Ultrasonic Guided Waves for Damage Detection in Cylindrical Geometries for Torsion and Corrosion Defects

A thesis report submitted in the partial fulfilment of the

requirements for the award of degree of

MASTERS OF ENGINEERING

IN

CAD CAM AND ROBOTICS

Submitted By

Gurpreet Singh

Roll No. 801081011

Under the Guidance of

Dr. Shruti Sharma

(Assistant Prof., CED)

Thapar University, Patiala

DEPARTMENT OF MECHANICAL ENGINEERING

THAPAR UNIVERSITY, PATIALA-147004, INDIA

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CERTIFICATE

This is to certify that the work which is presented in this thesis report entitled, "**Ultrasonic Guided Waves for Damage Detection in Cylindrical Geometries**" being submitted by **Gurpreet Singh** in partial fulfilment of requirements for the award of degree of Master of Engineering in Cad Cam & Robotics, at Mechanical Engineering Department, Thapar University, Patiala is an authentic record of the initial work carried out by him under the supervision of **Dr. Shruti Sharma**, Assistant Professor, Civil Engineering Department, Thapar University 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.

Gurpreet Singh

GURPREET SINGH

This is to certify that the above statement made by the candidate is correct and true to the best of my knowledge.

Dr. Shruti Sharma

Assistant Professor, CED, Supervisor

Thapar University, Patiala

Countersigned by:

Dr. Ajay Batish

Professor & Head

Mechanical Engg. Dept.

Thapar University, Patiala

Prof. S K Mohapatra

Dean(Academic Affairs)

Thapar University, Patiala

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GURPREET SINGH

801081011

ABSTRACT

In the area of Non destructive testing, ultrasonic testing using wave propagation is an emerging field. Ultrasonic testing uses transmission of high frequency sound waves into a material to detect imperfections or to locate changes in material properties. The most commonly used ultrasonic testing technique is pulse echo wherein sound is introduced into a test object and reflections (echoes) are returned to a receiver from internal imperfections. In this works, Negative spike pulse is used as an input signal to sending/receiving transducer at one end of the rod through Pulser/Receiver system and transmitted pulse is received at the same end by same transducer. The wave signatures obtained are analysed using digitizer card. The results obtained from Ultrasonic Testing were in the form of Voltage-Time curves. For different damage types, ideal modes of testing for frequency excitation were selected. Modes of different frequencies were generated and the best modes for the testing of torsion and corrosion defects on different diameter rods were identified.

This report presents the use of pulse echo technique to detect effect of corrosion and torsion damage in steel bars. Testing of rods is done in air by placing the transducer in direct contact with one end of rod where the wave travels through the rod from the transducer with the help of couplant (ultrasonic gel). The comparison of signatures in healthy and rods damaged to various extents (both in torsion and corrosion) leads to damage diagnosis.

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Chapter 1 Introduction

1.1 Objectives of the present study

Steel bars are the most popular machinery and construction material today due to their high tensile and compressive strengths. Shafts are used in hydro-electric projects, tunnel projects, earthmover projects, water supply system, waste water system as elevator shaft, ventilation shaft, pressure shaft, uptake or down-take shaft etc. In all these applications, shafts are used to transfer rotary movements and torsion moments. They are usually supporting elements for toothed wheels, pulleys, clutches, etc. and are loaded with spatial bends, torsion moments and axial forces. A major part of shafts is shaped with recesses, necking-down, grooves and holes, which cause undesirable stress concentrations. Due to the torsional loads, maximum shear stress in shaft is developed in outer surface. The outer surface will reach the maximum allowable working stress and if torque is again applied then it will lead to failure of shaft or bar.

Also with the passage of time, the bars deteriorate due to a variety of factors such as environmental degradation resulting from corrosion, fatigue, excessive loads, and natural calamities or simply due to long endurance combined with intensive usage. If the deterioration in the bars or shafts goes unnoticed, it can lead to catastrophic failures of the structures leading to large scale loss of life and property.

As the design and construction of mechanical structures continue to evolve, it is becoming imperative that these structures be monitored for their health. In order to meet this need, the discipline of Structural Health Monitoring (SHM) has emerged. It involves the application of wave propagation to mechanical structures and aims to assist engineers in realizing the full benefits of structural health monitoring. Health of several structures is monitored by recording propagation of stress waves through them. The wave characteristics change due to the deterioration in the structure and they are sensitive to the location, extent and character of damage. However, for a successful monitoring a priori knowledge of the wave characteristic due to different cases is imperative.

The main objective of the thesis is to investigate the feasibility of using ultrasonic guided waves for damage detection in cylindrical bars for torsion and corrosion effects. A correlation between ultrasonic voltage and in situ strength is also attempted in this work.

1.2 Structural Health Monitoring (SHM)

Structural health monitoring (SHM) is the practise of monitoring a structure over its lifetime to detect changes in its structural properties that may indicate a reduction in performance. It may be used to monitor aeronautical, mechanical, civil, electrical, and other systems. The change in structural properties may be sudden, such as those due to earthquake motion or violent wind gusts, or it may be slower due to corrosion for example.

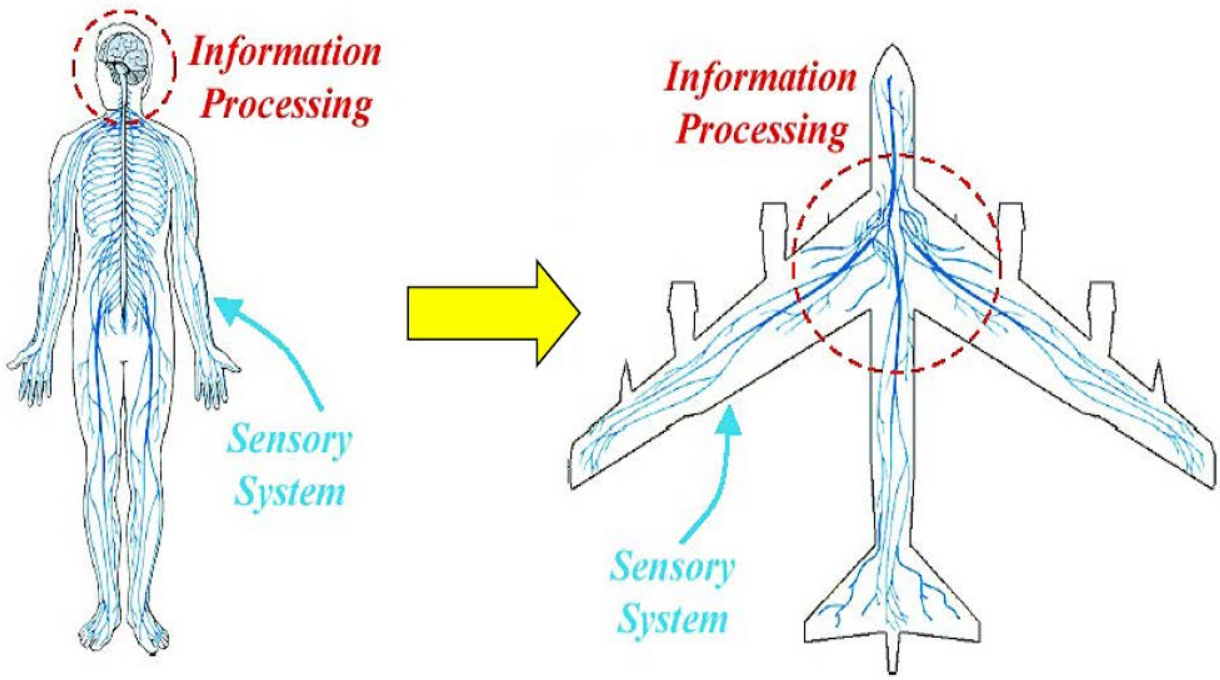

Fig. 1.1 Overview of Structural Health Monitoring [1]

SHM is particularly important for structures such as data server farms, biotechnology or other high technology manufacturing facilities and other buildings where valuable or hazardous building contents are at risk due to excess vibrations or other movements and where continuity of service is important. It is usually performed for one or more of the following three reasons. Qualitative and non-continuous methods have long been used to evaluate structures for their capacity to serve their intended purpose. Since the beginning of the 19th century, railroad wheel-tappers have used the sound of a hammer striking the train wheel to evaluate if damage was present. In rotating machinery, vibration monitoring has been used for decades as a performance evaluation technique. In the last ten to fifteen years, SHM technologies have emerged creating an exciting new field within various branches of engineering. Similarity between human sensory system and SHM is as shown in **Fig. 1.1**.

Main focus of SHM can be identified as:

1) **Damage Detection**

This is perhaps the most obvious and common reason. The structure is continuously monitored and any changes in its response are noted. For example, frequency shift methods (of modal frequencies) are a well-known class of damage detection techniques that may be used to infer damage to a structure (McConnell 1995). The aim is to make a rapid and accurate assessment the safety of a structure following an event, such as an earthquake, without requiring a dangerous and expensive manual inspection.

2) **Long Term Monitoring for Deterioration**

This differs from damage detection in that it aims to detect changes in a structure that take place over many years. The aim here is to be assured of the structural performance and continued value of the asset under "normal" conditions.

3) **Determine "As Built" Structural Properties**

A short term monitoring program can be used to determine the actual dynamic properties of a structure. These can be used by the designers to compare with design values to verify design assumptions. Ambient or forced vibrations can be used to determine these properties at different levels of motion.

1.3 Non Destructive Testing (NDT)

NDT is an examination, test, or evaluation performed on any type of test object without changing or altering that object in any way, in order to determine the absence or presence of conditions or discontinuities that may have an effect on the usefulness or serviceability of that object. Non-destructive tests may also be conducted to measure other test object characteristics, such as size; dimension; configuration; or structure, including alloy content, hardness, grain size, etc. Non-destructive examination (NDE), non-destructive inspection (NDI), and non-destructive evaluation (NDE) are also expressions commonly used to describe this technology. Although NDT cannot guarantee that failures will not occur, it plays a significant role in minimizing the possibilities of failure. Other variables, such as inadequate design and improper application of the object, may contribute to failure even when NDT is appropriately applied. NDT, as a technology, has seen significant growth and unique innovation over the past 25 years. It is, in fact, considered today to be one of the fastest growing technologies from the standpoint of uniqueness and innovation.

1.3.1 History of Non-destructive Testing

Where did NDT begin? There are those who would answer this question by referring to the account of the creation of the heavens and the earth in *Genesis:* "In the beginning, God created the heavens and the earth and He *saw* that it was good". This is a theme that has been used from time to time when discussing the history of non-destructive testing. As shown in **Fig. 1.2**, seeing that the "heavens and the earth were good" has been identified as the first non-destructive test—a visual test!

It is impossible to identify a specific date that would indicate exactly when non-destructive testing, as we know it today, began. In ancient times, the audible ring of a Damascus sword blade would be an indication of how strong the metal would be in combat. This same "sonic" technique was used for decades by blacksmiths as they listened to the ring of different metals that were being shaped. This approach was also used by early bell-makers. By listening to the ring of the bell, the soundness of the metal could be established in a very general way. Visual testing, while not "officially" considered a part of early NDT technology, had been in use for many years for a wide range of applications. Heat sensing was used to monitor thermal changes in materials, and "sonic" tests were performed well before the term "non-destructive testing" was ever used.

Fig. 1.2 Earth from Space (Courtesy of Library of Congress) [2]

1.3.2 Chronology of Early Key Events in NDT

BC (approx.) Visual testing becomes the first NDT method when God creates the heavens and earth and “sees” that it is good!

1800 First thermography observations by Sir William Herschel

1831 First observation of electromagnetic induction by Michael Farraday

1840 First infrared image produced by Herschel’s son, John

1868 First reference to magnetic particle testing reported by S. H. Saxby, by observing how magnetized gun barrels affect a compass

1879 Early use of eddy currents to detect differences in conductivity, magnetic permeability, and temperature initiated by E. Hughes

1880–1920 “Oil and whiting” technique, forerunner of present-day penetrant test used for railroad axles and boilerplates

1895 X-rays discovered by Wilhelm Conrad Roentgen

1898 Radium discovered by Marie and Pierre Curie

1922 Industrial Radiography for metals developed by Dr. H. H. Lester

1927–28 Electric current induction/ magnetic field detection system developed by Dr. Elmer Sperry and H. C. Drake for the inspection of railroad track

1929 Magnetic particle tests/equipment pioneered by A. V. deForest and F. B. Doane

1929 First experiments using quartz transducers to create ultrasonic vibrations in materials were conducted by S. Y. Sokolov in Russia

1930 Practical uses for gamma radiography using radium were demonstrated by Dr. Robert F. Mehl

1935–1940 Penetrant techniques developed by Betz, Doane, and DeForest

1935–1940’s Eddy current instrument developments by H. C. Knerr, C. Farrow, Theo Zuschlag, and Dr. F. Foerster

1940–1944 Ultrasonic test method developed in United States by Dr. Floyd Firestone

1942 First ultrasonic flaw detector using pulse-echo introduced by D. O. Sproule

(United Kingdom)

1946 First portable ultrasonic thickness measuring instrument, the Audigage, was introduced by Branson

1950 Acoustic emission introduced as an NDT method by J. Kaiser

Mid 1950's First ultrasonic testing immersion B and C scan instruments developed by Donald

C. Erdman

1.3.3 Non Destructive Vs Destructive Tests

Destructive testing has been defined as a form of mechanical test (primarily destructive) of materials whereby certain specific characteristics of the material can be evaluated quantitatively. In some cases, the test specimens being tested are subjected to controlled conditions that simulate service. The information that is obtained through destructive testing is quite precise, but it only applies to the specimen being examined. Since the specimen is destroyed or mechanically changed, it is unlikely that it can be used for other purposes beyond the mechanical test. Such destructive tests can provide very useful information, especially relating to the material's design considerations and useful life. Destructive testing may be dynamic or static and can provide data relative to the following material attributes:

- Ultimate tensile strength
- Yield point
- Ductility
- Elongation characteristics
- Fatigue life
- Corrosion resistance
- Toughness
- Hardness
- Impact resistance

Benefits of non-destructive testing

- The part is not changed or altered and can be used after examination
- Every item or a large portion of the material can be examined with no adverse consequences
- Materials can be examined for conditions internal and at the surface
- Parts can be examined while in service
- Many NDT methods are portable and can be taken to the object to be examined
- Non-destructive testing is cost effective, overall

Limitations of non-destructive testing

- It is usually quite operator dependent
- Some methods do not provide permanent records of the examination
- NDT methods do not generally provide quantitative data
- Orientation of discontinuities must be considered
- Evaluation of some test results are subjective and subject to dispute
- While most methods are cost effective, some, such as radiography, can be expensive
- Defined procedures that have been qualified are essential

Conditions for Effective Non Destructive Testing

- ➢ The product must be "testable."
- ➢ Approved procedures must be followed.
- ➢ Equipment is operating properly.
- ➢ Documentation is complete.
- ➢ Personnel are qualified.

