosion used in study

In natural environments, corrosion process takes several years to occur. Hence, the corrosion has been accelerated in this study by using the impressed current technique. Healthy mild steel plate specimen (600×mm×250 mm×4mm) in submerged state is scanned in PT using the selected surface and core sensitive modes at the marked locations shown in **Fig 3.9**. The initial mass of the plate is also recorded. The plate is then subjected to an impressed current corrosion.

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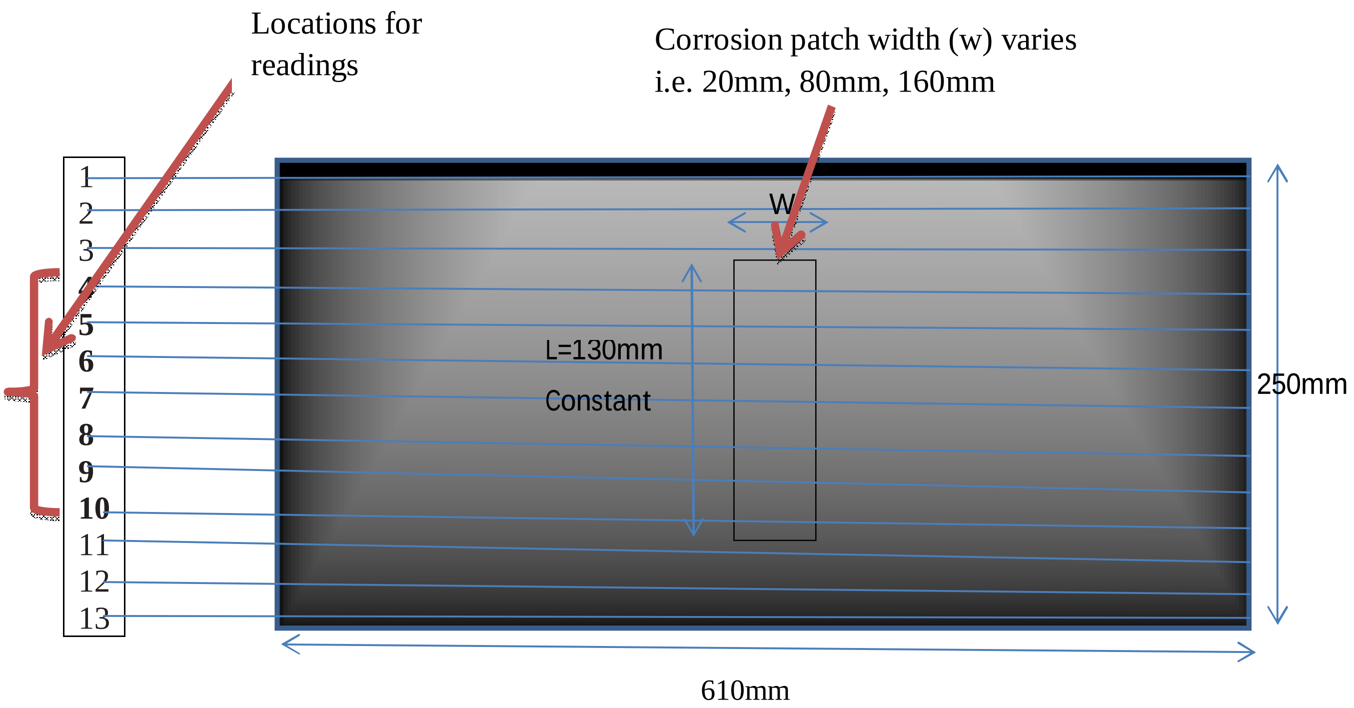

Fig3.9 Actual plate sample for accelerated corrosion

A constant voltage of 30 V was applied between the two terminals by means of a constant power supply device (Make Aplab Regulated Dual DC power supply LD6405) having maximum voltage of 32V and maximum current capacity of 2 Ampere.

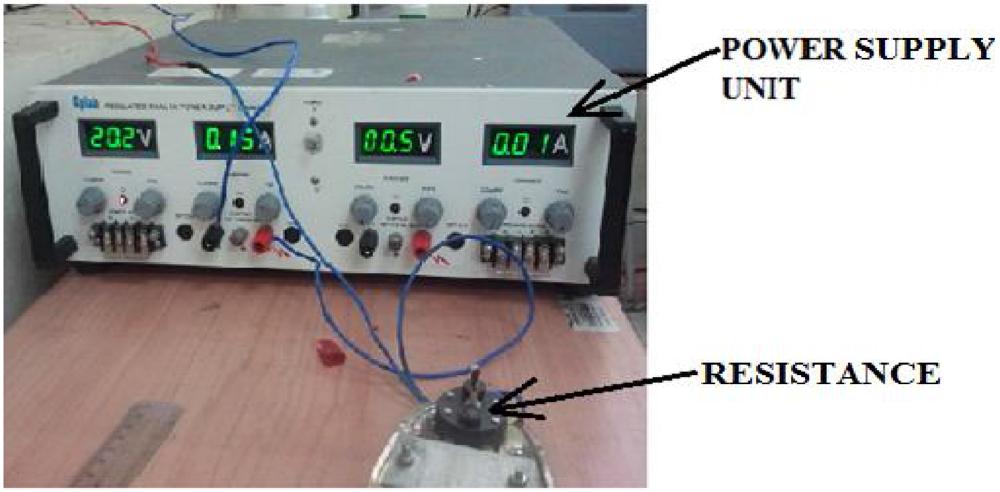

Fig 3.10 Power supply unit used in study

A bottomless acrylic tank with dimensions (200 mm×20mm×55 mm) is placed atop this steel plate for selective exposure of the specimen to corrosive environment. The tank is filled with 3.5% brine solution. A copper strip is dipped in the brine solution and is made cathode connected to negative terminal of power supply in the circuit while the plate acts as anode and is attached to positive terminal of power supply.

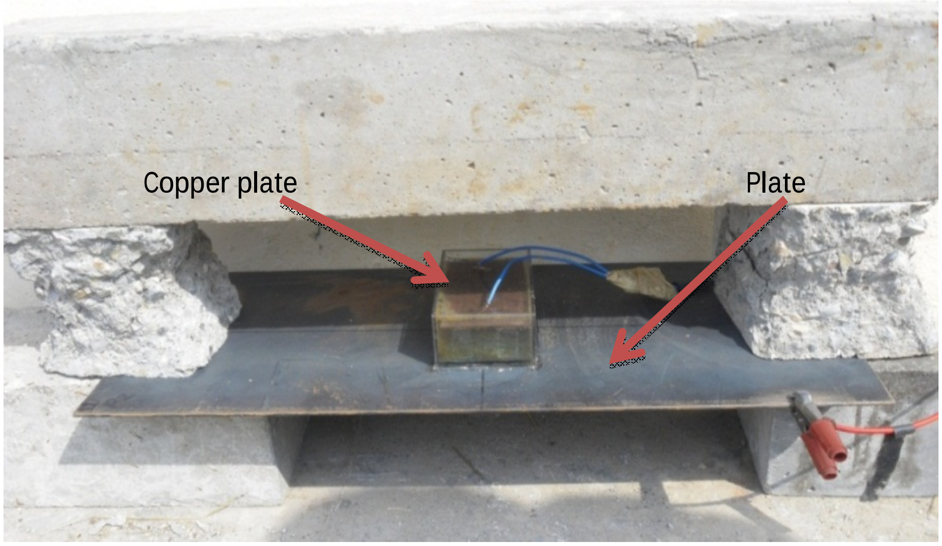

Fig 3.10(a) Accelerated corrosion setup

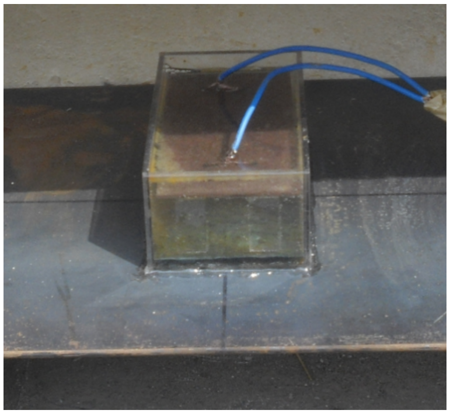

Fig 3.10(b) Acrylic tank

After every 24 h of exposure to accelerated chloride corrosion, the acrylic tank is dismantled, and ultrasonic scanning of the plate using both S_0 and S_1 modes is performed to monitor the changes in the PT signatures. Mass of the plate is also recorded for ascertaining the mass loss due to corrosion.

After ultrasonic testing, the acrylic tank is again fixed on the plate, and the accelerated corrosion process is continued. This procedure is repeated till the PT signal vanishes. In pitch catch transmission the distance between the probes was kept as 200mm and length of corrosion patch was kept constant at 130mm.The ultrasonic readings was taken along the location or along the length L. Width (W) of the patch varies from 20mm, 80mm and 160mm. Along all the locations PT readings will be taken. In healthy locations of the plate readings will be the same. But as the corrosion progresses the V-t signal attenuates from Location 4 to 10 because the corrosion decreases the thickness of the plate causing reflection and mode scattering in fall of signal.

3.4.3 TEST MATRIX

The test matrix for study of accelerated corrosion in submerged plates is divided as follows in **Fig 3.11**

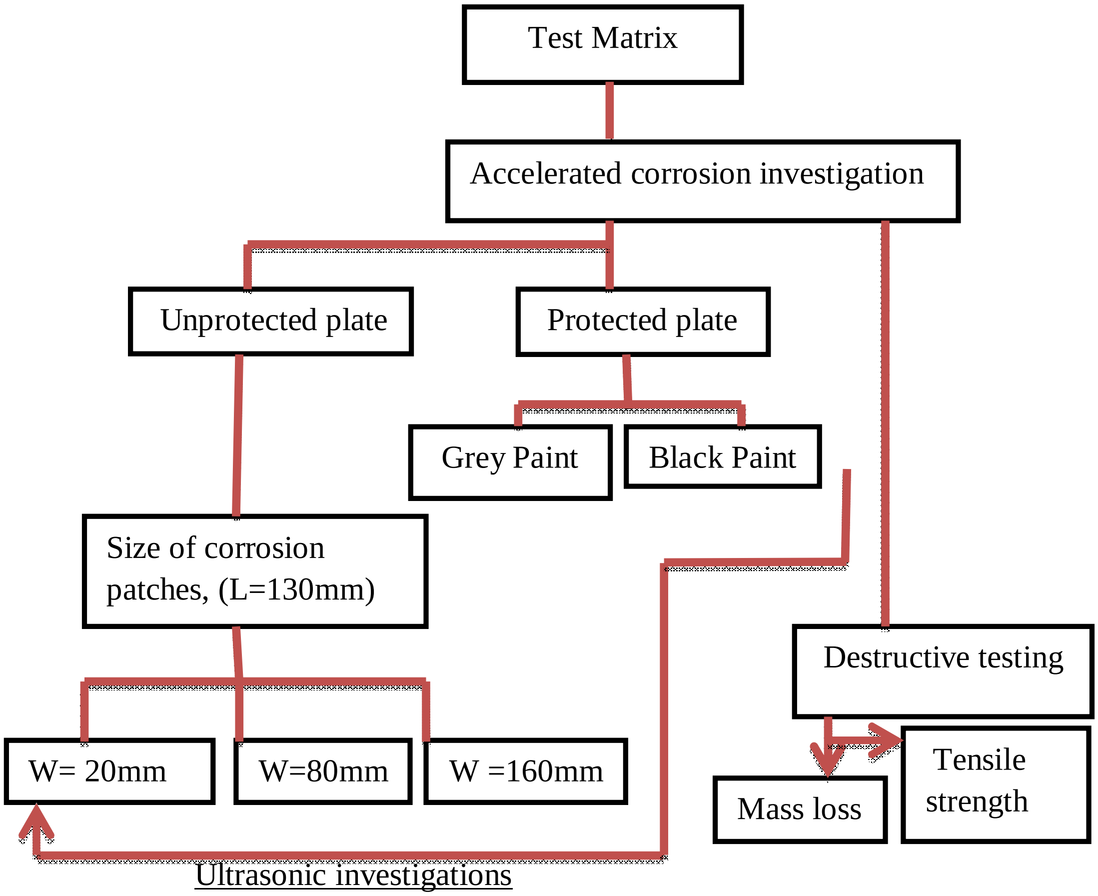

Fig 3.11 Test matrix

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The accelerated corrosion monitoring in submerged plates is carried out in two conditions. One set of plates which are uncoated and corrosion exposure (i.e. L×W) is varies as 20mm, 80mm, 160mm. Another set of plates are protected with surface modifications in the form of paints with corrosion exposure in W=20mm only. Two types of paints are used: Grey paint (Epoxy zinc rich primer, Hardener, Epidic (G) light grey). Black paint: (AD stov zinc rich primer, Interlac 1017 Black). Further in 20mm corroded patch plate, effect of initial scratch on the V-t signal is also observed. Similarly in plates with paints of initial damage on plates is also studied.