1.4 Various NDT methods

NDT does not permanently alter the article being inspected; it is a highly-valuable technique that can save both money and time in product evaluation, troubleshooting, and research. NDT is divided into various methods of non destructive testing, each based on a particular scientific principle. These methods may be further subdivided into various techniques. Common NDT methods include ultrasonic, magnetic-particle, liquid penetrant, radiographic, remote visual inspection (RVI), eddy-current testing, and low coherence interferometry. The various methods and techniques, due to their particular natures, may lend themselves especially well to certain applications and be of little or no value at all in other applications. Therefore choosing the right method and technique is an important part of the performance of NDT. Following are the widely used NDT methods:

- **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.
- **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 penetrant out of imperfections open to the surface. With visible dyes, vivid colour contrasts between the penetrant and developer make "bleed out" easy to see.
- **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.
- **Electromagnetic Testing (ET) or Eddy Current Testing:** Eddy currents are generated in a 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.
- **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.
- **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.

- **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.
- **Electromagnetic Acoustic Transducers (EMATs): T**hey 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.
- **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.
- **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 the temperature across a complete surface.
- **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.

When it is possible to use several inspection techniques, the choice of a specific technique will depend on the accuracy and cost of the inspection, balancing the money spent on safety measures with the business return of the system being maintained. The accuracy of a given technique must also be sufficient to detect defects considerably smaller than those that could result in failure because these defects can grow in size between inspections. The diverse nature of different NDT processes results in different sources of variance and possible impact on detection output capabilities. It is important to recognize the source and nature of variance in each NDT process and to take such information into consideration when applying margins to the NDT processes. The NDT methods and procedures are selected using a variety of practical implementation criteria, are represented in **Table 1**.

Table 1 a Comprehensive Overview of Major NDT methods [1]

Parameter	**Penetrant Testing**	**Magnetic Particle Testing**	**Ultrasonic Testing**	**Eddy Current Testing**	**Radiographic Testing**
Range of inspection	Large surface areas or large volumes of parts can be inspected rapidly.	Large surface areas of complex parts can be inspected rapidly.	Depth of penetration for flaw detection is superior to other methods.	Detects surface and near surface defects.	Can be used to inspect virtually all materials.
Geometry of part to be inspected	Parts with complex geometry are routinely inspected.	Can detect surface and subsurface flaws.	Only single sided access is required.	Test probe does not need to contact the part.	Detects surface and subsurface defects.
Geometry of part to be inspected	Indications are produced directly on surface of the part providing a visual image of the discontinuity.	Indications are produced directly on the surface of the part and form an image of the discontinuity.	Provides distance information.	Method can be used for more than flaw detection.	Method can be used for more than flaw detection.
Cost of inspection	Low	Low	Low	Low	Moderate

Cost of equipment **Surface**	Low	Moderate	Moderate	High	High
preparation	Surface preparation is critical.	Surface preparation is less critical.	Minimum part preparation is required.	Minimum part preparation is required.	Minimum part preparation is required.

1.5 Closing Remarks

Structural Health Monitoring is important for structures where valuable or hazardous building contents are at risk due to excessive vibrations or other movements and where continuity of service is important. SHM is required in almost all the fields like rail, aircraft, bridge, storage tank, wire rope, pipeline etc. Various NDT methods have their own advantages and disadvantages for specific application in terms of cost, geometry of part to be inspected, range of inspection etc. Ultrasonics have started being used as an effective NDT damage monitoring tool. The following chapter discusses in detail the basic principles of ultrasonic as a NDT tool.

Chapter 2 Ultrasonic as a Damage Monitoring Tool

2.1 General

Ultrasonic waves permit non-destructive testing of materials for the detection of component defects. Using this test procedure the precise location of cracks, pores, inclusions and fusion flaws can be determined. This method is used for testing metal, ceramic and plastic materials together with their bonding system (adhesion, welding, soldering). Images are generated either with a high-precision mechanical scanner or a phased array system.

2.2 Principle of Ultrasonic Testing

Ultrasonic non-destructive testing introduces high frequency sound waves into a test object to obtain information about the object without altering or damaging it in any way. A typical UT inspection system consists of several functional units, such as the pulser/receiver, transducer, and display devices. A pulser/receiver is an electronic device that can produce high voltage electrical pulses. Driven by the pulser, the transducer generates high frequency ultrasonic energy. The sound energy is introduced and propagates through the materials in the form of waves. When there is a discontinuity (such as a crack) in the wave path, part of the energy will be reflected back from the flaw surface. The reflected wave signal is transformed into an electrical signal by the transducer and is displayed on a screen.

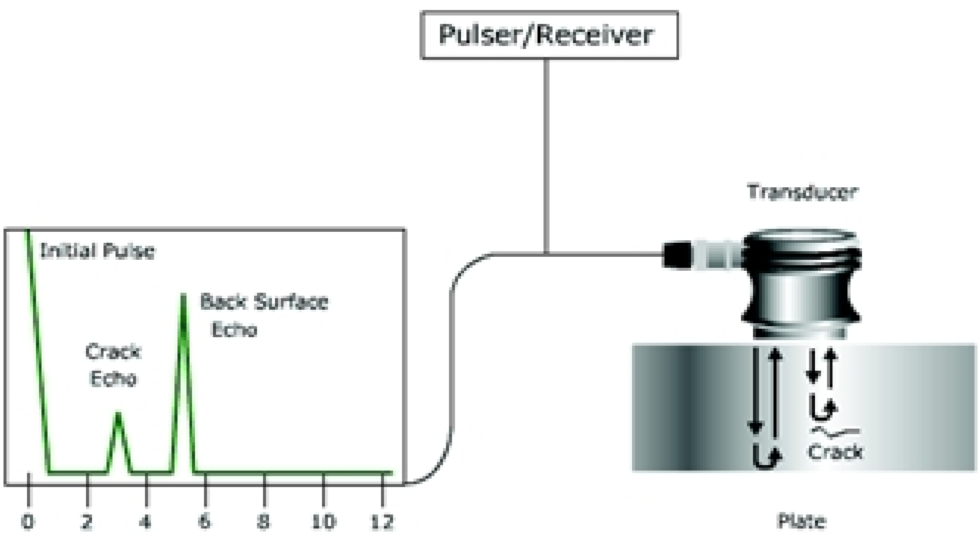

Fig. 2.1 General ultrasonic Inspection Principle (pulse echo method) [4]

General ultrasonic inspection principle for pulse echo method is as shown in **Fig. 2.1**. Two basic quantities are measured in ultrasonic testing; they are time of flight or the amount of time for the sound to travel through the sample, and amplitude of received signal. Based on velocity and round trip time of flight through the material the material, thickness can be calculated as follows:

$$T = c*t/2$$

T = Material Thickness

c = Material Sound Velocity

t = Time of Flight

Measurements of the relative change in signal amplitude can be used in sizing flaws or measuring the attenuation of a material. The relative change in signal amplitude is commonly measured in decibels. Decibel values are the logarithmic value of the ratio of two signal amplitudes. It can be calculated as twenty times logarithmic of ratio A1 to A2.

dB = Decibels

A1 = Amplitude of signal 1

A2 = Amplitude of signal 2

2.3 Modes of wave propagation

The ultrasonic waves propagate in a number of ways in a medium. Wave propagation depends on material properties of the structure. On the basis of the mode of particle displacement, these waves can be classified as:

1) Longitudinal or Compressional waves (L-waves).
2) Transverse or Shear waves (S-waves)
3) Surface or Rayleigh waves.
4) Lamb or Plate waves
5) Creeping or Head waves

1) Longitudinal or Compressional waves

In longitudinal waves, the oscillations occur in the longitudinal direction or the direction of wave propagation as shown in the **Fig. 2.2**. Since compressional and dilational forces are active in these waves, they are also called pressure or compressional waves. They are also sometimes called density waves because their particle density fluctuates as they move. Compression waves can be generated in liquids, as well as solids because the energy travels through the atomic structure by a series of comparison and expansion (rarefaction) movements.

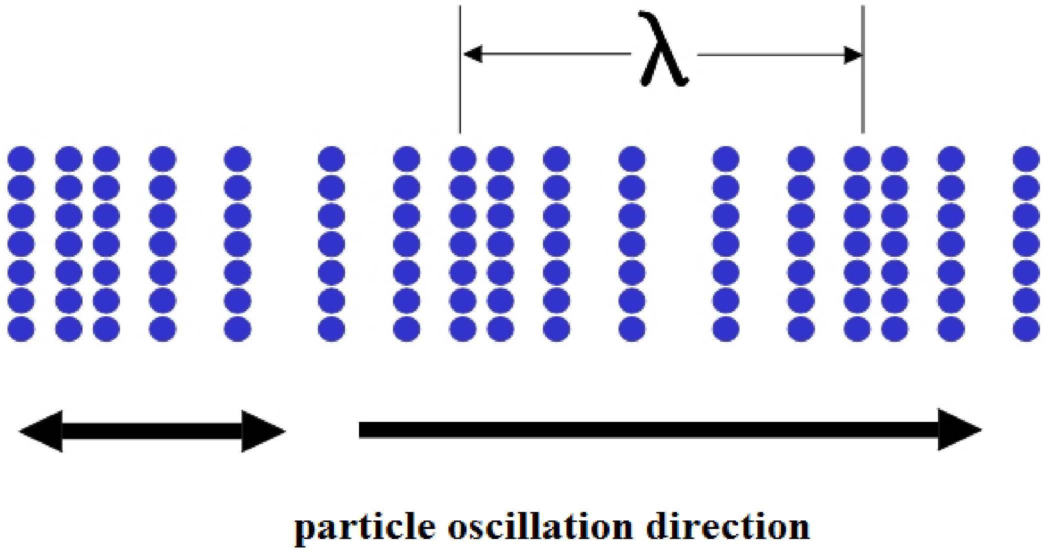

Fig. 2.2 Propagation of Longitudinal Waves [4]

2) Transverse or Shear wave

In the transverse or shear wave, the particles oscillate at a right angle or transverse to the direction of propagation as shown in the **Fig. 2.3**. Shear waves require an acoustically solid material for effective propagation, and therefore, are not effectively propagated in materials such as liquids or gasses. Shear waves are relatively weak when compared to longitudinal waves. In fact, shear waves are usually generated in materials using some of the energy from longitudinal waves. For the propagation of transverse waves, it is necessary that each particle exhibits a strong force of attraction to its neighbours, so that as a particle moves back and forth it pulls its neighbour with it. Due to this reason air and water do not support transverse waves. In gases, the forces of attraction between molecules are so small that shear waves cannot be transmitted. The same is true of a liquid, unless it is particularly viscous or is present as a very thin layer. The velocity of transverse waves is approximately 50% of the longitudinal wave velocity for the same material.

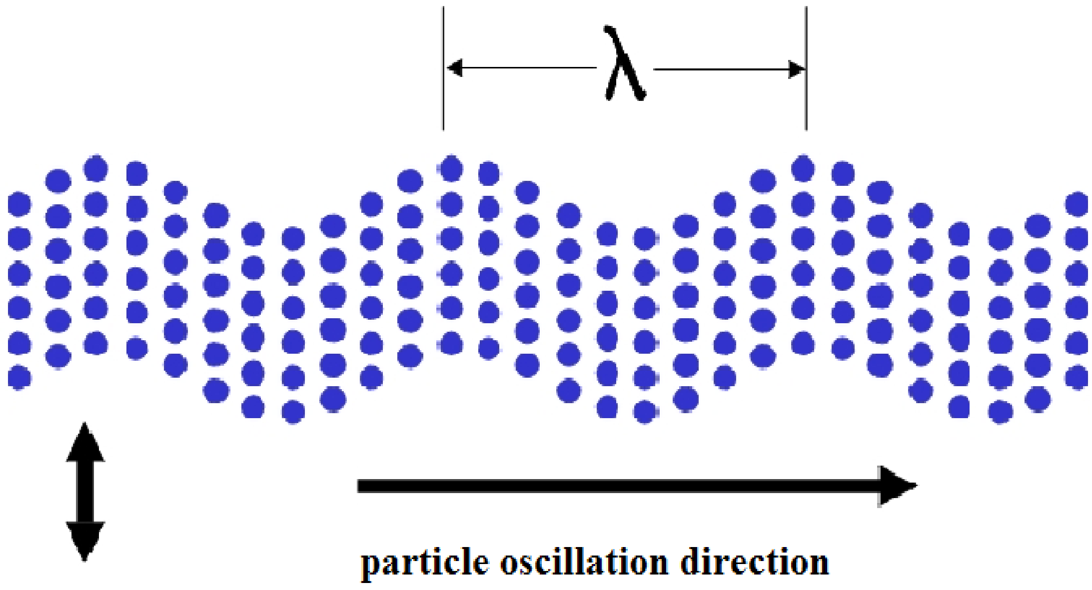

Fig. 2.3 Propagation of Transverse waves [4]

3) Surface (or Rayleigh) waves

Surface (or Rayleigh) waves travel on the surface of a relatively thick solid material penetrating to a depth of one wavelength as shown in **Fig. 2.4**. Rayleigh waves are useful because they are very sensitive to surface defects and they follow the surface around curves. These waves can travel along the flat and curved surfaces. These waves are subjected to less attenuation in a given material than the longitudinal or transverse waves. Because of this, Rayleigh waves can be used to inspect areas that other waves might have difficulty reaching.

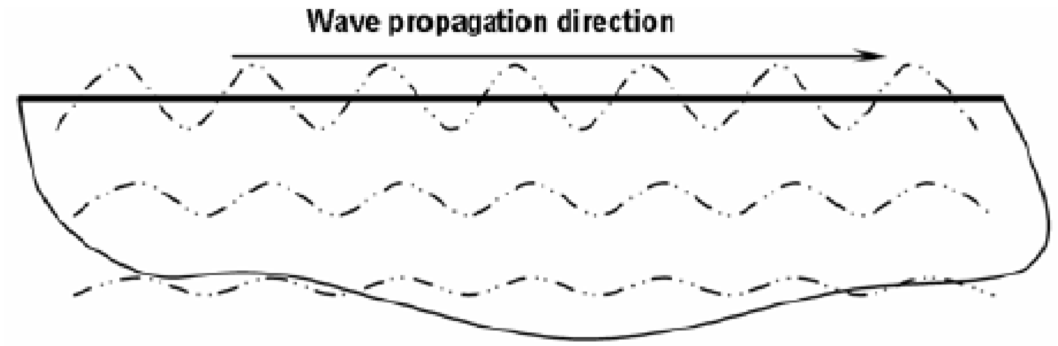

Fig. 2.4 Propagation of surface waves [4]

4) Lamb waves

Plate or Lamb waves can be propagated only in very thin metals. Lamb waves are the most commonly used plate waves in NDT. Lamb waves are complex vibrational waves that travel through the entire thickness of a material. Propagation of lamb waves depends on the density and the elastic material properties of a component. They are also influenced a great deal by the test frequency and material thickness.