3.5 CLOSURE

In this chapter a discussion on the experimental setup, specimen and methodology of work to be carried out in this investigation is explained in detail. Following chapter puts forth, the results obtained from this study of plates subjected to underwater corrosion.

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CHAPTER 4
RESULTS AND DISCUSSIONS

4.1 GENERAL

This chapter presents the results obtained from the study carried out for monitoring corrosion in submerged plates as detailed in Test Matrix in Chapter 3.

4.2 UNCOATED PLATES

4.2.1 Result of 20mm corrosion patch without initial damage

(a) Visual observation

In 20mm size, corrosion patch **(Fig 4.3)** ultrasonic signals were taken in Location 4-10 using Pitch Catch orientation as already explained. Steel plates undertaking accelerated chloride corrosion showed blackish brown corrosion products floating in the acrylic tank within 6 hours of exposure. The brine solution converted into a reddish brown liquid and was changed after every 12 hours, in order to ensure consistent current level in the corrosion circuit. After 2 days of exposing to corrosive environment, corrosion patches in the form of small pits were observed on the plate (**Fig 4.1a).** The pits extended and spread on the surface of the plate with increasing exposure. After 5 days, extensive corrosion areas were observed. This is because of the corrosion occurs is in the presence of chloride, it results in the formation of pits. Pits cause scattering and attenuation of the signals. Consistent loss in mass was observed after each day of corrosion. The process continued till 8 days and was stopped when pits gave way to holes in the plate. At this stage, corrosion exposure could not be continued further because the brine solution leaked from holes and the ultrasonic pulse transmission signals (PT) signals almost vanished.

(b) Observations with surface seeking mode (S_1 mode at 1MHz)

Ultrasonic PT signals were recorded at the marked locations on the plate using surface sensitive S_1 mode at 1MHz. Initially for the healthy plate, the signature is characterized

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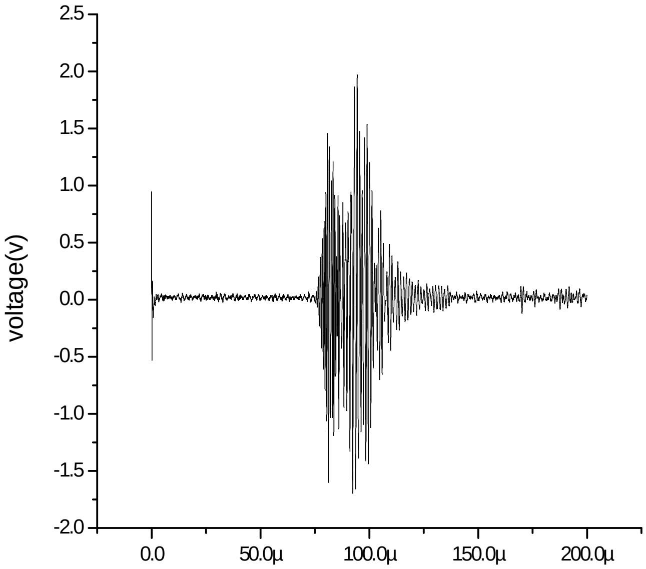
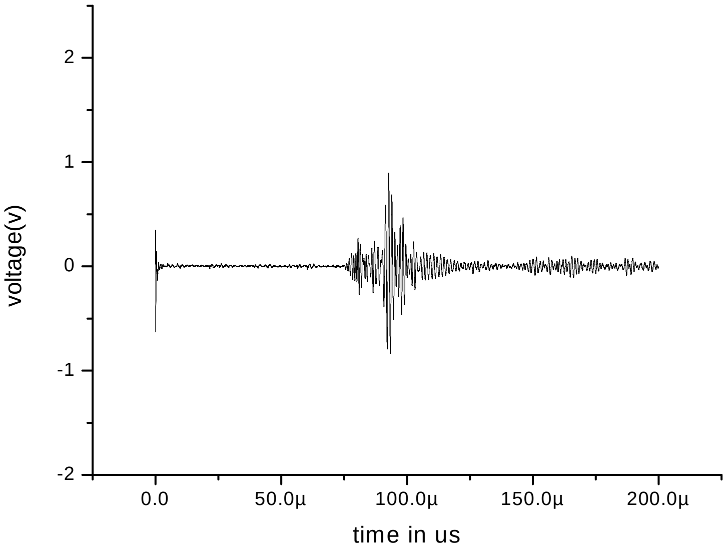
by a strong pulse at all locations on the plate **(Fig 4.1a**). As the corrosion progressed, changes are observed in PT signatures. The signature obtained after 3,5 8 days of corrosion as shown in **Fig 4.1(b-d)**. It is observed that the transmitted signal attenuates with increasing exposure to corrosive environment indicating material loss due to corrosion. Maximum drop in voltage amplitude is observed at locations marked 7-9 on the plate. It suggests significant localized corrosion in these regions leading to formation of holes. After 8 days of corrosion **Fig (4.3c)**

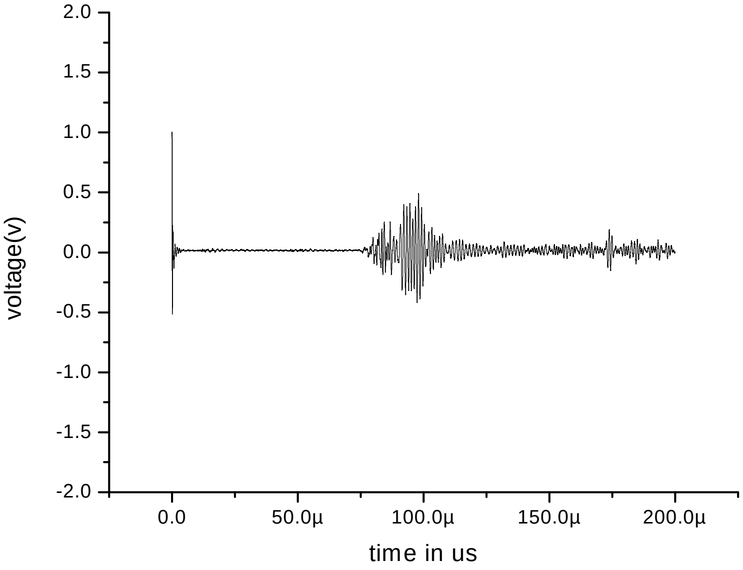
The behavior of this mode can be explained by the mechanism of corrosion in the presence of chlorides. Corrosion in the presence of chlorides is characterized by pitting and localized loss of material. Because of non-uniform loss of material from the plate surface, the smooth waveguide in the healthy plate is disturbed resulting in scattering of the wave and hence, attenuation of the transmitted signal. It drops to 20% of its original value in the first 5 days (**Fig 4.4).** As corrosion progresses (6–8 days), no significant attenuation in the signal is observed. This is due to the surface sensitive nature of the mode, which picks up early surface modifications but is not responsive to deep pits with increasing exposure



(a) Healthy



(b) 3 days



(c) 5 days

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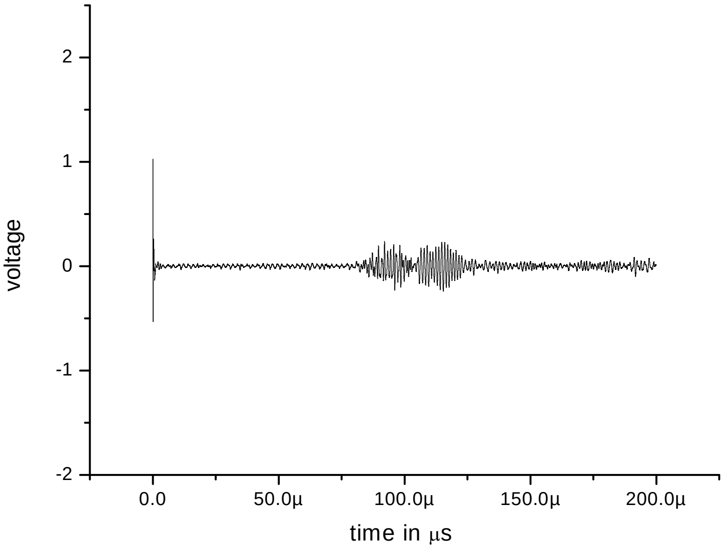

(d) 8 days

Fig 4.1 Signatures using S_1 mode at 1MHz

(c) Observation with core seeking mode (S_0 mode at 0.5MHz)

PT signals of the plate using this mode exhibits relatively less changes during the initial 2 days as compared to the surface sensitive S_1 **(Fig 4.2 a,b)** . This mode does not sense surface deteriorations as effectively as S_1 mode does. As corrosion further progresses, consistent drop in voltage amplitude of PT signal is observed with this mode throughout the corrosion period **(Fig 4.2 b,c,d)** This is due to the core sensitive nature of the mode. As the corrosion progresses there is continuous drop in signal with core seeking mode **(Fig 4.4)**.

Hence, it can be concluded that as the surface sensitive mode picks up the initial surface changes due to corrosion, the core sensitive mode is effective in picking up the progression of corrosion leading to pitting. Due to attenuation in signal in core seeking mode is due to the degradation in the plate because of chloride induced corrosion which eats up the signal.

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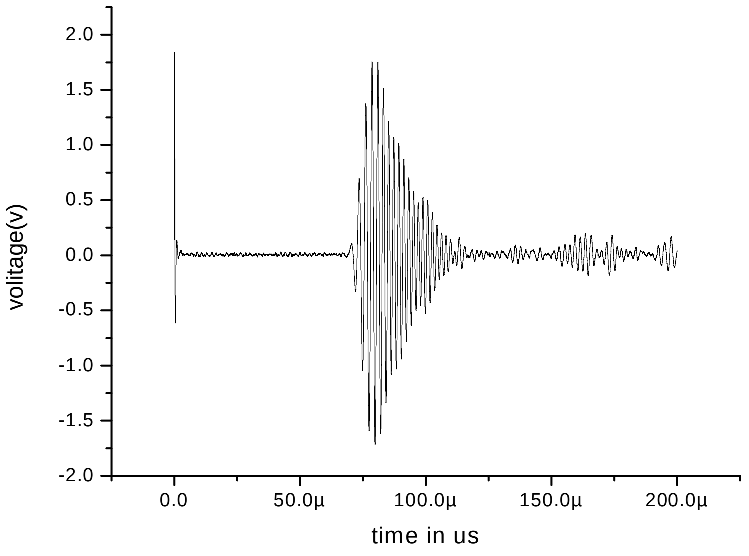
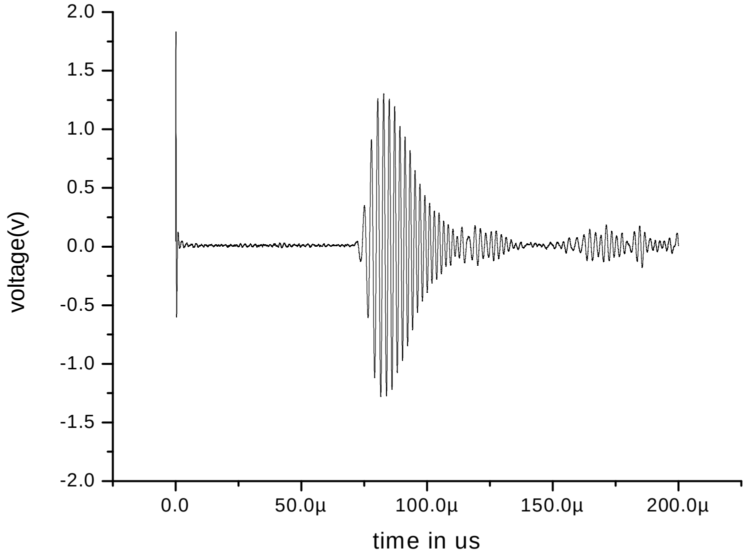