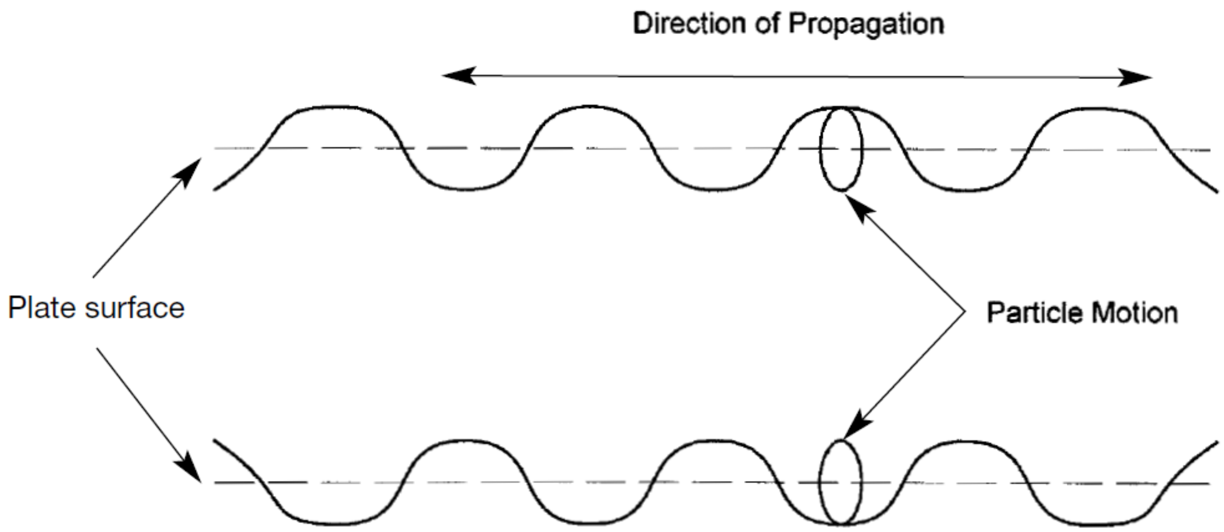

Fig. 2.5 Lamb Wave mode Symmetric (S mode) [1]

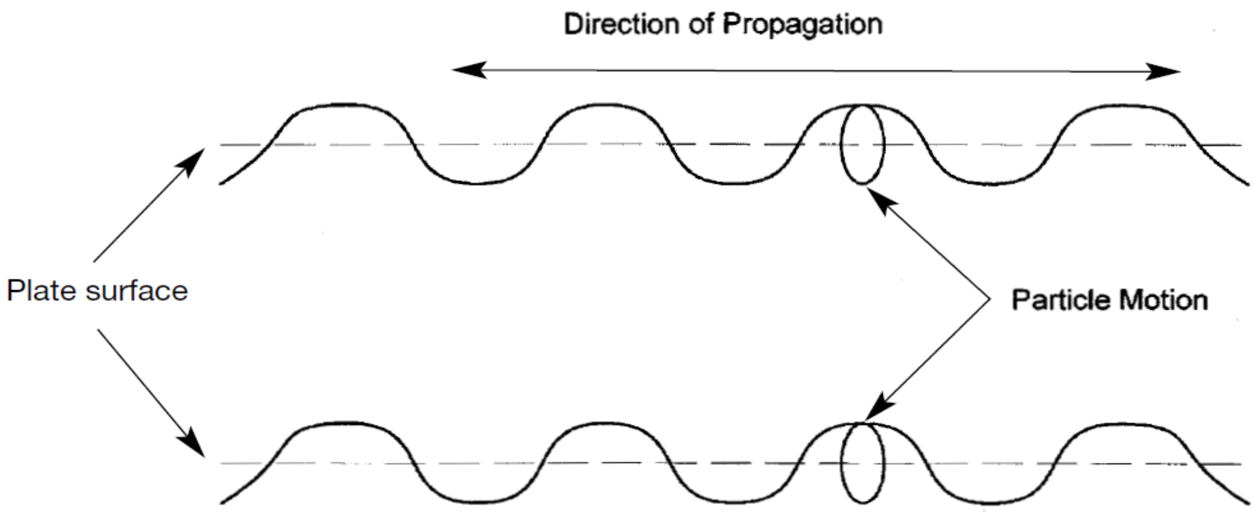

Fig. 2.6 Lamb Wave mode Anti-symmetric (A mode) [1]

With lamb waves, a number of modes of particle vibration are possible, but the two most common are symmetrical and asymmetrical as shown in the **Fig. 2.5** and **Fig. 2.6** respectively. 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. Wave motion in the symmetrical mode is most efficiently produced when the exciting force is parallel to the plate. The asymmetrical lamb wave mode is often called the "flexural mode" because a large portion of the motion moves in a normal direction to the plate, and a little motion occurs in the direction parallel to the plate. In this mode, the body of the plate bends as the two surfaces move in the same direction.

5) Creeping waves

These waves are also called head waves. The behaviour of creeping waves is similar to that of longitudinal waves. They travel as fast as longitudinal waves and the creeping waves should not be misunderstood as moving slowly. These are generated parallel to scanning surface, enabling detection of surface breaking defects. These have limited range and as these travel just below the surface and not on the surface, so the couplant has no influence. Lamb waves are most preferred waves for the ultrasonic testing in damage detection in steel plates, since the lamb waves propagate only in very thin metals. Symmetric lamb waves are used to find the damage in normal plates whereas anti symmetric lamb waves are used to find the damage in plates with the bend.

2.4 Types of Transducer

Transducers are classified into groups according to the application. The inside of a transducer is as shown in **Fig. 2.7**.

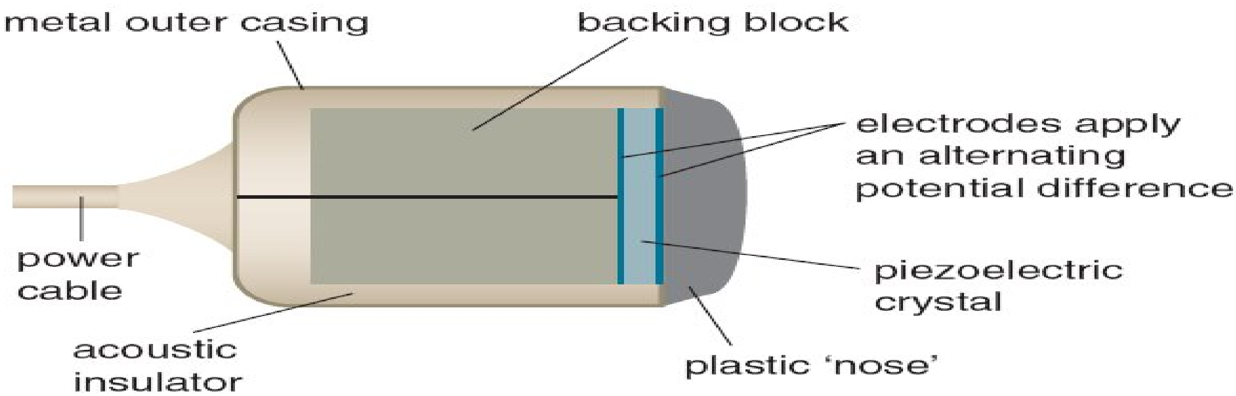

Fig 2.7 Inside of A Transducer [5]

Contact transducers are used for direct contact inspections, and are generally hand manipulated. They have elements protected in a rugged casing to withstand sliding contact with a variety of materials. These transducers have an ergonomic design so that they are easy to grip and move along a surface as shown in **Fig. 2.8**. They often have replaceable wear plates to lengthen their useful life. Coupling materials of water, grease, oils, or commercial materials are used to remove the air gap between the transducer and the component being inspected.

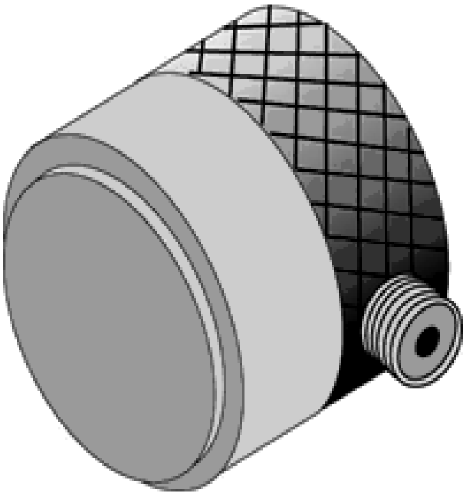

Fig. 2.8 Contact Transducer [4]

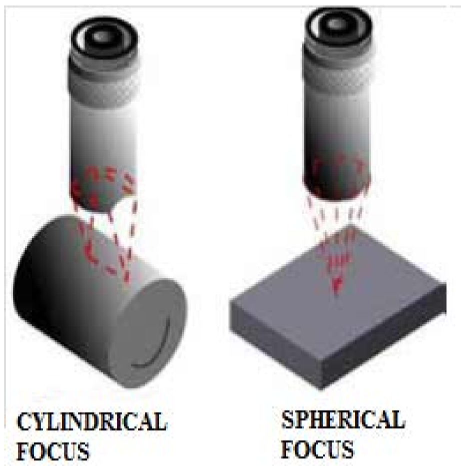

Fig. 2.9 Immersion Transducer [4]

Immersion transducers do not contact the component. These transducers are designed to operate in a liquid environment and all connections are watertight, as shown in **Fig. 2.9**. Immersion transducers usually have an impedance matching layer that helps to get more sound energy into the water and, in turn, into the component being inspected. Immersion transducers can be purchased with a planer cylindrically focused or spherically focused lens. A focused transducer can improve the sensitivity and axial resolution by concentrating the sound energy to a smaller area. Immersion transducers are typically used inside a water tank or as part of a squirter or bubbler system in scanning applications.

2.5 Methods of ultrasonic testing

1. Pulse echo method
2. Through transmission method

3. Two transducer method

2.4.1. Pulse echo method

In the pulse-echo method, a piezoelectric transducer with its longitudinal axis located perpendicular to and mounted on or near the surface of the test material is used to transmit and receive ultrasonic energy as shown in **Fig. 2.10**. The ultrasonic waves are reflected by the opposite face of the material or by discontinuities, layers, voids, or inclusions in the material, and received by the same transducer where the reflected energy is converted into an electrical signal. The electrical signal is computer processed for display on a video monitor or TV screen. The display can show the relative thickness of the material, depth into the material where flaws are located, and (with proper scanning hardware and software), where the flaws are located in the X-Y plane.

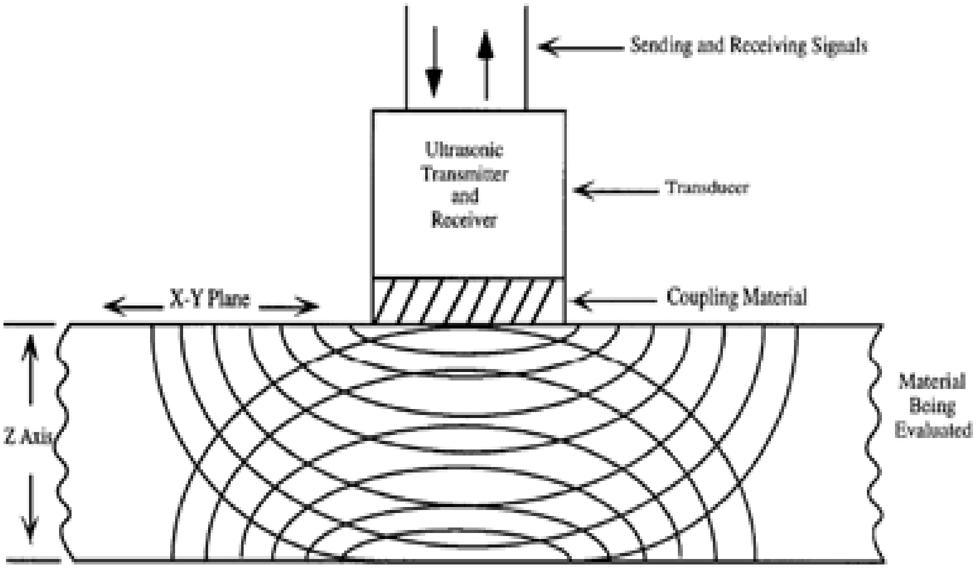

Fig. 2.10 Principle of pulse echo method of inspection [4]

2.4.2. Through transmission method:

In the through-transmission method, an ultrasonic transmitter is used on one side of the material while a detector is placed on the opposite side as shown in **Fig. 2.11**. One unit acts as transmitter and the other unit as receiver. The beam from the transmitter T travels through the material to its opposite surface where the receiving transducer R is placed. Scanning of the material using this method will result in the location of defects, flaws, and inclusions in the X-Y plane.

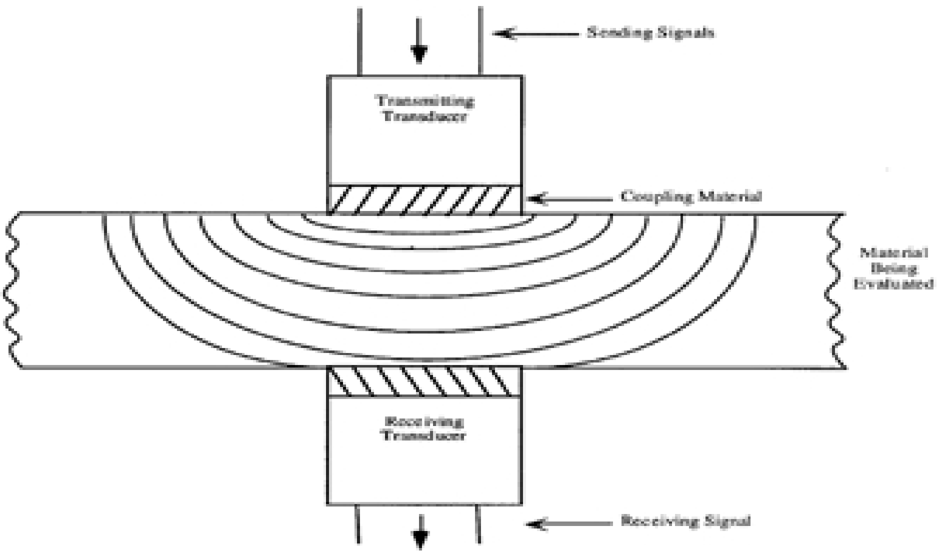

Fig. 2.11 Principle of through transmission of ultrasonic testing [4]

2.4.3. Two transducer method

The pulse echo method can be used with either single or double crystal unit. In single transducer unit the probe acts as both transmitter and receiver .In two transducer arrangement, one transmits and other receives the ultrasonic waves .These are placed on same side of specimen. Pulse wave is sent in to the specimen by the transducer T and the echoes reflected from the back surface or any defect are received by the transducer R and displayed on the flaw detector screen. For specific applications like wall thickness measurement special type of transducers in which the transmitting and the receiving crystals are housed in a single unit are also used .These transducers are popularly known as 'twin' or T-R probes .

2.6 Ultrasonic Guided Waves in Cylindrical Geometries

The major difference between bulk wave propagation and guided wave propagation is the fact that a boundary is required for guided wave propagation. The need is for a reliable inspection method that can interrogate a long length steel of circular cross section. Guided waves can easily be excited from the exposed ends of rods, and because they travel in the structure as a whole, they can be used to interrogate the whole structure. Conventional ultrasonic tests are only capable of examining a single line, either between two transducers or by using a single transducer in a pulse-echo configuration. In both conventional and guided ultrasound tests, defects and breaks will act as reflectors that will reflect some of the energy travelling in the system, which can then be detected and analysed. The two main limitations are the decay of the signal due to leakage into the embedding material or material scattering and the reflection coefficient for defects such as breaks and corrosion patches. **Fig. 2.12** shows body waves and surface waves generated by an ultrasonic source.

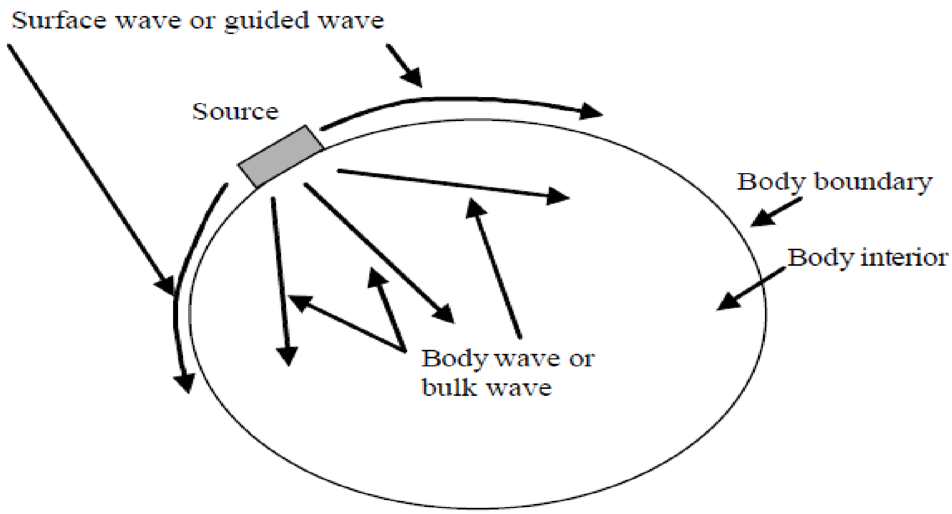

Fig. 2.12 Body waves and surface waves generated by an ultrasonic source [7]

Phenomenon of Dispersion

The use of guided waves in any industrial inspection is complicated by the fact that the ultrasonic energy can travel in a number of different modes. These modes are often dispersive, meaning that different frequency components of a given input signal travel at different speeds, altering the shape of the signal as it propagates. In this respect, guided waves are completely different from conventional ultrasonic inspection techniques, which use bulk waves that propagate at the speed of sound for the particular material. A global matrix method is employed for solution of wave propagation equation using optimization techniques. The development of the general purpose guided wave modelling software 'Disperse' [27] has allowed the behaviour of guided waves in the rods to be studied in much greater detail than site testing alone would allow. Disperse was used to trace the modal solutions for the steel rods, and to calculate the mode properties. These properties are commonly displayed as dispersion curves, which show how the properties of each guided wave mode vary with frequency.

For a cylindrical system, waves propagate in three modes due to dispersive effect of boundaries i.e longitudinal (*L*), flexural (*F*) and torsional (*T*) modes. The modes are numbered according to the format used by Disperse, which closely follows that defined by Silk and Bainton. Each mode is identified by the use of a letter and two reference numbers. The three waveforms are represented by $L(m, n)$, $T(m, n)$ and $F(m, n)$ for longitudinal, torsional and flexural modes respectively. The '*m*' variable refers to the variation in displacement around the circumference of the bar. This variable is zero by definition for the axially-symmetric longitudinal modes. For the flexural modes the '*m*' variable is determined by the number of displacement cycles around the outside of the bar, hence the displacement varies as $\cos(m\theta)$ around the bar circumference. The second reference number '*n*' is a counter variable, the modes being numbered sequentially as they appear with increasing frequency. The lowest frequency axially symmetric mode is therefore numbered $L(0, 1)$. Specific modes can be excited selectively by choosing a frequency bound. Longitudinal waveforms have axial and radial displacements but no angular displacements. L modes are easiest to invoke by keeping the transducer parallel to the rod. Torsional waveforms have only angular displacements and no radial or axial displacements. To produce a torsional wave, a couple must be created on the circumference of the guiding configuration. It has been successfully done by investigators by coupling a shear transducer on the top and bottom of the bar. Flexural waveforms have all three displacements and can be excited by coupling a transducer perpendicular to the axis of the bar.

For example, phase velocity vs. frequency curve for 25mm steel bar in concrete by Disperse software is as shown in **Fig. 2.13**. Phase velocity dispersion curves show the fundamental L(0,1) mode starting at zero frequency with each higher order mode starting from a higher cut off frequency. Each of the higher modes shows a plateau region around the steel longitudinal bulk velocity line. But L(0,7) mode shows a different pattern. Instead of each plateau region belonging to a single mode, L(0,7) breaks from this pattern and links the subsequent plateau regions together to form a single mode that propagates close to the longitudinal bulk velocity of steel. The phase velocity as obtained from dispersion curve at this frequency is 6 km/s.

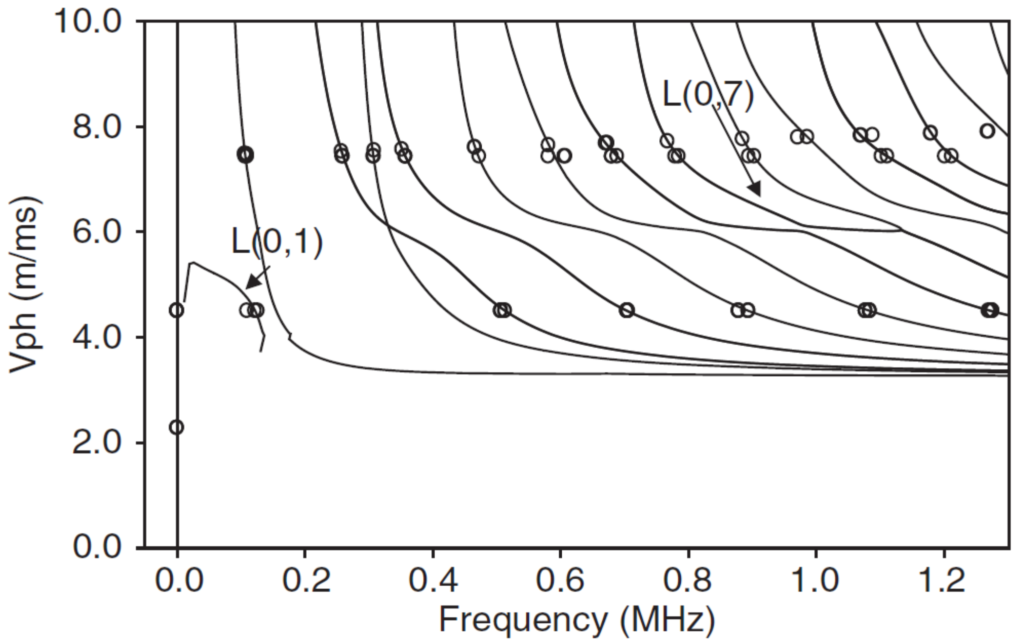

Fig. 2.13 phase velocity vs. frequency curve for 25mm steel bar in concrete [20]

2.7 Closing Remarks

Ultrasonic Guided Waves are ultrasonic waves which are guided along particular geometry of the specimen. These waves interact with defects at suitable frequency which appears a signature on oscilloscope or computer screen with the help of digitizer card. The excitation frequency is decided by dispersion curves. Disperse Software is used for developing dispersion curves. Depending upon the geometry of structure and boundary conditions, the frequency of excitation is chosen for monitoring damages in rods.

Chapter 3 Literature Review

One of the most commonly used NDT techniques is Ultrasonic Testing, utilizing guided waves. This chapter presents a review of literature on utilization of ultrasonic guided waves for damage defection in cylindrical rods or shafts, pipes etc. This gives an idea of study carried out in this area up to this stage.

Kwun and Teller [8] studied a method and apparatus for the inspection of ferromagnetic and non-ferromagnetic pipes, tubes or other cylindrical shell structures utilizing the manetostrictive effect to detect defects such as corrosion pits, wall thinning and cracks. The apparatus and method constitute an active testing application, wherein a transmitting coil element generates a mechanical pulse within a cylindrical shell structure through the magnetostrictive effect and a second coil detects reflected mechanical waves within the pipe, this by the inverse magnetostrictive effect. The present invention also anticipates a passive monitoring application with a detection coil that continuously monitors ferromagnetic or non-ferromagnetic tubes, pipes, etc., for mechanical or acoustic wave emissions and either record this monitored information or alerts the appropriate personnel to the existence of mechanical or acoustic wave emissions indicative of deterioration. Non-ferromagnetic pipes, tubes, etc., are made able to inspection by attaching a layer of ferromagnetic material such as nickel on either the inner or outer walls of the pipes, tubes, etc. by plating or bonding such material in a local area where the sensor is to be placed.

Yeih and Huang [9] studied the amplitude attenuation method in ultrasonic testing was used to evaluate the corrosion damage of reinforced concrete members. It is found that the amplitude attenuation method has good performance in corrosion detection for reinforced concrete members. There exists a consistent relationship between the average amplitude attenuation and the electrochemical parameters such as open circuit potential values, the instantaneous corrosion rate, and thickness loss.

Kundu and Bae Na [10] conducted an inspection of the interface between a steel bar and concrete using the combination of a piezoelectric zirconate-titanate transducer and an electromagnetic acoustic transducer. The PZT is used for generating elastic waves by mechanical vibration and then the EMAT is used for receiving the transmitted ultrasonic guided waves. The experiments are conducted on different types of steel bars: corrosion-free, naturally corroded, and zinc-coated as well as corroded bars. It is shown that the PZT-EMAT combination is very effective for inspecting the steel bar-concrete interface. Using this technique, small separation at the steel bar concrete interface can be effectively detected for corroded as well as corrosion-free specimens.

Scalea et al. [11] studied guided stress wave method for stress monitoring and defect detection in seven-wire strands. A simplified acoustoelastic formulation of the Pochhammer-Chree vibrations in cylindrical waveguides is derived. Magnetostrictive transducers were used to excite and detect the waves in the experiments. Results from acoustoelastic measurements on single wires and on strands are presented, showing the feasibility of the method for stress measurement. Improvements to the inherently low sensitivity of acoustoelastic stress measurements are suggested by adding the effect of strand elongation. The role of the strand anchorages is also examined in the context of wave attenuation. Finally, the suitability of the guided wave method for the detection of indentations and broken wires in the strands is demonstrated.

Beard et al. [12] studied the development of a portable non-destructive testing instrument for evaluating the condition of rock bolts. It is proposed that guided ultrasonic waves can be used to solve this inspection problem, using a pulse-echo test carried out from the free end of the bolt. Suitable test frequencies have been identified through the use of modelling software, and successful laboratory and site trials. The research has shown that the proposed approach is capable of determining the bolt length, and of identifying major defects such as necking, deformation, and loss of resin encapsulation.

Rose [13] studied the principal advantage of guided waves inspection over long distances with excellent sensitivity from a single probe position. There is also an ability to inspect hidden structures and structures under water, coatings, insulations, and concrete. Basic theoretical aspects of dispersion curve analysis, wave structure, source influence, sensor types and instrumentation possibilities and commercialization ventures discussed along with a variety of practical applications on ship hull, containment structures, aircraft, ice detection, pipelines, rail, overlap joints, and crystal manufacture. Phased array focusing in pipes and across elbows will be highlighted. Computational aspects of FEM and BEM analysis for defect classification and sizing analysis will be outlined. Future directions of leave in place sensors and wireless activity will also be presented.

Pan et al. [14] analysed the fracture failure reasons of a cantilever shaft in an expending drier via microfractography analysis, metallographic examination and mechanical tests. The results showed that the main fracture failure reason of the shaft was caused by the combined action of corrosion and cyclic stress. Insufficient quenching and tempering heat treatment, together with material defects contributed to the shaft failure.

Apostolopoulos et al. [15] presented the effects of the gradually accumulating corrosion damage due to laboratory salt spray corrosion on the mechanical behavior of reinforcing steel bars Class BSt 500s tempcore. The experiments have shown that the corrosion exposure causes an appreciable mass loss which increases with increasing duration of exposure. This leads to a significant increase of the applied stress, the tensile properties of the steel bars drop to values lying below the limits which are set in the standards presently in force for using steels in reinforced concrete members.

Mayer [16] presented the theoretical considerations and the practical realisation of a load train to perform ultrasonic torsion fatigue tests. Cyclic torsion and cyclic tension–compression endurance data of 2024-T351 are compared using Mises equivalent stresses. Crack initiation and propagation in cyclic torsion is in the directions of maximum shear stresses.

Kim et al. [17] developed a new ultrasonic transducer capable of transmitting and receiving guided-waves in a rotating shaft. The key idea in this development was the use of wireless capability of the magnetostrictive effect. In this investigation, relatively low-frequency longitudinal waves are generated by Terfenol-D, a giant magnetostrictive alloy (GMA). After an underlying magnetostrictive transducer configuration is presented, the effects of various design parameters on the transducer performances are studied experimentally. The material behavior of Terfenol-D is also briefly discussed. To show the effectiveness of the developed transducer, the transducer is used for guided-wave damage inspection in a rotating shaft having an artificial crack.

Ervin et al. [18] studied the creation of an embeddable ultrasonic sensing network for assessment of reinforcement deterioration. Guided ultrasonic waves were used to monitor reinforced mortar specimens undergoing accelerated uniform and localized corrosion. Longitudinal waves were invoked at higher frequencies 2–9 MHz, where the attenuation is a local minimum. Using a through-transmission configuration, waveforms were sensitive to both forms of corrosion damage. Scattering, mode conversions, and reflections from irregularities at the bar surface from uniform corrosion and the severely tapered cross section from localized corrosion are thought to cause the increase in attenuation.