(a) Healthy



(b) 3 days

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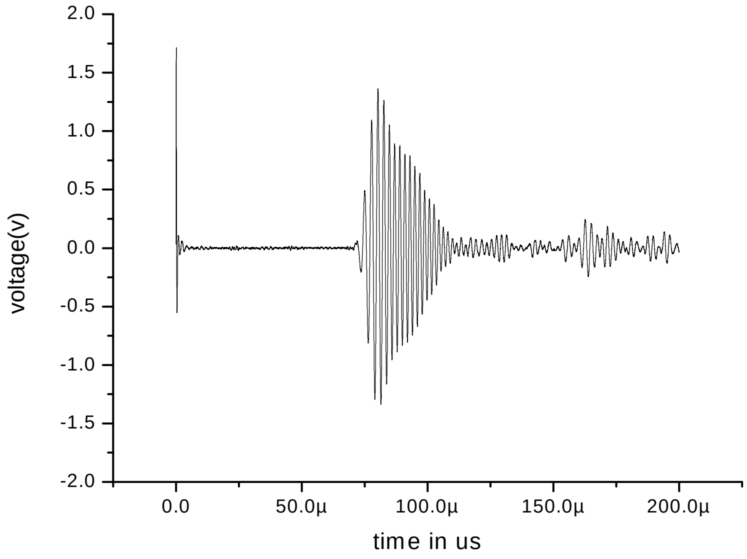
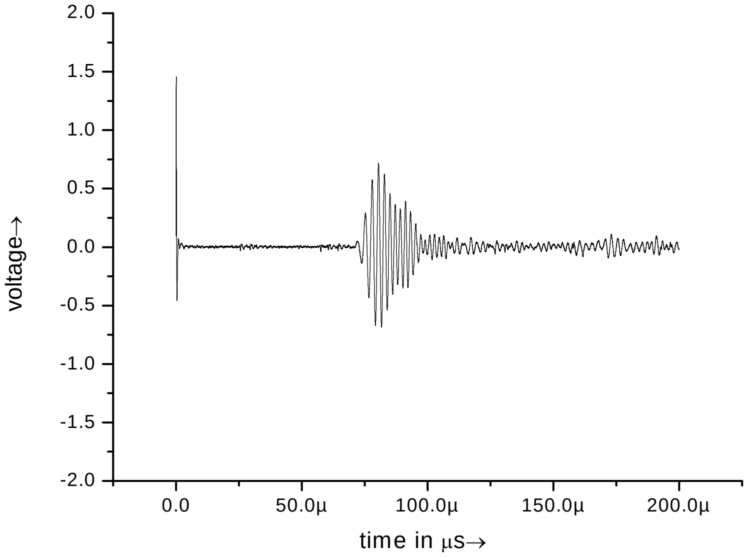
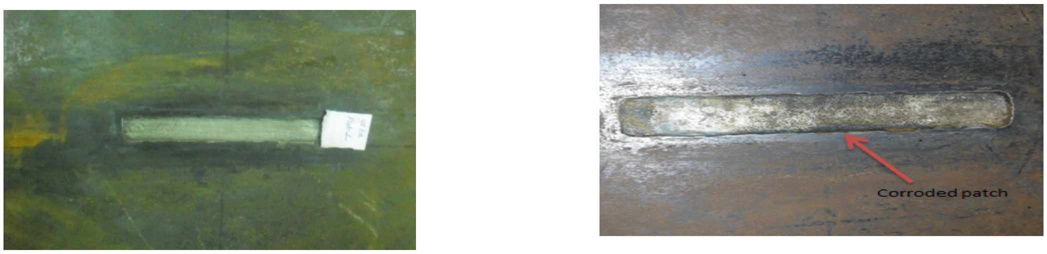


(c) 5 days

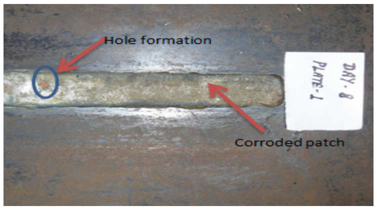


(d) 8 days

Fig 4.2 Signatures using S_0 mode at 0.5MHz frequency



(a) After 2 days corrosion **(b) 3days**



(c) 8days

Fig 4.3 Corrosion on the plate with Patch of 130mm×20mm

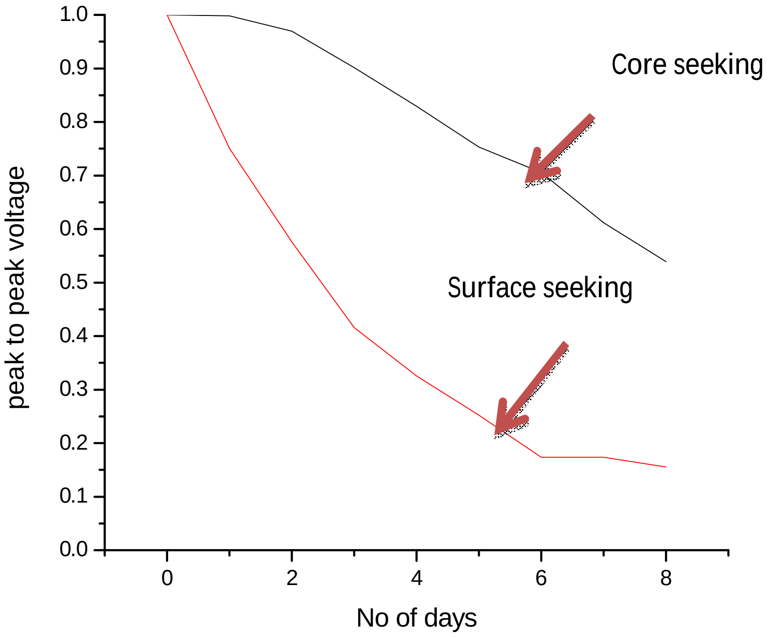


Fig 4.4 Trend of Peak-Peak voltage with increasing exposure to corrosion with both modes.

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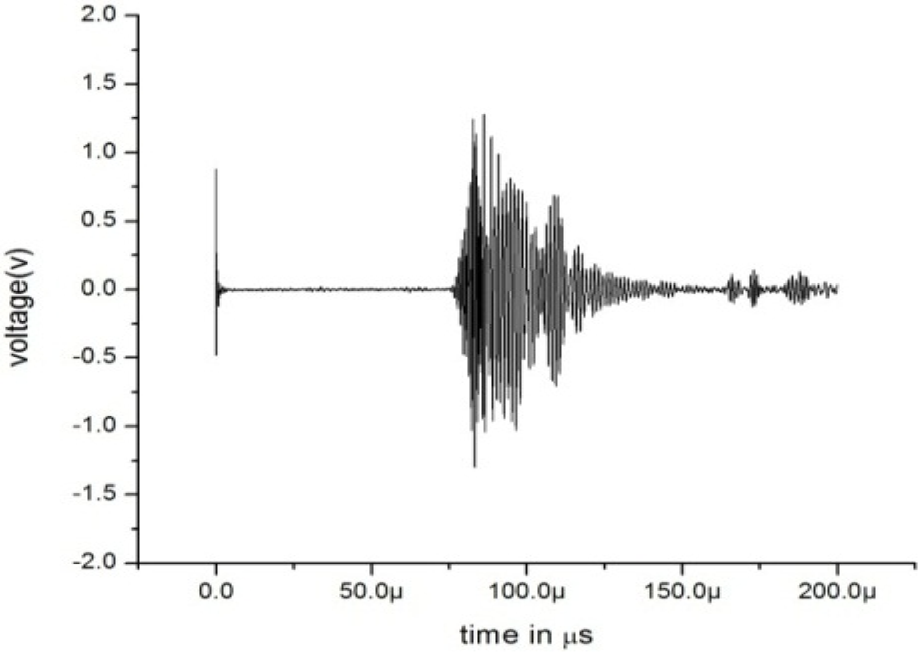
4.2.2 20mm patch with initial damage

An initial damage in the form of a scratch with a nail is put in the 20mm patch to be exposed to corrosion to initiate corrosion and creates a local corrosion site. It is done to simulate the in situ underwater condition where the plates are not always in perfect or healthy condition and investigate how initial UT signal changes or picks up the degradation. The following **Fig 4.6** shows the signatures obtained with core seeking mode (S_0 mode at 0.5MHz) and **Fig 4.5** shows the signature obtained with surface seeking mode (S_1 mode at 1MHz) at different ages of corrosion.



(a) Healthy

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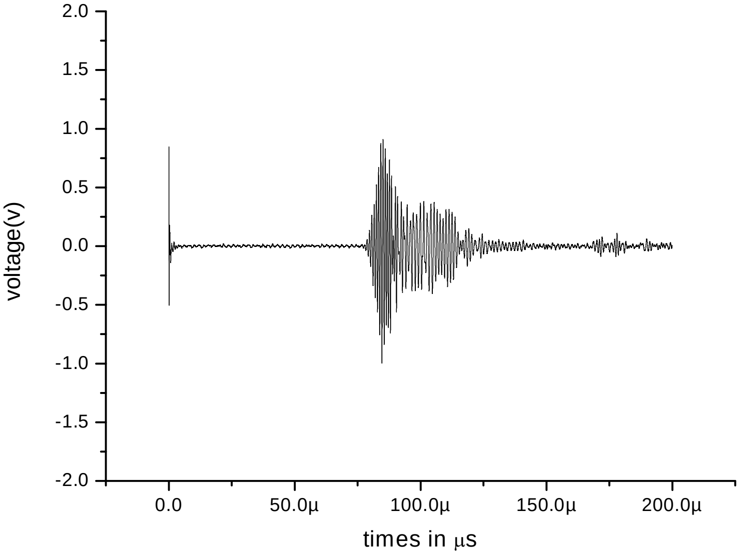
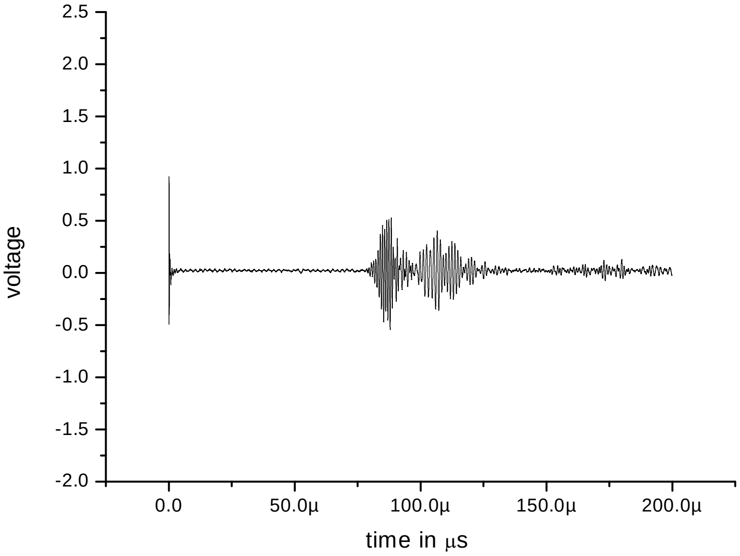


(b) 3 days



(c) 5 days

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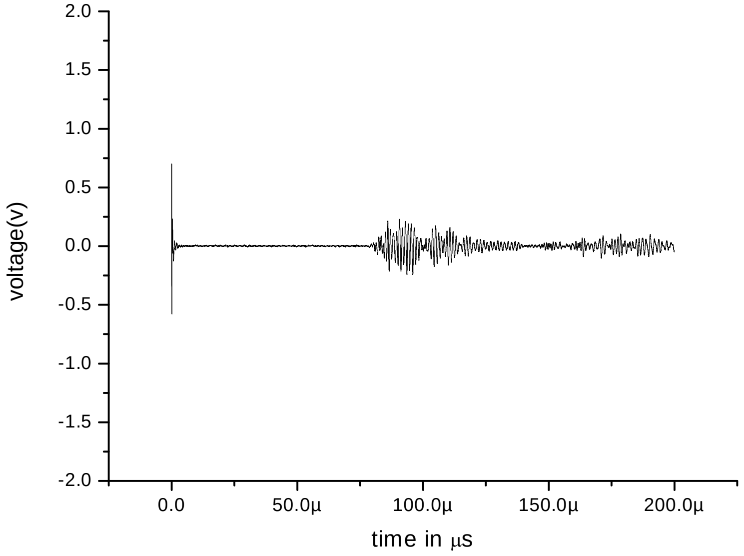
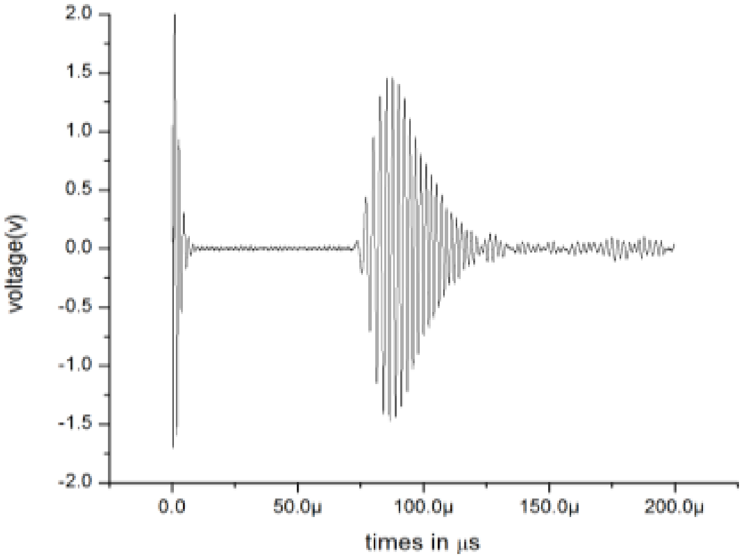


(d) 7days

Fig 4.5 Signatures using S_1 mode at 1MHz frequency



(a) Healthy

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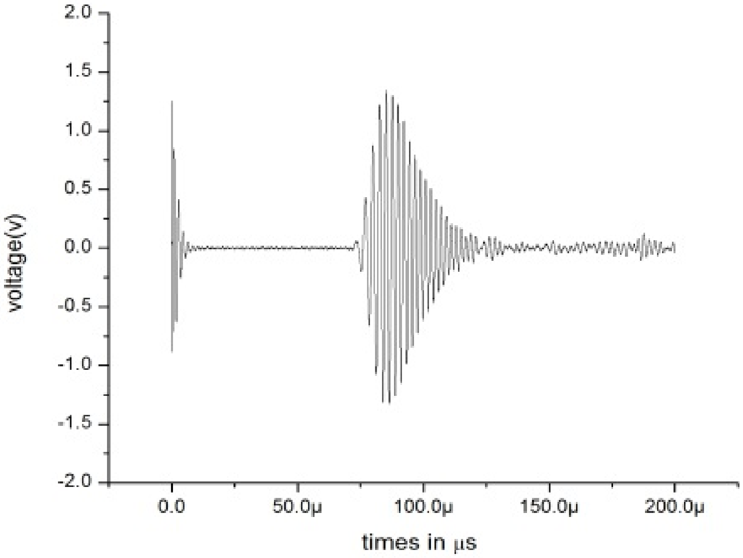
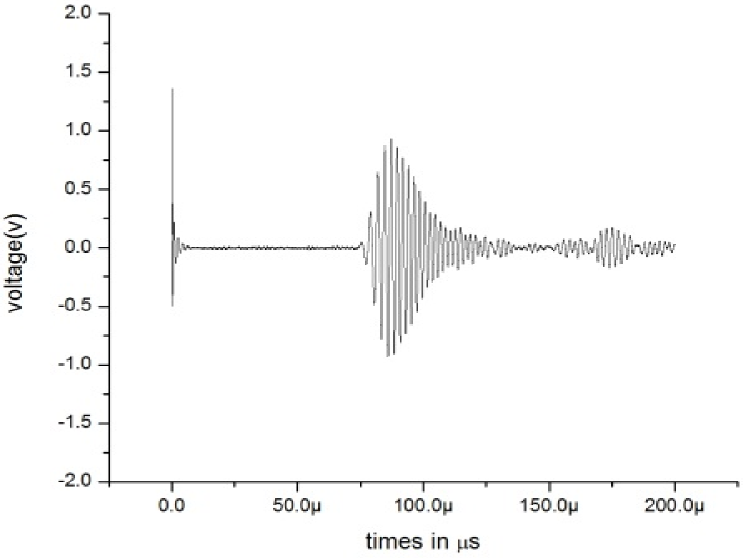


(b) 3 days



(c) 5 days

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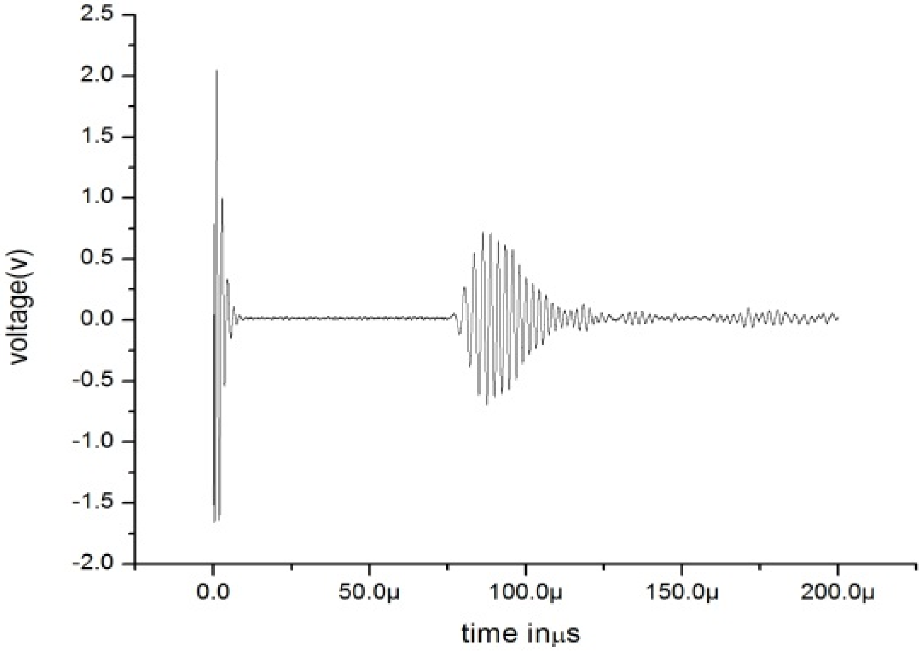
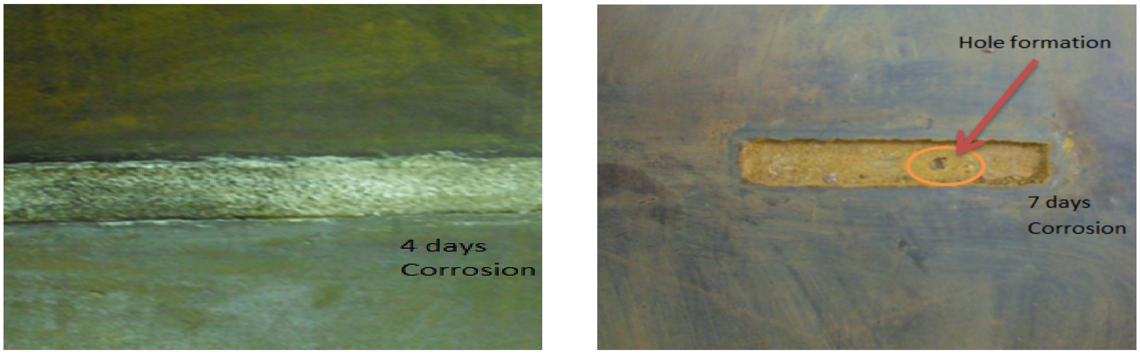


(d) 7 days

Fig 4.6 Signatures using S_0 mode at 0.5MHz frequency

Fig 4.7 shows the condition of the plate after 4 days & 7 days.



(a) 4 days corrosion **(b) 7 days corrosion**

Figure 4.7 Corrosion on the plate with Patch of 130mm×20mm (L×W)

From the signature obtained with both modes, it is observed that the trend of fall in signal with both the modes 20mm patch with initial damage remains same as that of 20mm

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patch without damage .The only difference observed was that the hole was formed in 7 days as against 8 days due to initial corrosion site created in the plate.

Hence , the corrosion monitoring methodology using the specific guided wave modes picks up the corrosion successfully in plates in any condition(healthy slightly damaged). The trends of the results of received signal obtained with both modes shown in **Fig 4.8** shows the same results.

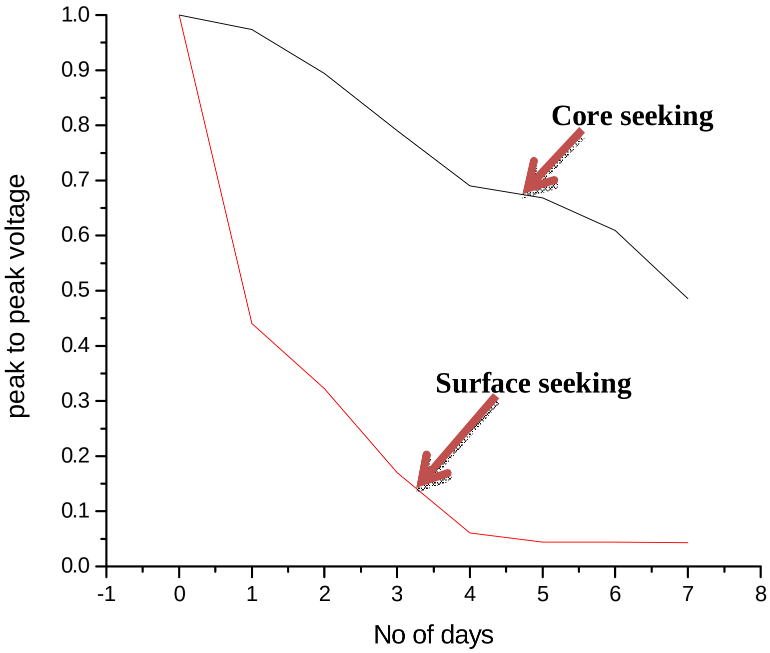
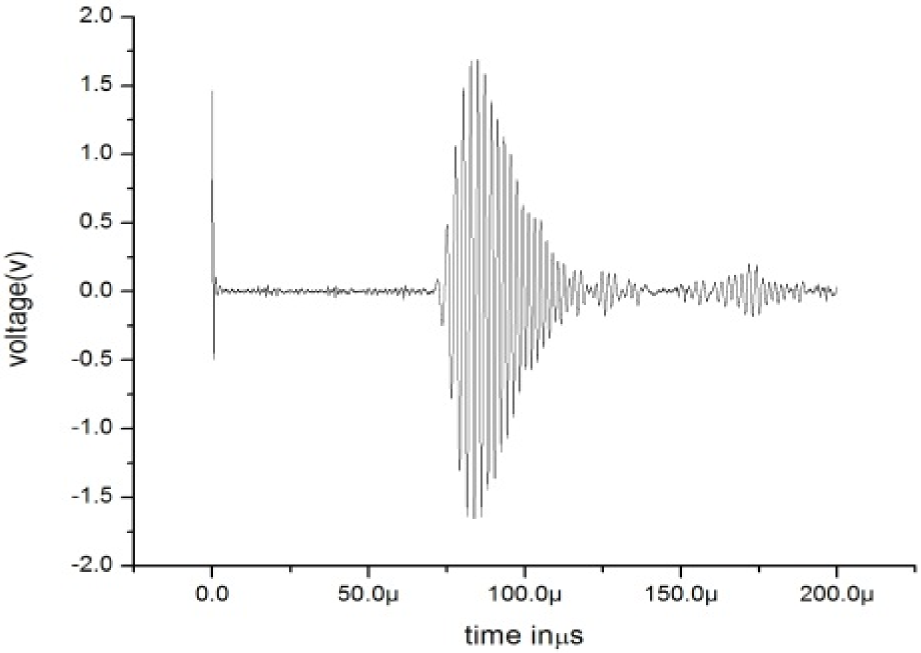


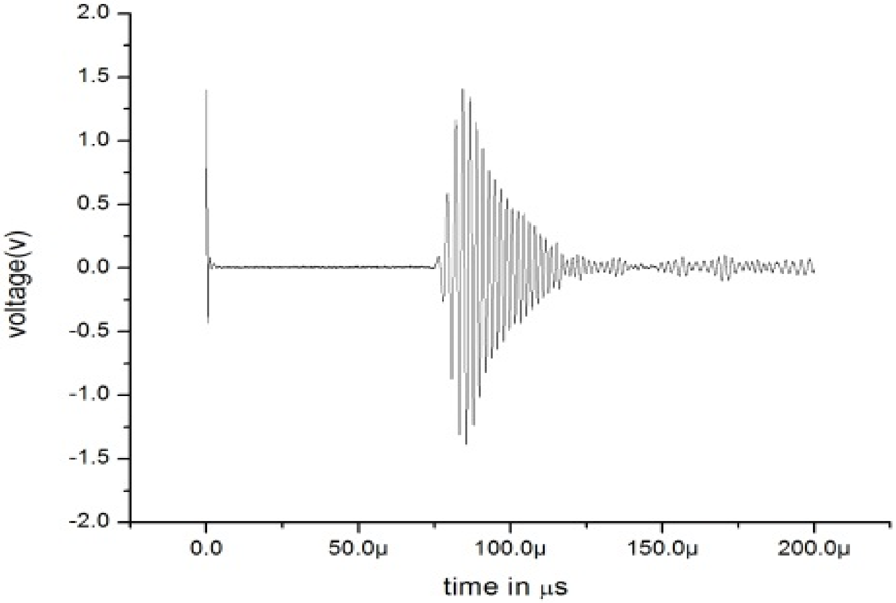
Fig 4.8 Trend of Peak-Peak voltage with increasing exposure to corrosion with both modes