Zhang et al. [19] investigated **t**he dispersion and excitation characteristics of the guided waves in a rod surrounded by an infinite solid medium (cladding). First, the bisection technique is employed to find all the roots of the dispersion function on the basis of theoretical analysis and to obtain the complex phase and group velocity dispersion curves of the guided modes. Second, according to their different dispersion characteristics, the guided modes are divided into two categories: normal modes and Stoneley modes. And it is concluded that the normal modes merely exist in the "hard cladding" while the Stoneley modes in cylindrical interface are highly dispersive and merely exist in the model whose acoustical parameters satisfied the existence condition of the Stoneley waves. Third, guided waves, excited by three source models: symmetric point source, axial and radial force sources are simulated respectively. Attention is paid on the dominant mode which has better excitation sensitivity and the suitable excitation frequency range.

Sharma and Mukherjee [20] discussed a nonintrusive corrosion monitoring technique for early detection of damages in steel embedded in concrete. Corrosion manifests itself in debond and pitting steel bars. Guided ultrasonic waves offer a potentially attractive solution for this problem. Longitudinal guided ultrasonic waves have been utilized to monitor notch and debond defects in steel bars in concrete simulating pitting and delamination phenomena caused by corrosion. The developed methodology is successfully applied for real time monitoring of RC beam specimens.

The methodology established in the study using low and high frequency ultrasonic pulse echo and pulse transmission on simulated notch and debond damages can be applied for in situ corrosion monitoring of embedded reinforcements in RC beams. It not only indicates the presence of damage but also gives the exact location and magnitude of damage by efficient combination of the two ultrasonic monitoring techniques.

Sharma and Mukerjee [21] utilized specific guided wave modes to distinguish corrosion occurring in different environments of chlorides and oxide environments.

Sharma and Mukherjee [22] reported a complete non destructive evaluation strategy for corrosion occurring in RC structures.

Sharma et al. [23] has made an attempt by developing a damage monitoring technique for the deterioration of reinforcing bars.

Raiˇsutis et al. [24] studied Application of ultrasonic guided waves for NDT of defective CFRP rods with multiple delaminations. During manufacturing of CFRP, in order to build the arbitrary spar profile, these small diameter (few millimetres) rods are glued together into epoxy filled matrix. Still, defects present in the rods, such as break of fibres, multiple delaminations due to lack of bonding and reduction in density affect construction strength markedly and are extremely complicated to eliminate. The regularities of ultrasonic guided wave propagation in a defective CFRP circular-shape rod with multiple delaminations have been investigated using 3D numerical simulations, finite difference and finite element models. The set-up of the 3D numerical model for investigation of ultrasonic guided wave propagation in a defective CFRP rod is as shown in **Fig. 3**.

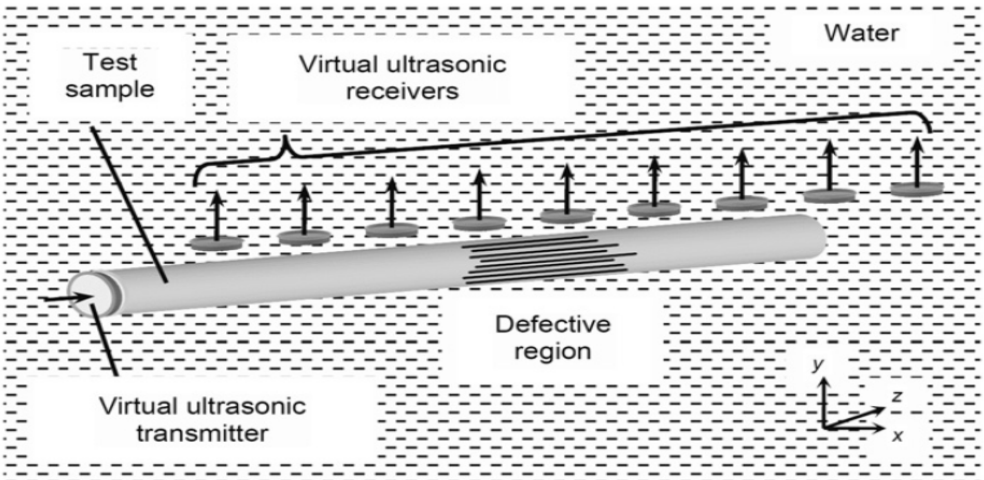

Fig. 3 The set-up of the 3D numerical model for investigation of ultrasonic guided wave propagation in a defective CFRP rod [21]

Xue and Bathias [25] conducted torsion fatigue tests at 20 kHz ultrasonic fatigue testing systems, and compared to the torsion fatigue data generated on 35 Hz conventional fatigue test machine to determine if there are any frequency effects, for steels including D38MSV5S steel and 100C6 steel. Results indicated that the S–N curves exhibit decrease in fatigue strength beyond 107 cycles. The initiation in the Gigacycle regime is related to defects sometimes located beneath the surface which shows a competition between the maximum shear at the surface and the stress concentration under the surface, even in torsion.

Closing Remarks

In this chapter, review of the latest work done using ultrasonic guided waves has been discussed. The studies were focused to identify defects in embedded bars, underground pipes, strands, corrosion monitoring in RC structures etc. Ultrasonic guided wave inspection is expanding rapidly in many different areas of manufacturing and in-service inspection.

4.1 GENERAL

Steel bars are the most popular machinery and construction material today due to their high tensile and compressive strengths. Bars are used as a tensioning device in reinforced concrete and reinforced masonry structures. In mechanical applications, shafts are used in Automobiles, Rails, Ships, Aeroplanes, as propeller shafts, drive shaft, line shaft, gear box, electric motors for transmitting torque and rotation. Under torsion load bars or shafts undergo change in physical properties. Also with the passage of time, the bars deteriorate due to a variety of factors such as environmental degradation resulting from corrosion, fatigue, excessive loads, and natural calamities or simply due to long endurance combined with intensive usage.

The focus of present study is to investigate the deterioration in cylindrical bars using guided waves. The damages considered in the research are directed towards finding effect of torsion and environmental degradation due to corrosion in cylindrical bars. Both Torsion and Corrosion damages have been considered for study in the subsequent chapters.

4.2 Experimental Investigations

Ultrasonic Guided Waves have been used as damage detection tool for non destructive testing purposes.

4.2.1 Set-up Details

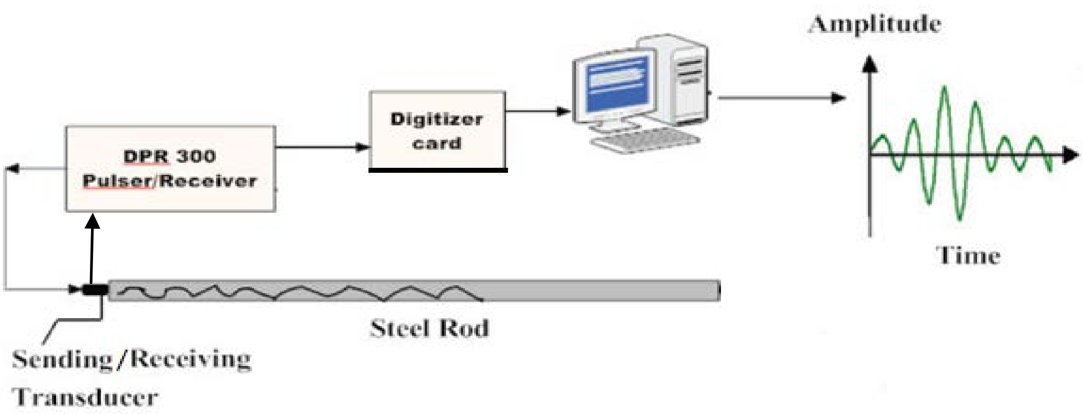

Fig. 4.1 Experimental setup used for capturing the wave signatures

The experimental setup consisting of a typical ultrasonic system, with pulser/receiver that generates the pulse for every given time interval. The pulse was generated by an ultrasonic transducer which transmits the ultrasonic pulse to the specimen through a coupling medium. The same tranducer acts as receiver in pulse echo mode of testing which was used in this study. The received pulse is then digitized using a digitizer card (ACQUIRIS make) and displayed as voltage-time (v-t) signature.

4.2.2 Details of Set-up Components

1. **Transducer**

A contact transducer [**Fig. 4.2**] is a single element longitudinal wave transducer intended for use in direct contact with a test piece. It can be used in straight beam flaw detection and thickness gauging, detection and sizing of delamination, material characterization and sound velocity measurements, inspection of plates, billets, bars, forgings castings, extrusions, and a wide variety of other metallic and non-metallic components.

Fig. 4.2 S 24 HB contact transducer of 1 MHz frequency and 25mm diameter

2. **JSR Ultrasonics DPR 300 Pulser/ Receiver System**

DPR300 pulser produces a high voltage electrical excitation pulse and applies this pulse to the instrument’s T/R connector. An ultrasonic transducer connected to the T/R connector via a coaxial cable is then employed to convert the electrical energy of the excitation pulse into an ultrasonic pulse that is 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 is 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 is used to detect acoustic pulses that have propagated through a test material or medium. The circuit diagram is shown in **Fig. 4.3**.

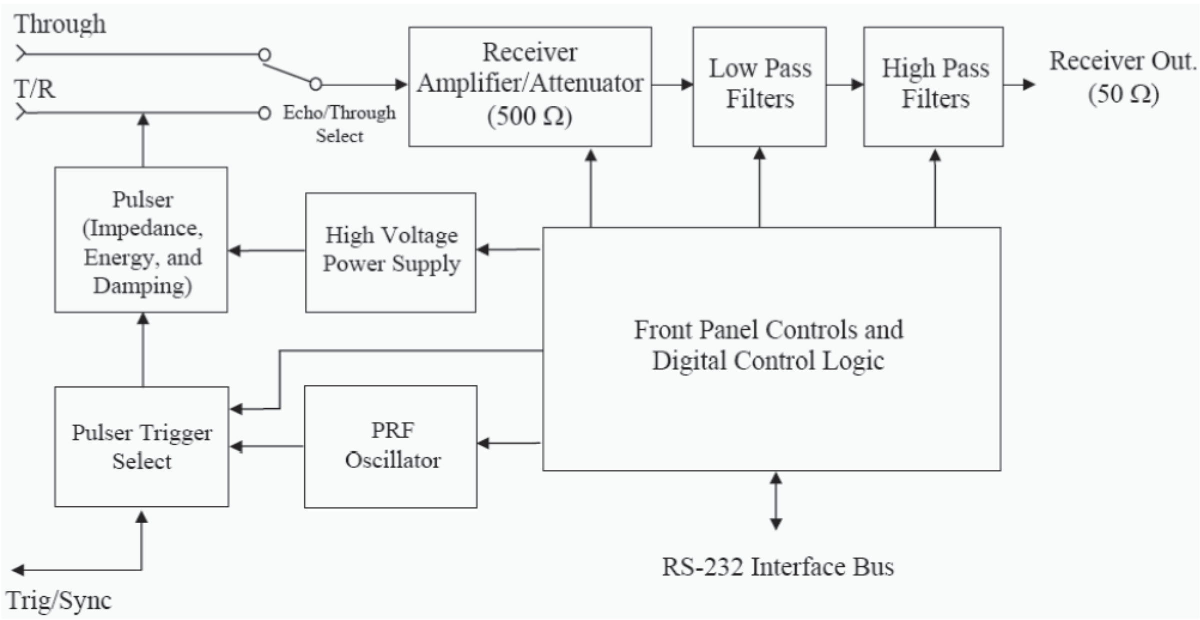

Fig. 4.3 Detail circuit diagram of Pulser/Reciever system

3. **PRF Oscillator & Pulser Trigger control:** 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 or an external source applied to the Trig/Sync connector as trigger sources for the DPR 300 Pulser.
4. **Pulser (Impedance/Energy/Damping):** The pulser generates an excitation pulse upon receiving a trigger event from a selected source. There are four energy and two impedance values, and the single Energy and impedance control adjusts the pulse energy and the pulser impedance.

5. **Receiver amplifier:** It controls the amplification or attenuation of signals processed by the DPR300 receiver. The receiver gain can be varied from -13dB to 66 dB.
6. **Low Pass and High Pass filters:** Low filters are available for reducing the bandwidth of the

DPR300 receiver. High Pass filters are available for eliminating undesirable low frequency energy from the DPR300 receiver signal. High pass filtering can be used as a means of providing faster receiver recovery from strong signals such as the excitation pulse or strong interface echoes.

Pulser	
Pulse Type	Negative Spike Pulse
High Voltage Supply	100V to 475V
Initial Transition (Fall Time)	<5 ns (10-90%) typical for 475V pulsers
Pulse Amplitude	-475V peak. Amplitude depends on Energy, Impedance, Damping control settings, and pulser type
Pulse Energy	1.55 _Joules minimum, 304 μjoules maximum for 475V pulsers. Dependent upon energy and voltage setting
Pulse Duration	Typically 10-70 ns FWHM for 50 _ load. Function of the Energy, Impedance, and Damping controls
Damping	16 Damping values: 331, 198, 142, 110, 92, 77, 67, 59, 52, 47, 43, 39, 37, 34, 32, and 30 ohm.
Mode	Pulse-echo or through transmission
Through Mode Isolation	Typically 80 dB at 10 MHz
Pulser Repetition rate	Internal: 100 Hz - 5 kHz for 475V pulsers. External: 0 - 5 kHz for 475V pulsers.
Sync Output	Maximum +5 V, tr < 30 ns, tw = 50 ns. min. TTL and CMOS compatible. Minimum value of load impedance is 50 ohm.
Pulser Trigger Source	Selectable by computer between internal oscillator and external source
External Trigger Input	3 - 5 V positive going pulse. Triggering will occur

	synchronously with leading edge of trigger signal. TTL and CMOS compatible
Receiver	
Gain	-13 to 66 dB in 1 dB steps controlled by the host computer
Phase	0degree (noninverting)
Input Impedance	500 ohm(through transmission)
Bandwidth	.001-35 MHz (-3 dB) or .001-50 MHz
High Pass Filter	DC,1, 2.5, 5, 7.5 and 12.5 MHz
Low Pass Filter	3,7.5,10,15,22.5 (35 MHz BW) or 5,10,15,22.5,35 (50 MHz BW)
Receiver Noise	Typically 49 µV pk-pk input referred(measured at 60dB,35 MHz bandwidth)
Output Impedance	50 ohm
Output Voltage	± 0.5 V into 50 ohm

7. Dual-Channel High-Resolution Waveform Digitizer

Model DC438 Dual-channel, 12-bit, 100 MHz, 200 MS/s, 4 M point acquisition memory card 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.