4.2.3 80 mm corrosion patches:

Following **Fig 4.9 & 4.10** shows the V-t signals obtained from both modes S_0 & S_1 mode, in a large corrosion patch having dimensions of 130 mm length and 80mm width as against 20mm width in earlier case



(a) Healthy



(b) 5 days

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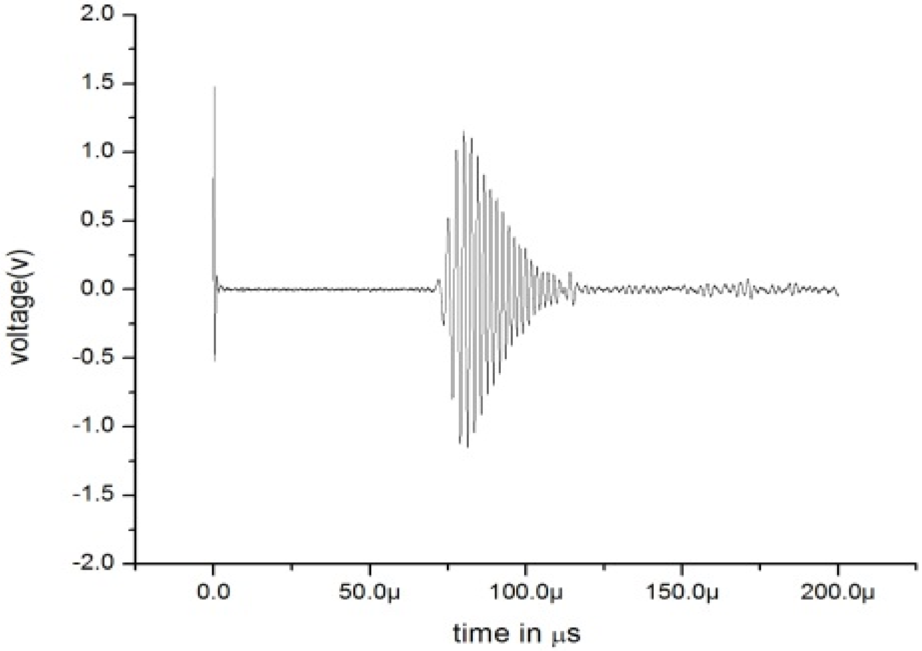
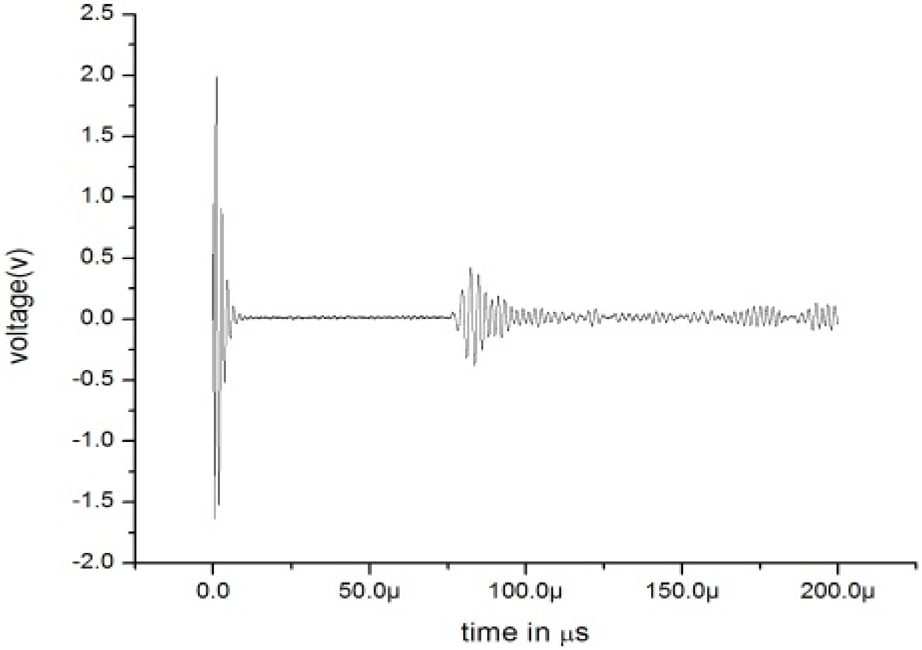
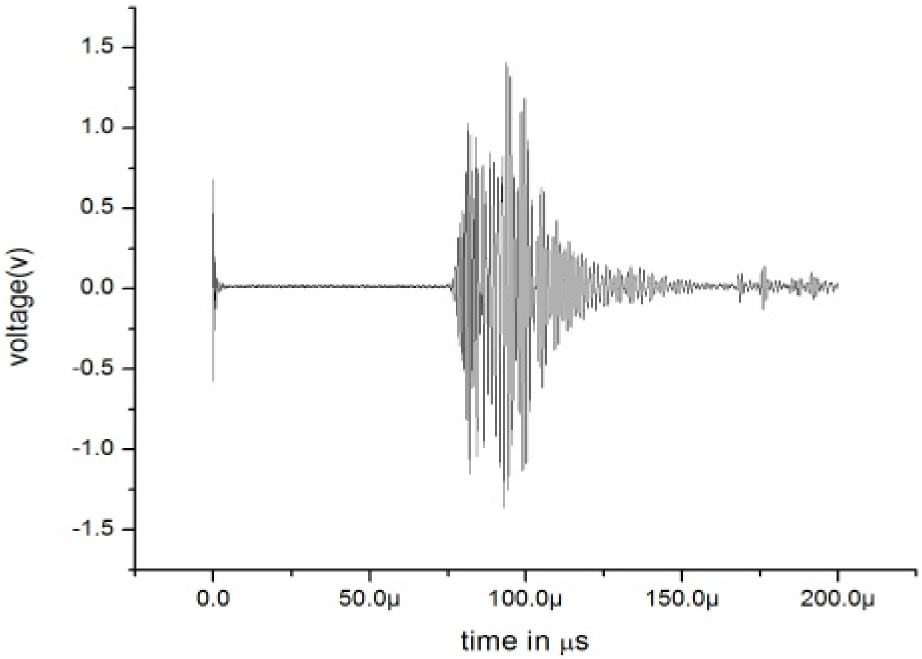


(c) 10 days

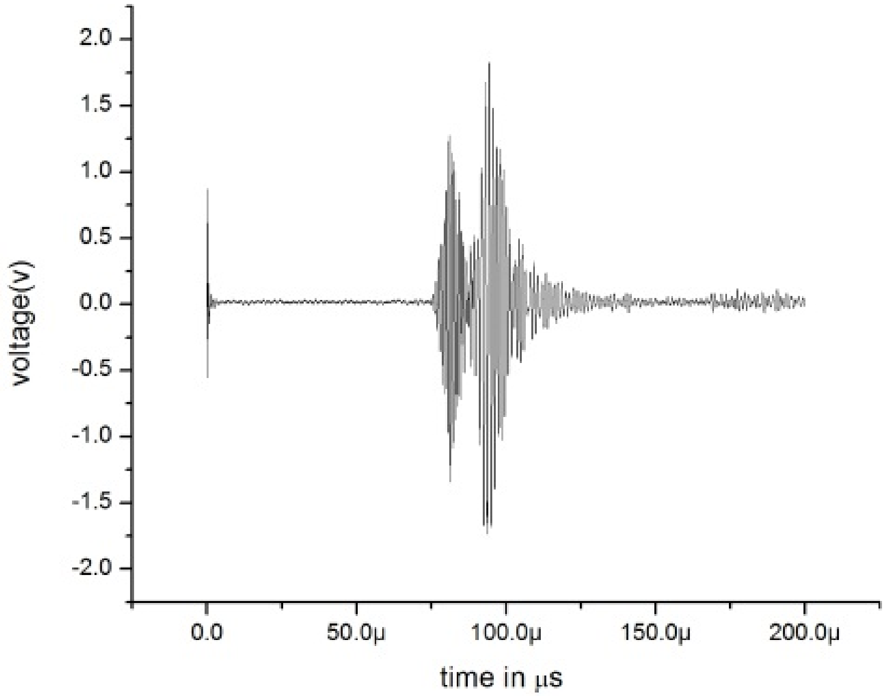


(d) 19 days

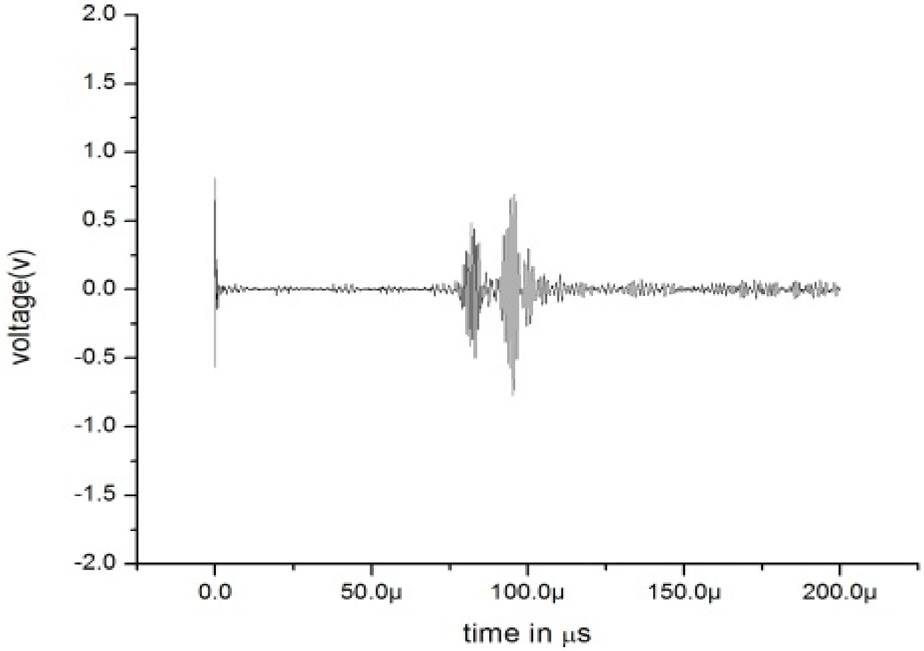
Fig 4.9 Signatures using S_0 at 0.5 MHz frequency



(a) Healthy



(b) 4 days



(c) 7 days

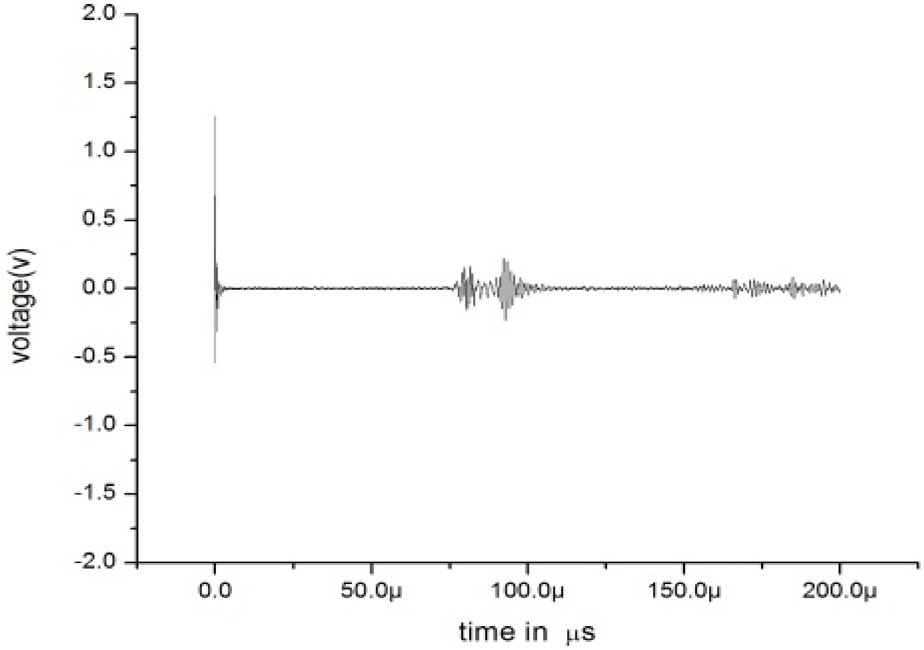
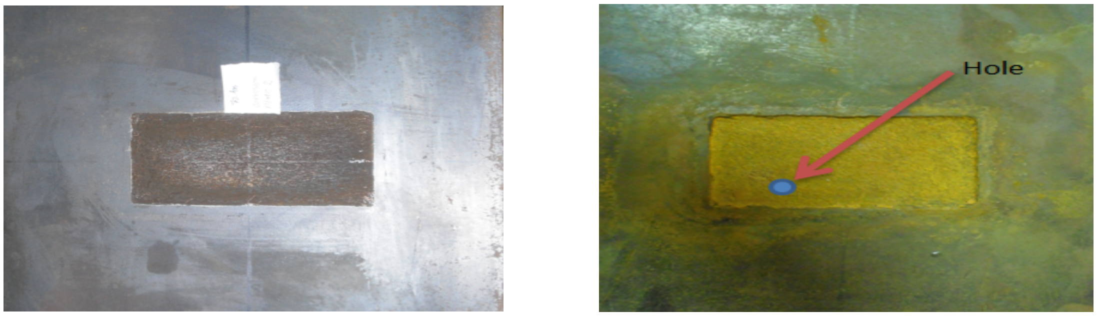