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

4.2.3 Specimen Details

The geometry of specimen used for study is as shown in **Fig. 4.4**. The material of specimens was extruded mild steel and dimensions 25 mm diameter and 380 mm length used. The ends of specimens are made such that it could be held by the jaws of the Torsion Testing Machine without slipping. The torsion damage was induced by twisting the MS bars by Torsion Testing Machine up-to various angle of twist. Torsion testing Machine used to twist the specimens is as shown in **Fig. 4.5** and has max capacity of 60000 CM kg and is made by THE AVERY Co. Ltd. BIRMINGHAM. Fig. 4.6 shows applying torque to rod and rod undergoes to particular angle of twist. Twelve sets of specimens used as shown in **Table 4.1**. Three specimens were twisted up to ultimate torsion moment to obtain the maximum angle of twist and the maximum angle of twist was found to be 250 degree. **Fig.4.7** shows the failed specimen due to torsion to find maximum angle of twist. Seven specimens were twisted to 0%, 20%, 40%, 60% and 80% of maximum angle of twist as shown in **Fig. 4.8**. Rest two specimens were retained for destructive testing purposes. **Fig. 4.9** shows specimen S4 before and after twist.

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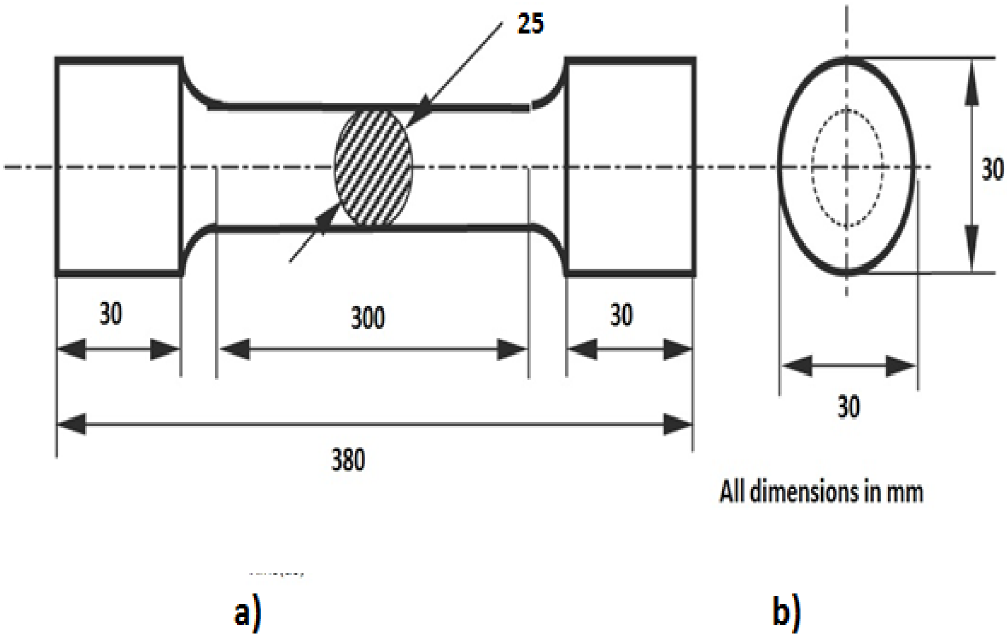

Fig. 4.4 Specimen Dimensions

Fig. 4.5 Torsion Testing Machine

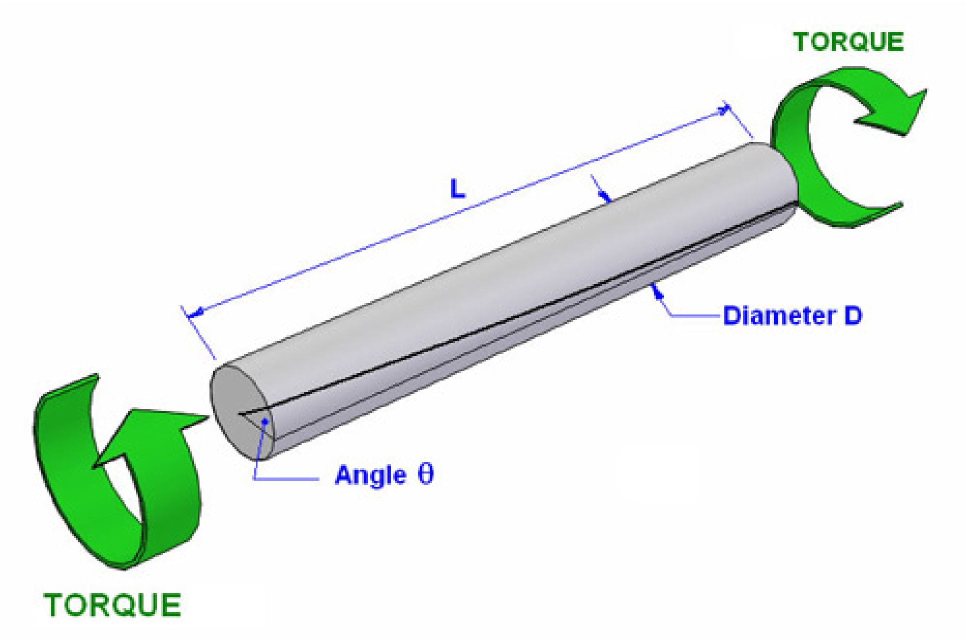

Fig. 4.6 Steel bar under Applied Torque

Table 4.1 Torsion Damage Detection in bars

Specimen Number	Angle of Twist
S1,S2,S3	Up to destruction to find the maximum angle of twist and was obtained 250 degree
S4,S5	20% of max. Angle of twist(50 degree)
S6,S7	40% of max. Angle of twist(100 degree)
S8,S9	60% of max. Angle of twist(150 degree)
S10	80% of max. Angle of twist(200 degree)
S11,S12	Retained Healthy for destructive purposes

Fig. 4.7 Specimen S2 twisted to destruction to find the maximum angle of twist

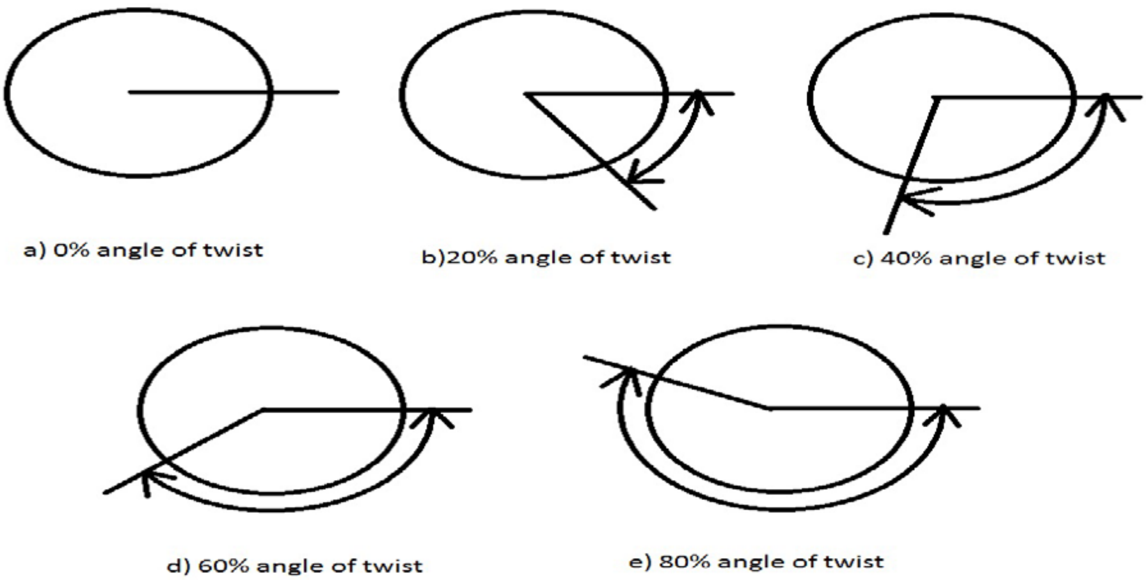

Fig. 4.8 Steel bars with a) 0%, b) 20%, c) 40%, d) 60% and e) 80% of max. Angle of twist

Fig.4.9 a) Healthy specimen b) Twisted Specimen 20% of max. angle of twist(50 degree)

4.3 Ultrasonic Investigations

4.3.1. Ultrasonic Testing

In non destructive testing of metals, the *ultrasonic pulse-echo* (UP-E) technique has proven to be a reliable method for locating cracks and other internal defects. An electro-mechanical transducer is used to generate a short pulse of ultrasonic stress waves that propagates into the object being inspected. Reflection of the stress pulse occurs at boundaries separating materials with different densities and elastic properties. The reflected pulse travels back to the transducer that also acts as a receiver. The received signal is displayed on computer screen through receiver and digitizer card. By knowing the speed of the stress wave, the distance to the reflecting interface can be determined.

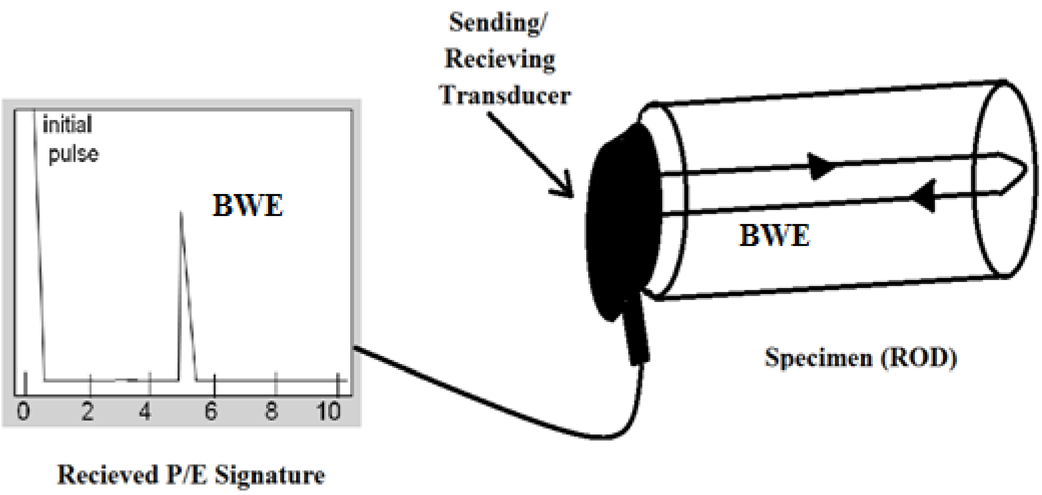

Fig. 4.10 Pulse Echo Method

4.3.2. Selection of Excitation Mode

Dispersion curves for 25 mm diameter rod in air are shown in **Fig. 4.11, 4.12** for steel. Only longitudinal modes have been considered in the study as the flexural and torsional modes experience high theoretical attenuation. Also it is easier to invoke a strong longitudinal wave. Guided longitudinal waves were produced in the bar by keeping compressional transducer parallel to the guiding configuration at the one end of the bar. The selection of frequencies for testing was done based on the phase velocity dispersion curves. High frequency low loss modes are found to be best. Each of the higher modes shows a plateau region around the steel longitudinal bulk velocity line. In these regions, phase velocity is almost equal to longitudinal bulk velocity and longitudinal partial wave is almost parallel to the bar axis. The input parameters for Disperse are shown in **Table 4.2**.

Therefore, the modes L(0,7) and L(0,8) at 1 MHz were obtained from phase velocity curve. But from group velocity curve, the mode L(0,8) at 1 MHz was chosen. The group velocity as obtained from dispersion curve at this frequency is 4.58 km/s. The velocity in the mode chosen for 25mm bars are close to the longitudinal bulk velocity of steel.

Table 4.2 Material Properties for Steel Bar

MATERIAL PROPERTIES FOR STEEL BAR USED FOR MODELING IN DISPERSE		
S. No.	Material Property(Extruded Steel)	Value
1	Modulus, *E* (GPa)	210
2	Density(ρ), (kg/m3)	7932
3	Longitudinal Attenuation (np /wl)	0.003
4	Shear Attenuation (np/wl)	0.008
5	Longitudinal Velocity (m/s)	5960
6	Shear Velocity (m/s)	3260
7	Poisson’s Ratio	0.2865