Fig 4.10 Signatures using S_1 at 1MHz frequency



(a) 3 days **(b) 16 days**

Figure 4.11 Corrosion on the plate with Patch of 130mm×80mm (L×W)

The trends of 80mm patch are same as that of 20mm patch without damage. The only differece observed was that the hole formed in 19 days instead of 8 days. This because of the increased area of the patch, which showed rate of corrosion and the modes S_0 & S_1 were able to pick up degrating. The surface seeking mode pick up initial surface modification in 8 days and become constant after that. The core seeking mode further pick up deterioation by rapid by rapid fall of signal in 3-21 days. Hence the PT monitoring using Lamb waves can detect and monitor corrosion irrespective of the size of local corrosion in underwater plates.

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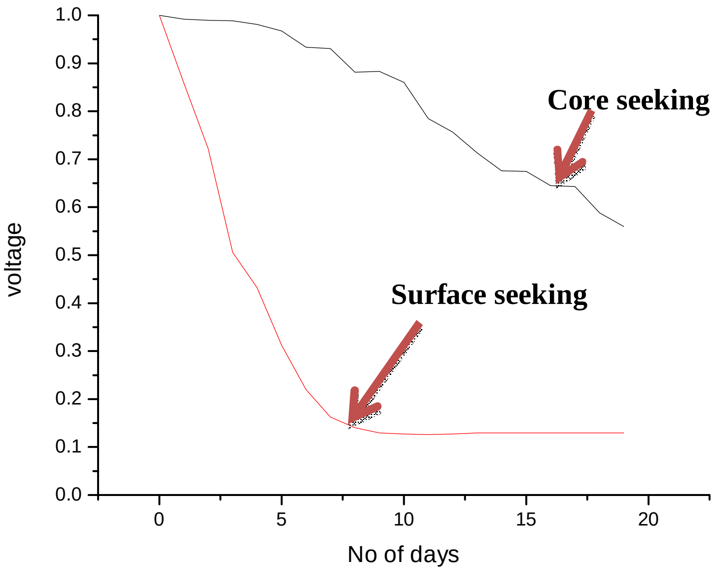

Fig 4.12 Trend of Peak-Peak voltage with increasing exposure to corrosion (80mm patch)

4.2.4 160mm corrosion patch

The study is further extended to a large corrosion patch of L=130mm, W=160mm to ascertain the repeatability of the Lamb wave study for corrosion monitoring in submerged plate. A bottomless acrylic tank with dimensions (130mm×160mm×55mm) is placed atop this steel plate for selective exposure of the specimen to corrosive environment. The tank is filled with 3.5% brine solution. A copper strip is dipped in the brine solution and is made cathode in the circuit while the plate acts as anode. A constant voltage of 30V was applied between the two terminals by means of a constant power supply device.

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(a)10 days **(b)23days**

Fig 4.13 Corroded specimen.

The trend of 160mm patch with initial damage is same as that of 20mm patch 80mm patch. But the hole was formed in 23 days instead of 8 days in 20mm patch and 19 days in 80mm patch. This is because of the increased exposure to corrosion causing agent.

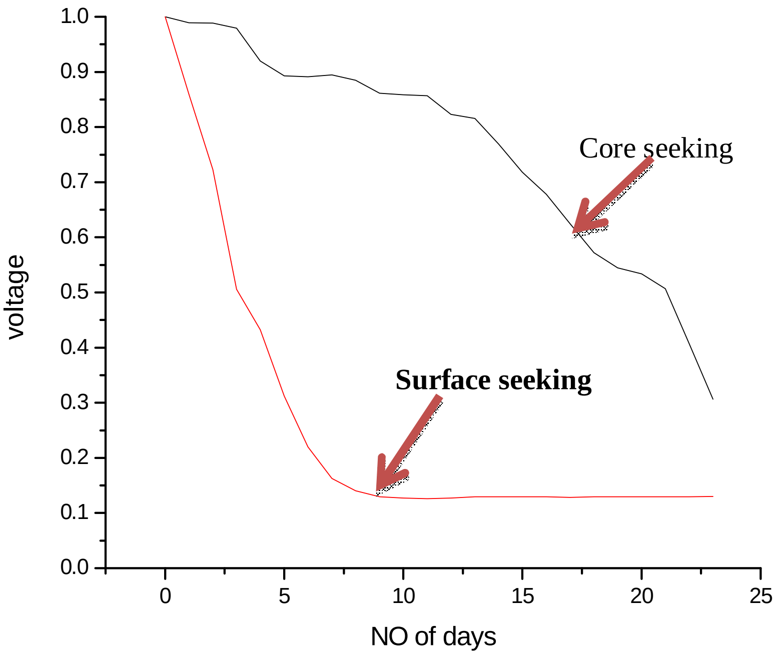

Fig 4.14 Trend of Peak-Peak voltage with increasing exposure to corrosion(160mm patch)

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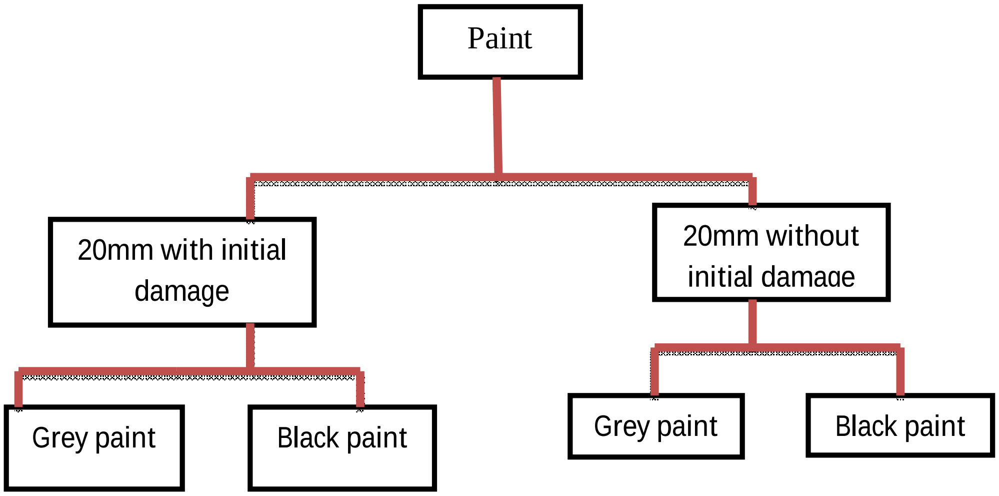
The ultrasonic PT investigations using the surface and core seeking modes indicated the same pattern of trends as in earlier two plates. Rapid fall in signal with surface sensitive mode is observed in first 7 days after which it become constant where core seeking mode signal deteriorates throughout the period though initially slow and then rapid after 20 days. Both the modes together can be effectively used to pick up entire corrosion process in plates

4.2.5 Comparission of UT with different sizes of patches

Increasing the corrosion patch area 80mm and 160 mm patches, the process of corrosion delayed. so It takes more time for hole or pit formation. But the trend of signal drop remain same with both core and surface seeking modes.

4.3 PROTECTED PLATE



4.15 Test matrix of paint

An initial coating was used with paint before exposure to corrosion was done to protect the steel plate from corrosion. Two type of paints (a) Grey paint (b) Black paint which are commercially used for protection of marine structures (**Figure 4.15).** Firstly the surface of the plate was cleaned with thinner to remove impurities from the surface of steel plate. After that first coat of primer applied then leave for drying. After drying primer properly second coat of the paint applied. Before applying the paint and primer mixed with thinner to reduce viscosity of the paint and primer.

The basic properties of the paints used are as below

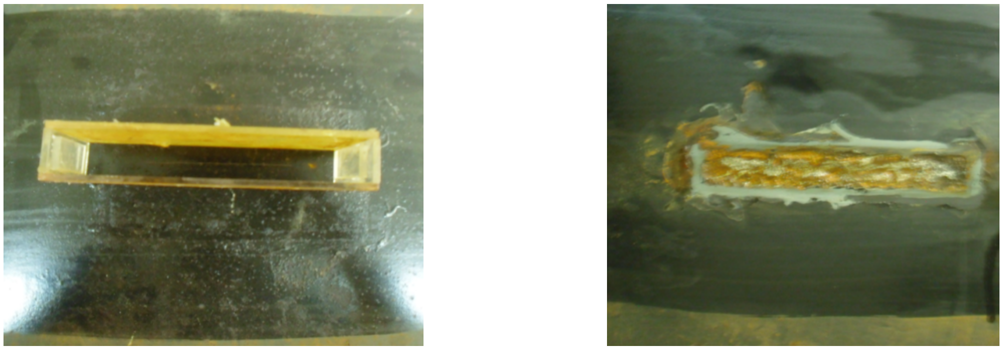
- **Grey paint**
  Commercial Name: EPIDEC (G) LIGHT GREY
  Manufacture: Maruthi Paints & chemicals
  Epoxy zinc rich primer
  Hardener
  Epidic(G) light grey
- **Black paint**
  Commercial Name: AD stov zinc rich primer Interlac 1017 Black
  Manufacturer: Akzo Nobel Coating India Pvt Ltd.

(a) Grey paint **(b) Black paint**

Fig 4.16 Paints used in study

After applying paints, corrosion was accelerated in the plate and ultrasonic PT study was done. Only 1MHz (S_1 mode) mode is used in this experiment because it is surface sensitive and would read the surface modification in a better way than core seeking mode. It is investigated to find out the effect of surface paint on corrosion initiation and progression and how ultrasonic PT technique can monitor the delay due to paint and its further effect on plate. Two types of plates, one with initial scratch and other without scratch were studied. From **Fig 4.17,** it can be observed that the scratched area of the plate is more affected than unscratched plate.

(a) With scratch **(b) 3 day corrosion**



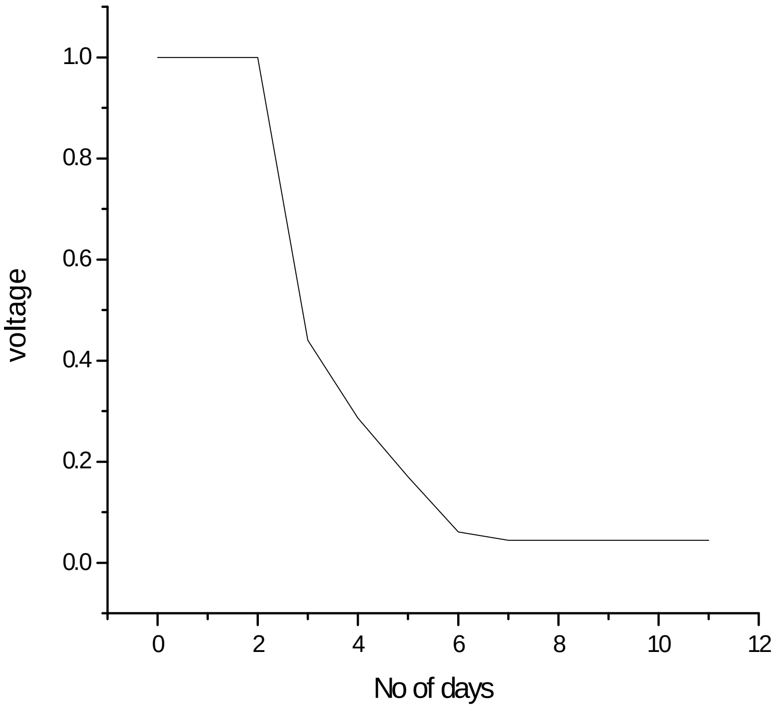
(c) With scratch **(d) After 4 days corrosion**

Figure 4.17 Conditions of the plates with paint and with and without initial scratch .