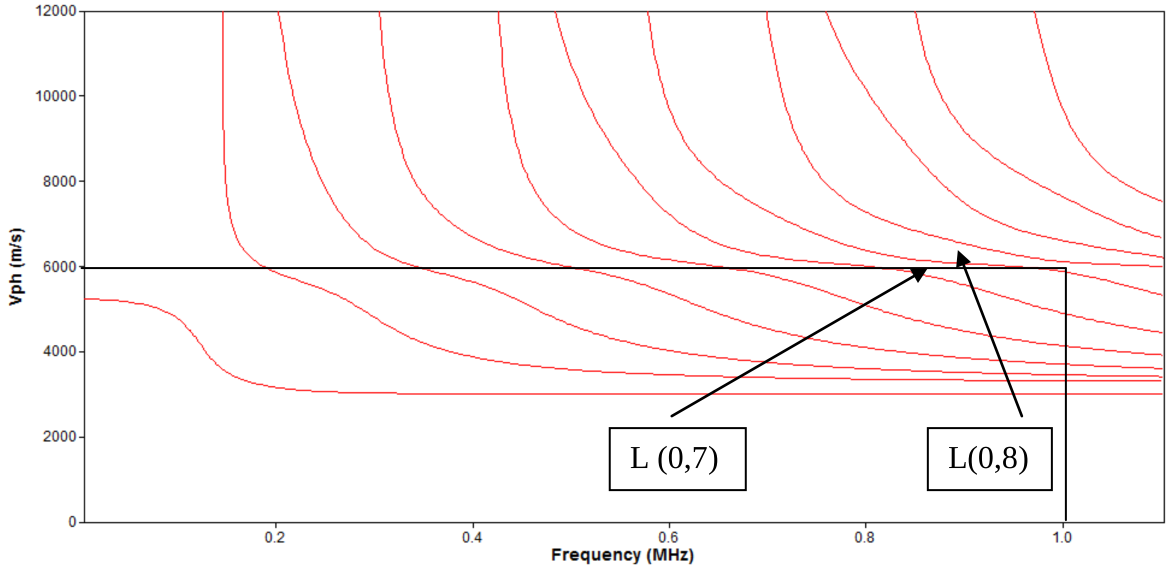

Fig. 4.11 Phase Velocity vs. Frequency for 25 mm bar in air

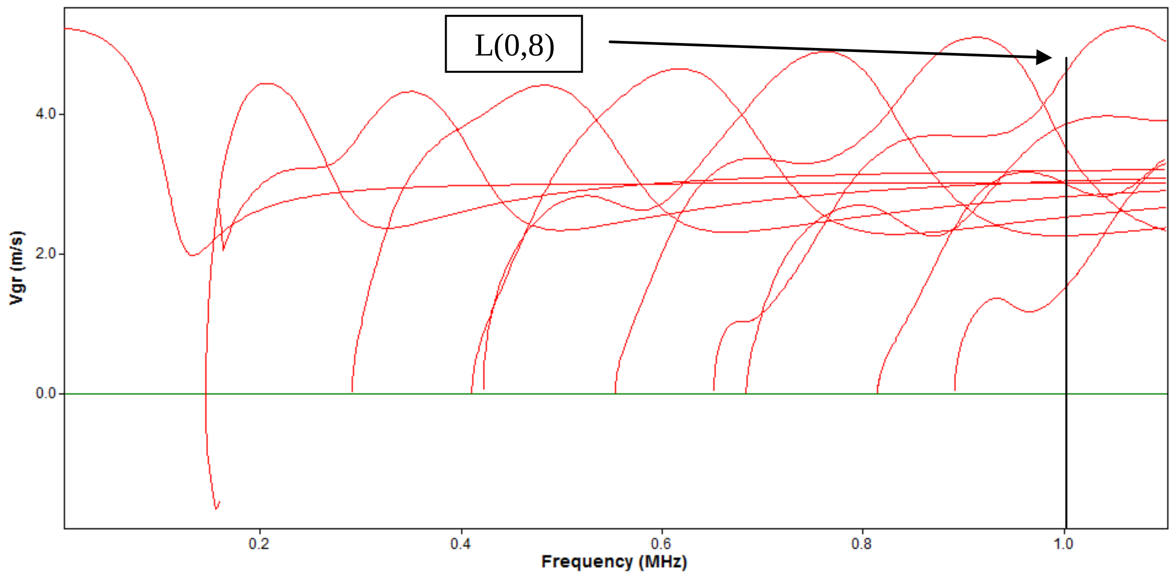

Fig. 4.12 Group Velocity vs. Frequency for 25 mm bar in air

4.3.3. Ultrasonic Results

Pulse Echo signatures were taken for seven different specimens (as discussed in previous section) subjected to various degree of torsion. For every specimen first healthy ultrasonic signatures were taken in Pulse Echo mode. The specimens were then twisted to pre decided degree of torsion and corresponding ultrasonic signature were taken of the twisted specimens. For every specimen, the magnitude of pulse received after reflection in healthy and twisted specimen was taken called back wall echo (BWE). The voltage was read corresponding to peak at calculated Time of Flight (as shown below) using phase velocity of particular mode in a particular diameter of bar. Two specimens were tested for each degree of torsion to ensure the repeatability of the test.

Calculation of Time of Flight

From Pulse Echo Method

D= (V*t)/2

V= Group velocity from dispersion curve (4.58 km/s)

D= Length of Rod (380 mm)

T= Time of flight to be calculated

Thus, T= 165 us.

Pulse Echo Signatures of Specimens for Various Degree of Torsion

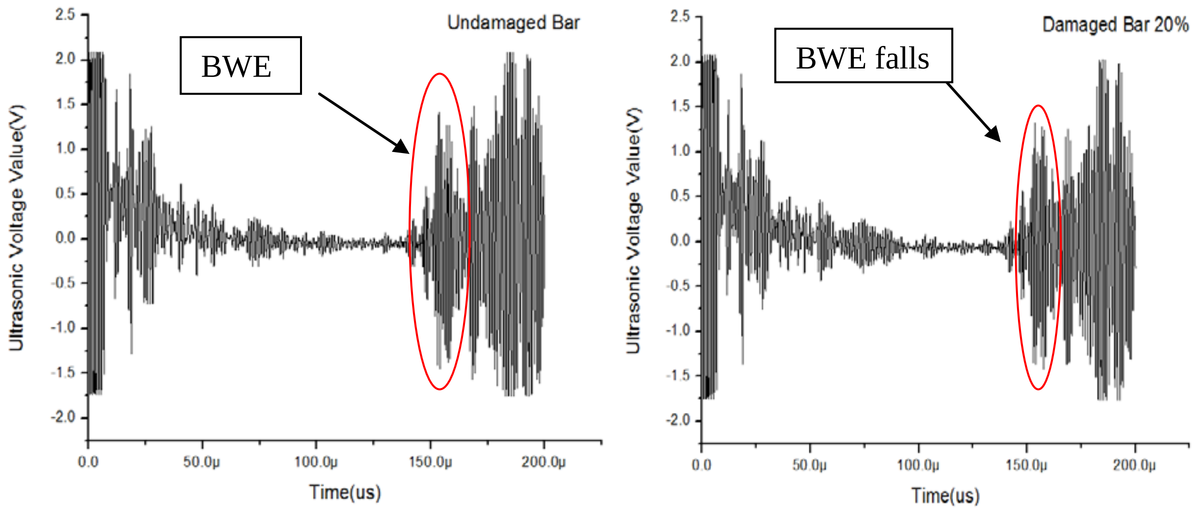

Fig. 4.13 Ultrasonic signatures for a) Undamaged (Healthy state) b) 20% twist bar (50 degree)

Similarly, ultrasonic signatures are shown for 40% angle of twist and 60% angle of twist for 1MHz frequency.

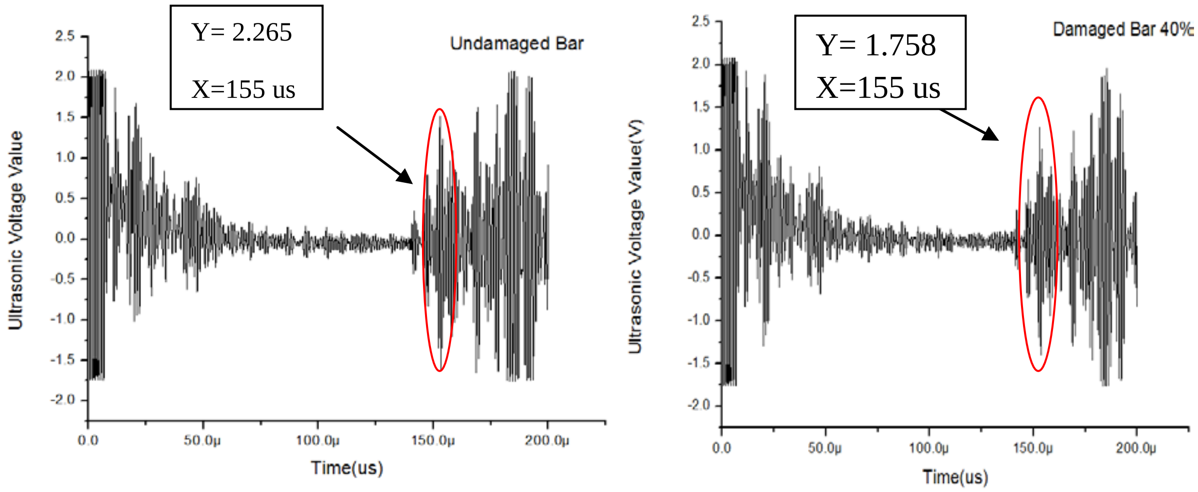

Fig. 4.14 Ultrasonic signatures for a) Undamaged (Healthy state) b) 40% twist bar (100 degree)

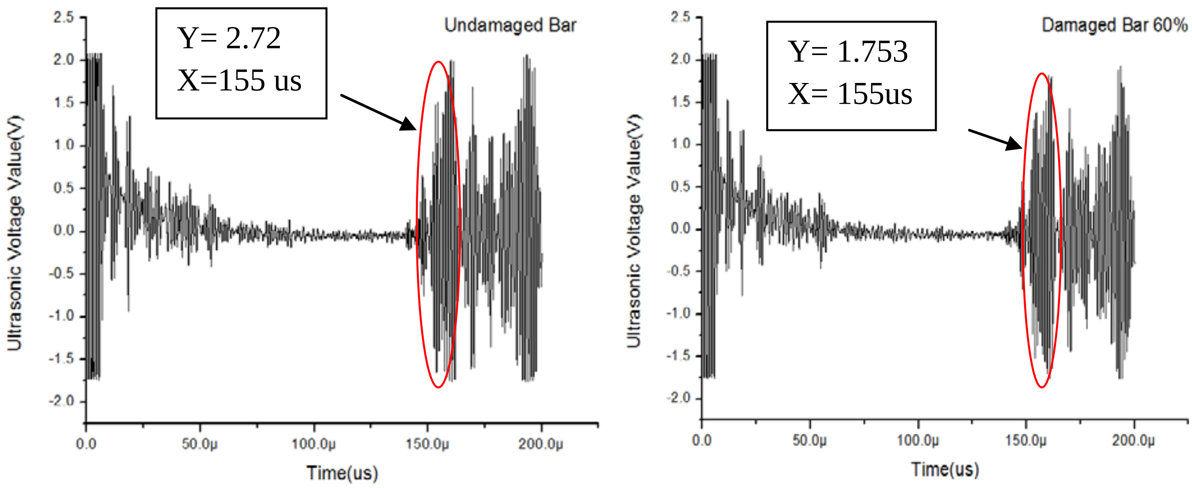

Fig. 4.15 Ultrasonic signatures for a) Undamaged (Healthy state) b) 60% twist bar (150 degree)

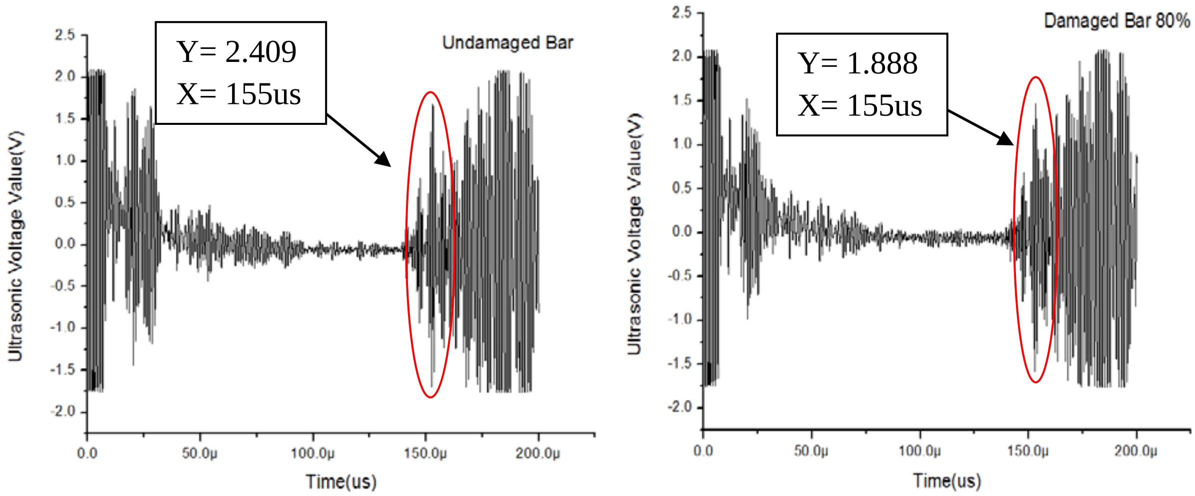

Fig. 4.16 Ultrasonic signatures for a) Undamaged (Healthy state) b) 80% twist bar (200 degree)

Fig. 4.17 shows the voltage amplitudes of BWE received in bars for varying angle of twist with reference to their healthy specimen voltages. **Fig. 4.18** shows the effect of varying degree of torsion on voltage amplitude of BWE as torsion increases.