4.3.1 20mm patch with paint and without scratch

In this study of plate with two types of grey paint and black paint were investigated. The primer and paint was applied on the plate. 20mm corrosion patch size was used. Readings were taken of only surface seeking mode using 1 MHz transducer. The trends of PT with both the paints is as shown **(Fig 4.20)**

From the trend it is observed that due to the application of paint PT signal does not fall initially for 3 days. Fall in signal is from 3-6 days in grey paint plate and 5-7 in black paint plate after which it become constant. Further the core seeking mode will pick up the deterioration over the paints give way and can be used. Grey paint plate takes 9 day for complete corrosion or hole formation and black paint takes 13 days for the same. The grey paint paint could resist the accelerated corrosion for 3 days and the black paint was more effective and did not show signs of degradation for 5 days.



(a) Grey paint

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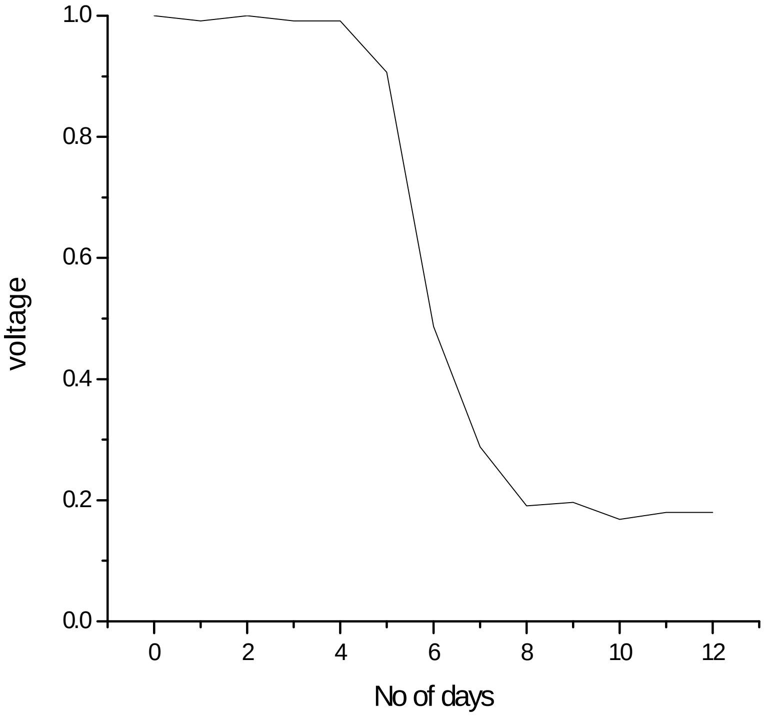

(b) Black paint

Fig 4.20 Trends of paints

Hence, it can be concluded that paints are affective in preventing corrosion attack dependency upon their composition and Lamb waves can not only pick up corrosion but also protection offered by paints.it is well depicted by constant signal in surface seeking mode is sensitive to initial modifications. Different types of paints protect the plates to varying degree as in this study. Black paint was more effective than grey paint. Once the paint give way, ultrasonic PT investigation can pick up progression corrosion in normal plates with paint.

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4.4 DESTRUCTIVE TESTS AND RESULTS:

In this experiment, effect of corrosion on mechanical properties of tensile stress and mass was investigation and how it relates to corrosion. Various steps involved in this study are shown in the block diagram as shown in **(Fig 4.20)**

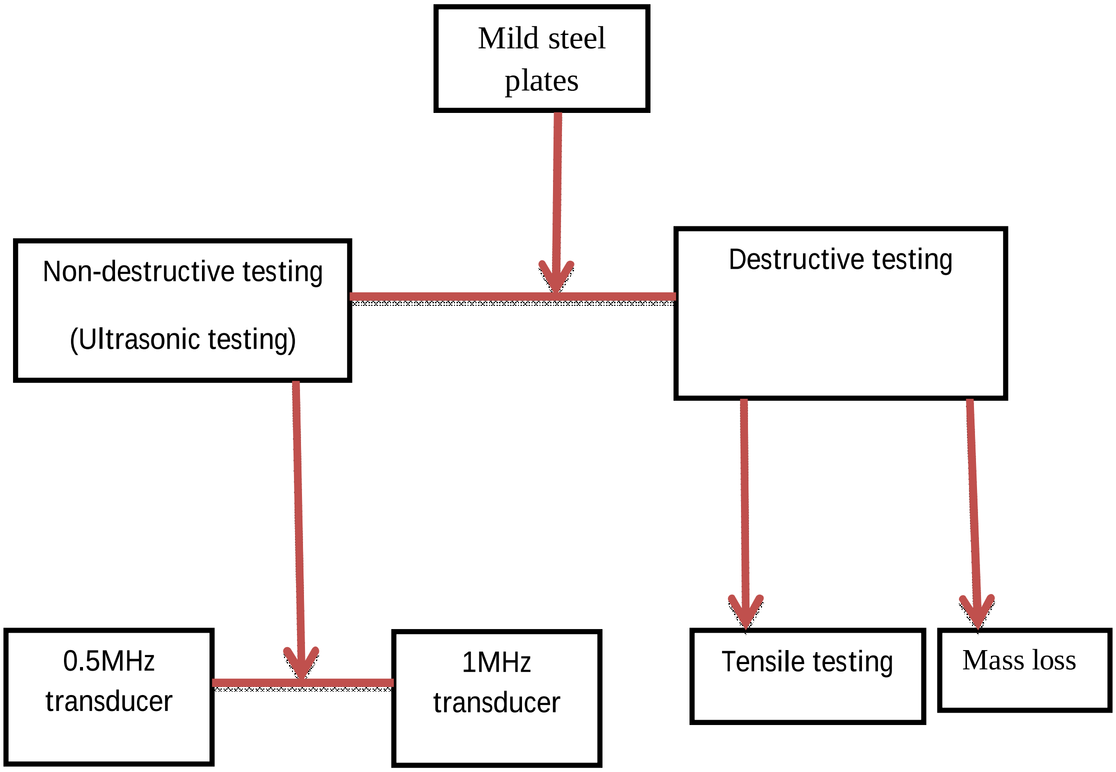

Figure 4.20 Block diagram representing various steps of study

4.4.1 Methodology for destructive Testing: A destructive test programme was developed for accelerated corrosion of different durations to investigate the effect on physical/ mechanical properties in a 20mm corrosion plate. Mass loss and tensile strength was measured after 2,4,6,8 days of corrosion exposure. Five steel plate samples (609mm×20mm×4mm) were prepared and the initial mass of these samples was recorded. Subsequently, these samples were exposed to accelerated corrosion of varying durations of 2, 4, 6 and 8 days. And its effect on tensile strength and mass loss was measured

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Tensile testing Setup used: - A Universal Tensile testing machine shown in **(Fig.4.21)** has been used for the testing of mild steel plates for its tensile strength. Maximum Capacity of UTM is 1000 kN. The test specimens have been prepared according to ASTM-D-3790. This is computer controlled machine having hydraulic grippers for holding the specimen. This machine is capable of performing both tensile as well as compression tests. This machine has been used for subjecting the specimens at different levels of mechanical loading.

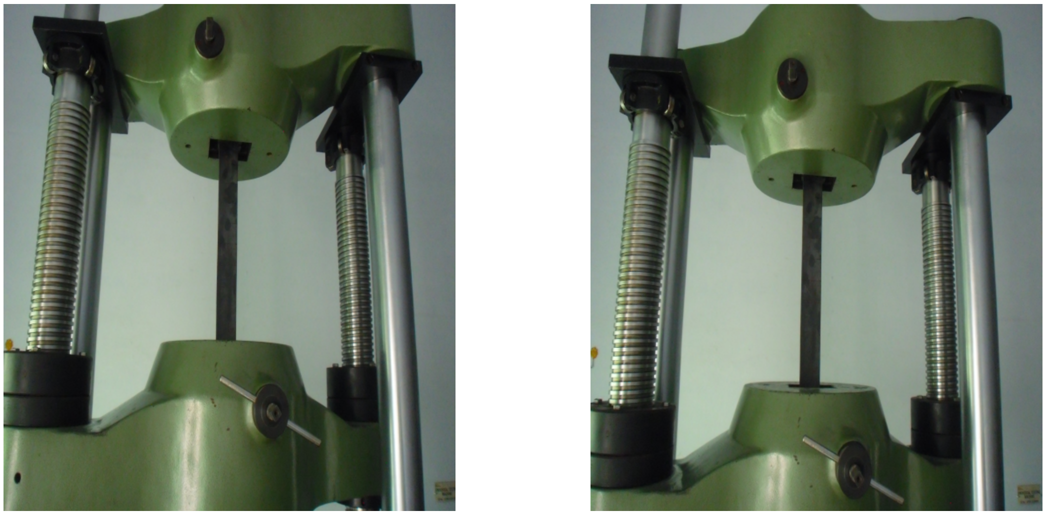


Figure 4.21 Setup for tensile testing on UTM

Table 4.1 shows the variation of tensile strength and mass loss at different ages of corrosion. **(Fig 4.22)** shows the healthy and corroded plates at varying degree of exposure.

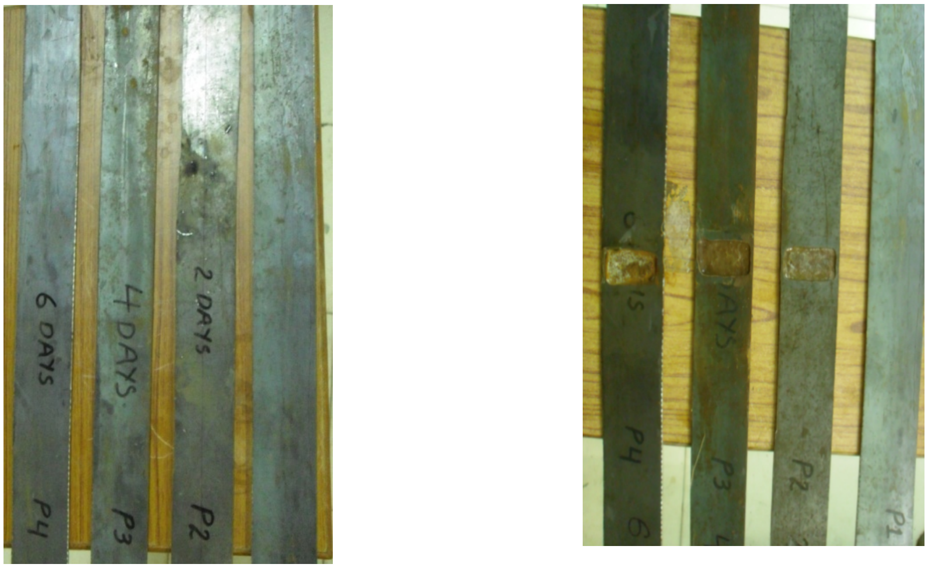


Figure 4.22 Healthy and corroded plate specimens.

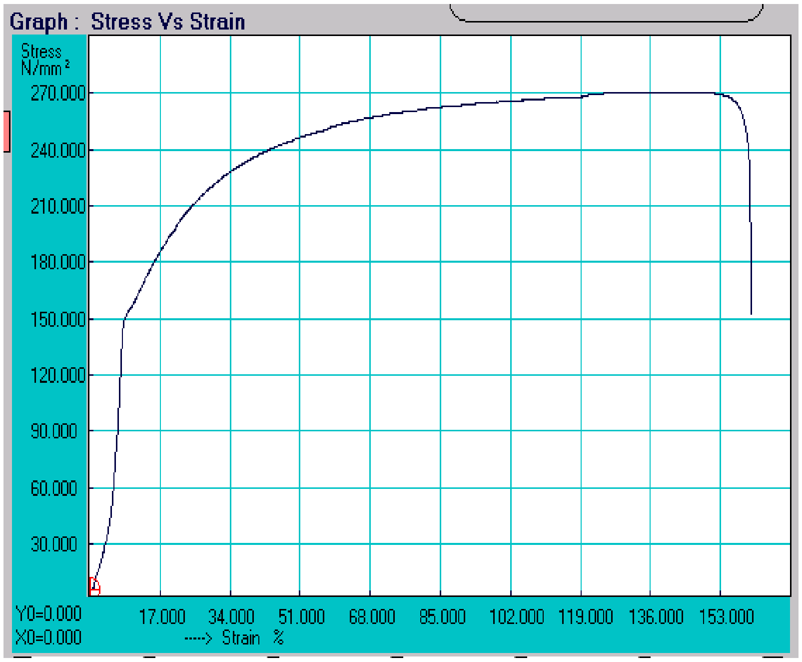
Table II. Variation in destructive test parameters with increasing exposure to corrosion.

Exposure to corrosion (no of Days)	0	2	4	6	8
Mass Loss (%)	0	1.596	2.41	2.61	2.91
Tensile strength (N/mm2)	270.588	105.093	102.455	64.871	33.173
Loss in Tensile Strength (%)	61.161	48.863	31.698	36.68	2.510

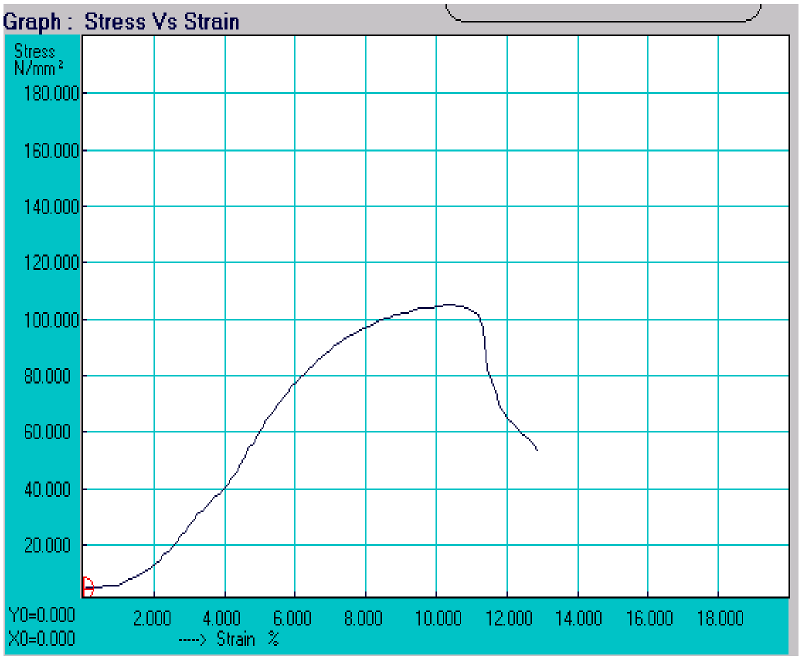
Figure 4.23 Failed tensile test specimens at different ages of corrosion

4.4.2 Stress–strain curves behavior:-

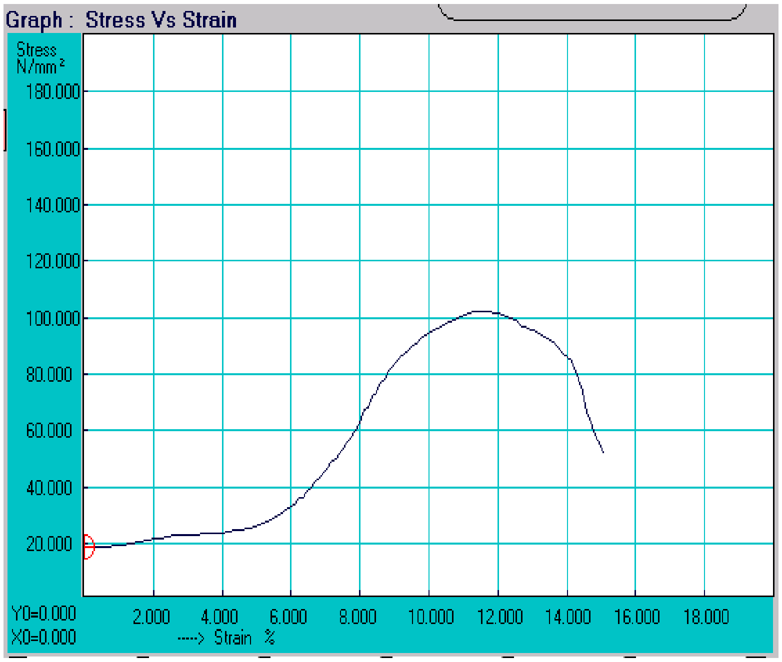
The stress–strain curves of all the specimens are shown in **(Fig 4.24)**. The stress has been calculated with respect to original cross-sectional area of the specimen, and strain is measured between two points separated by 90mm in fitted specimen in UTM. The healthy plate specimen shows a ductile behavior with well-defined elastic and plastic regions. On the other hand, as corrosion in samples increases, the plastic region in the stress–strain curves weakens and vanishes indicating brittleness in the samples. Although there is a huge loss of strength, the initial stiffness and the elastic modulus of the corroded samples remain largely unaffected. This is indicated by very little change in the initial slopes of stress–strain curves with varying ages of corrosion.



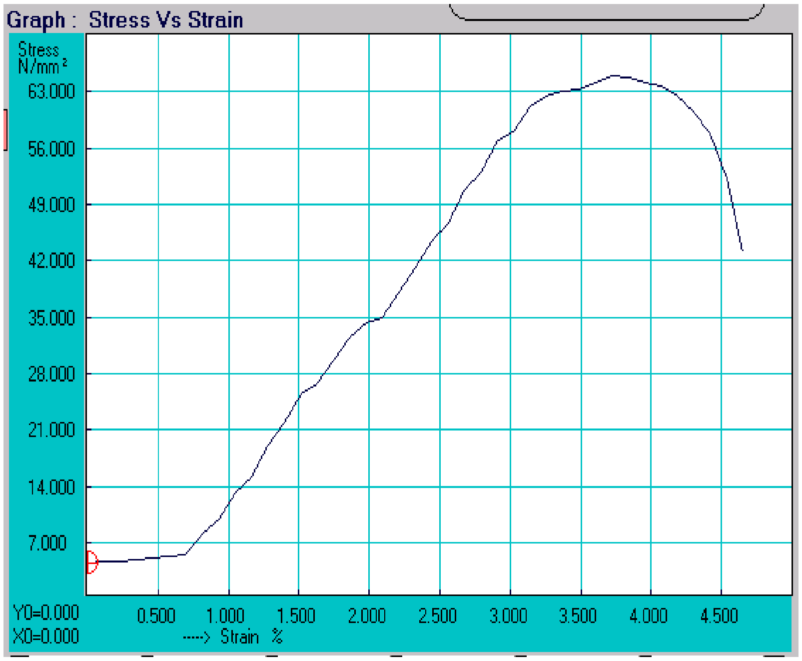
(a) Healthy



(b) 2 days



(c) 4 days



(d) 6 days

Fig 4.24 stress strain behavior

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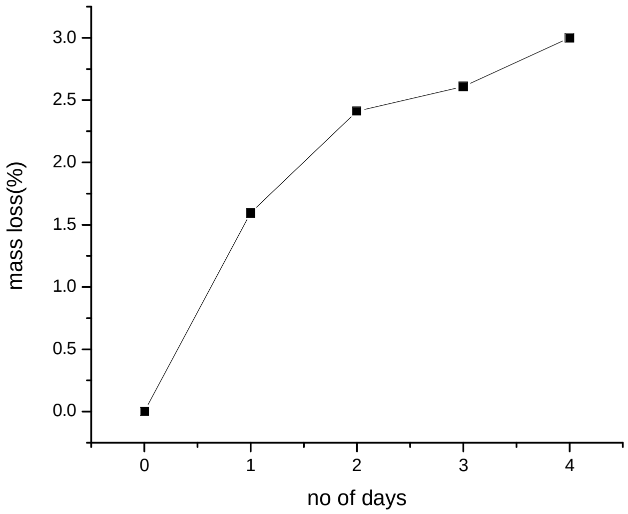
The trends of variation in mass loss, yield stress and ultimate stress with increasing corrosion exposure is plotted in **(Fig 4.25**). Loss in tensile strength with increasing corrosion indicates the loss of cross-sectional area of the plate due to the pitting effect of chloride corrosion.



(a) Mass loss (%) vs. days of corrosion exposure

Mass loss is uniform and varies linearly with no of day i.e. as the no of days increases mass loss increases. It is evident that because of the localized nature of corrosion, even a moderate mass loss may affect the strength substantially.

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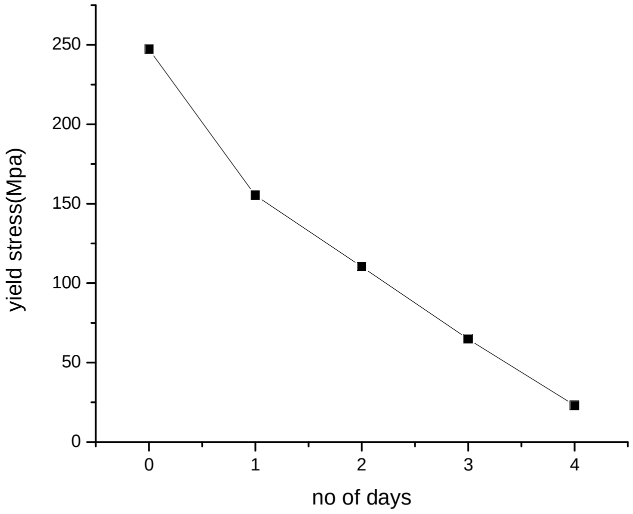
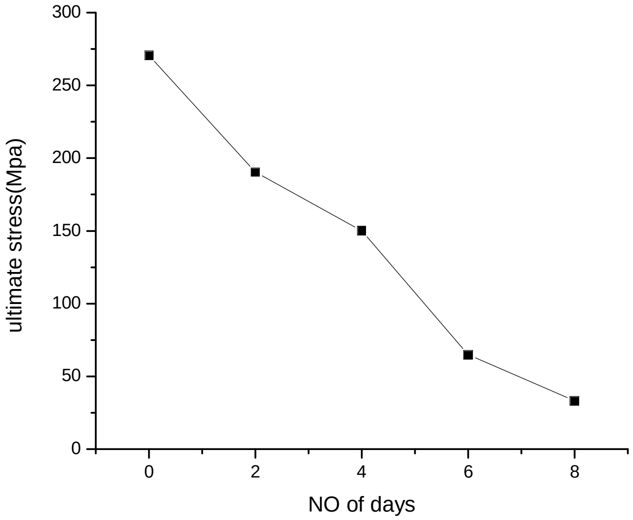


(b) Yield stress vs days of corrosion exposure

As the days of corrosion exposure increases yield stress decreases.



(c) Ultimate stress vs. no of days

Fig 4.25 Variation in destructive parameters with increasing exposure to corrosion.

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Figure 13 (a–b) shows a consistent and rapid fall in ultimate stress with increasing corrosion. There is a drastic fall in ultimate strength with 3 days of corrosion pointing towards the catastrophic effect of even small corrosion damage. The ultimate stress falls gradually with progression of corrosion.

4.5 CLOSURE

From the ultrasonic investigation of plates subjected to varying degree of corrosion ,it has been showed that ultrasonic lamb waves can not only pick up initiative of corrosion but also progression in plates in various in-situ (unprotected /protected) conditions.

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CHAPTER 5

CONCLUSION AND FURTHER SCOPE OF WORK

5.1 CONCLUSION

The results obtained from ultrasonic guided wave monitoring for submerged plate specimen subjected to accelerated corrosion using impressed current technique done in this research work, can be summarized as:

- Ultrasonic guided wave technique has proven to be very effective in monitoring the initiation as well as progression of corrosion in underwater conditions.
- Surface seeking and the core seeking modes able to explain the behavior of plate specimen subjected to accelerated corrosion.
- The surface seeking mode effectively picks the initial corrosion and initial surface loss. As the corrosion progresses in the plate core seeking mode is well suited and relates better to the degradation in plate.
- The effect of varying corrosion patches/areas also well picked up by ultrasonic monitoring techniques. With the increase in the area of pond on the plate it takes longer for plate to get corroded
- With scratch/initial damage get corroded faster than the plate without scratch and is also successfully monitored by various modes
- Paints are effective in preventing corrosion attack dependency upon their composition and Lamb waves can not only pick up corrosion but also protection offered by paints. It is well depicted by constant signal in surface seeking mode sensitive to initial modifications.
- ultrasonic lamb waves can not only pick up initiative of corrosion but also progression in plates in various in-situ (unprotected /protected) conditions.

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5.2 FURTHER SCOPE OF WORK

Numerical modeling of the wave propagation in plates with and without damages needs to be investigated and correlated with the experimental results using FEM analysis tools like ANSYS, Abaqus etc.

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