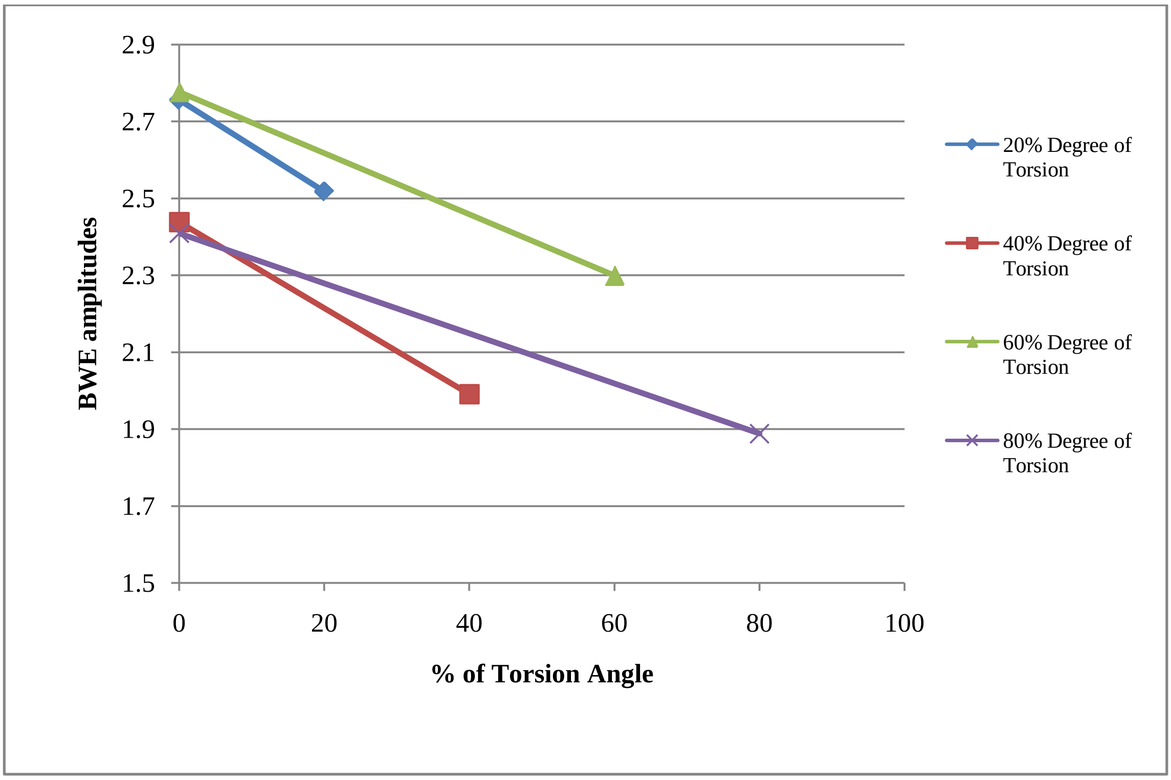

Fig. 4.17 Ultrasonic Voltage vs. Percentage of maximum torsion angle

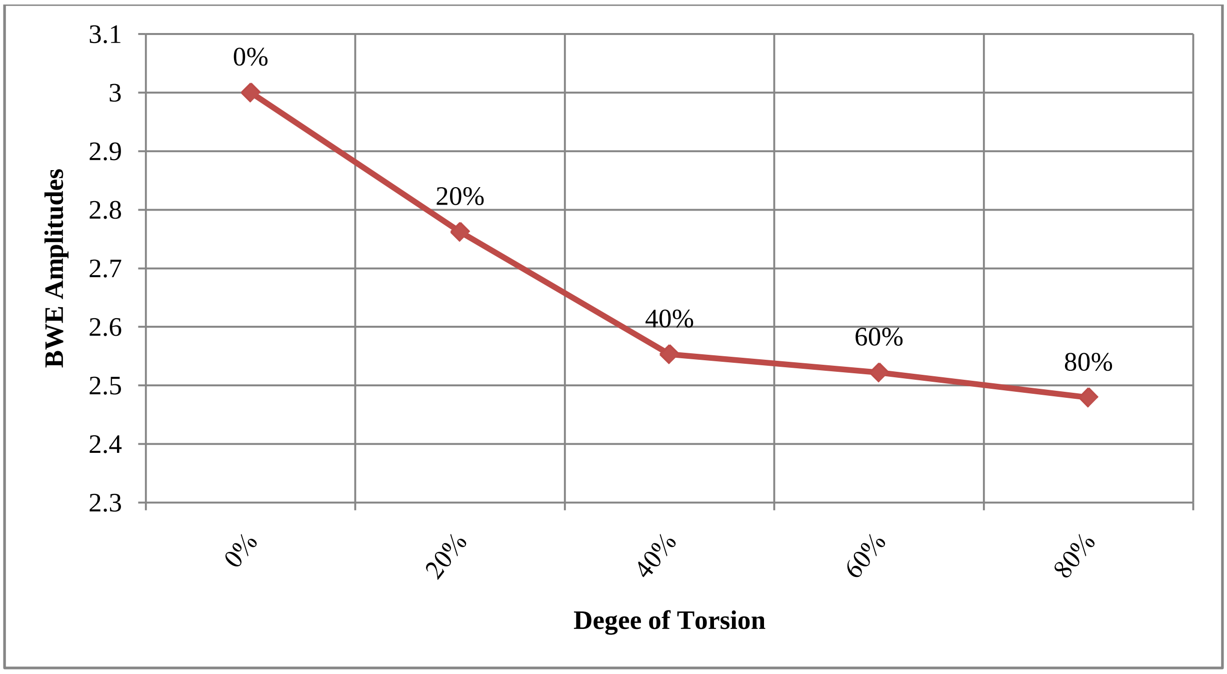

Fig. 4.18 Ultrasonic Voltage vs. Percentage of maximum torsion angle

From the Pulse Echo signatures obtained for specimens subjected to various degree of torsion following observations are made

1) As the angle of twist is increased from healthy to a particular angle of torsion, received ultrasonic guided wave signal changes and magnitude of ultrasonic voltage falls shown in **Fig. 4.17**. This indicates that increase in torsion, distorts the bars and damages it internally and voltage amplitudes of BWE falls.
2) If all the healthy ultrasonic signatures are normalized to single value, it is observed that with the increase in angle of twist, received BWE decrease.

Hence guided waves have the capability to pick up degradation due to torsion in bars. Reduction in amplitude of BWE with increases angle of twist, relates to the increase in damage due to torsion in bars. Thus pulse echo method of testing can be successfully applied to detect torsion damage in rods.

4.4 Destructive Testing and Results

To establish a correlation between ultrasonic testing results (i.e voltages) and a mechanical strength parameter, tensile testing was chosen. Healthy bars (two in number) were subjected to ultimate tensile loading in UTM and average ultimate tensile load was calculated. Then retained seven specimens previously twisted to various degree of torsion were subjected to tensile testing and tensile load was calculated. A Universal Tensile testing machine shown in **Fig. 4.19a** has been used for the testing of the steel rod specimen for its tensile strength. Maximum Capacity of UTM is 1000 KN. **Fig. 4.20** shows specimen S11 subjected to tensile testing.

a) b)

Fig. 4.19 (a) Tensile testing machine (b) Gripped specimen

Fig. 4.20 Failed Specimen S11 after tensile test

Table 4.3 Tensile Test Results

Specimen No.	% Degree of Twist, Angle of Twist	Tensile Load(kN)	Tensile Strength(N/mm^2)
S11	0%, 0 degree	209.620	166.89
S12	0%, 0 degree	207.420	165.14
S4	20%, 50 degree	217.465	173.14
S5	20%, 50 degree	214.785	171.00
S6	40%, 100 degree	216.605	172.45
S7	40%, 100 degree	223.015	177.55
S8	60%, 150 degree	240.430	191.42
S9	60%, 150 degree	222.155	176.85
S10	80%, 200 degree	225.600	179.61

Table 4.3 shows the tensile strength of all torsion specimens to failure. From the table following observations were made

1) It is observed that as the bars are subjected to increasing torsion, first the ultimate tensile strength increases up to a particular twist and then starts falling.
2) As the angle of twist increases, tensile strength of specimens also increases, reaches to a particular highest value then starts decreases as shown in **Fig. 4.21** This can be explained in a way that due to increase in angle of twist, the grains of steel bar specimen orient themselves such that tensile strength increases up to a certain angle of twist. But when angle of twist increases beyond a particular value and the specimen has high degree of torsion, the tensile strength decreases. It may be probably due to damage permanently in the bar due to high twist because of which the tensile strength falls.
3) Correlation between percentage decrease in ultrasonic voltage and tensile strength is attempted and shown in **Fig. 4.22**

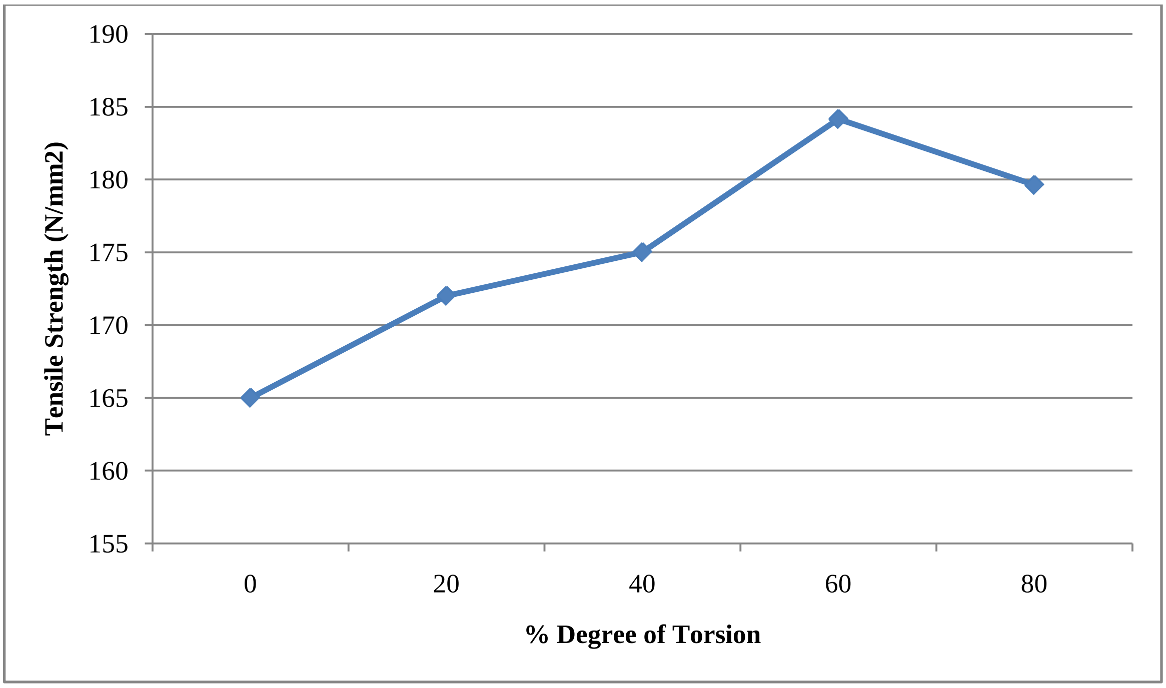

Fig. 4.21 Tensile Strength vs. Percent degree of Torsion

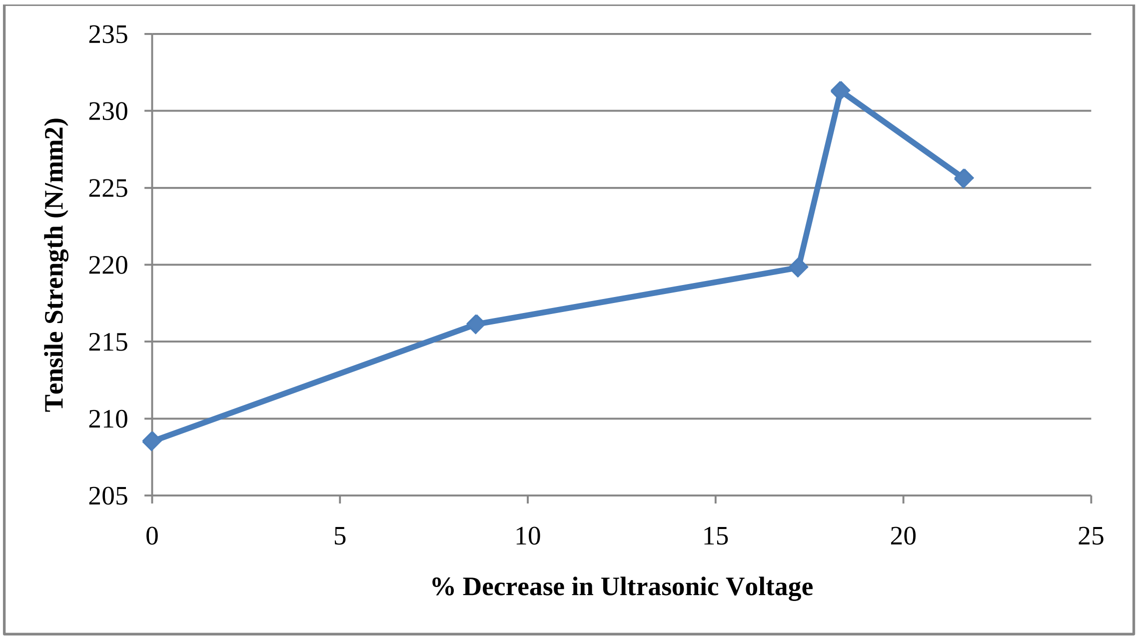

Fig. 4.22 Tensile Strength vs. Percentage decrease in ultrasonic voltage

From the figure it is clear that as torsion increases, ultrasonic voltage amplitude decreases and tensile strength increases. An empirical relation between percentage decrease in ultrasonic voltage and tensile strength can be established up to a point the graph between two is linear. But at high degree of torsion, it has to be assisted by more exhaustive experimental investigations.

4.5 Closing Remarks

From the experimental ultrasonic and destructive investigation, it can be concluded that ultrasonic guided wave can be used as damage detection tool for picking up torsion damage. Successful correlation between angle of twist, pulse echo amplitude and in-situ strength in the form of tensile strength has been successfully established. Guided waves can be successfully be used for damages in bars due to torsion.

Chapter 5 Damage Detection for Corrosion in Bars

5.1 GENERAL

Steel bar is a versatile, economical, and successful construction and machinery material due combination of good compressive strength with the excellent tensile strength. It has proven to be a successful in terms of structural, mechanical performance and durability. However, in some cases it does not perform adequately due to its poor design, poor construction, inadequate material selection, a more severe environment than anticipated, or a combination of these factors. But one major flaw, namely its susceptibility to environmental attack, can severely reduce the strength and life of these structures and machinery. Pitting corrosion may also reduce the ductility of the steel bar by introducing notches on the surface of the steel bars that lead to premature necking. Corrosion, if undiscovered can cause catastrophic failure of the structure. It is important to pick up degradation of cylindrical bars due to corrosion phenomenon. In this study, the feasibility of using UGW for damage detection due to corrosion is employed. Before employing the use of guided waves for corrosion, brief description of various aspects of corrosion discussed.

5.2 Corrosion in Bars

5.2.1. Types of Corrosion

There are many types and causes of corrosion and depending on a particular scientist's or corrosion engineer's tendencies to look upon the subject more broadly or narrowly there is no clear and exact total for the number of corrosion types. The basic varieties of corrosion [26] listed below.

ATMOSPHERIC: Atmospheric corrosion and its severity is essentially determined by four variables:

1. air pollution (volcanic gases)

2. airborne salt spray or droplets

3. temperature

4. and moisture.

The presence of industrial pollutants in the polar ice caps demonstrates that even the most remote corners of the Earth are not immune to its effects. Nitrogen and sulfur compounds can form acids when discharged or acidic material may be released to the atmosphere directly by some industries accelerating the corrosion process on metal these substances encounter. Of course urban areas and those areas in close proximity to or downwind from "smokestack type" industries and power plants are subject to the most corrosive effects of airborne pollution.

GALVANIC: When dissimilar metals are connected in the presence of an electrolyte a galvanic corrosion reaction occurs. Both the presence of an electrolyte solution and a bi-metallic coupling is required for this type of corrosion to occur.

Electrolytes are electrically conductive solutions such as sea water or road salt spray which contain chloride or rain, mist or dew containing sulfur or nitrogen compounds. The most common sources of chloride contamination are marine and coastal environments as well as winter road salting spray. When two dissimilar metals are connected electrically through an electrolyte or salt bridge one metal will become anodic with reference to the other and the potential difference will create the corrosion current causing the more anodic metal to corrode.

UNIFORM/GENERAL: When corrosion occurs uniformly over a wide area of the metal surface producing a general thinning of the metal leading to eventual failure. The rate of general corrosion is usually relatively predictable.

PITTING: Pitting corrosion is quite often evident on metal surfaces where no uniform corrosion is present and is usually highly localized. Pitting usually proceeds fairly rapidly and is accelerated by the presence of chlorides and is particularly common at the base of breaks in coatings. Pitting corrosion takes advantage of the different metallurgical phases present on the surface of most common modern alloys. Generally it is considered to be the product of localized anodic dissolution where the anodic portion of the corrosion cell is dwarfed by the larger cathodic portion.

STRESS CORROSION CRACKING: Stress corrosion is the product of tensile stress (including residual stress remaining after fabrication) and localized corrosion which combine to produce a brittle cracking of metal under certain conditions. Examples of environments which enhance stress corrosion are high pH amine solutions for most common steels and chloride bearing solutions for most stainless steels as well as certain aluminium alloys.

CREVICE CORROSION: Crevice corrosion occurs in sheltered, localized areas such as crevices, joints, bolted and threaded parts and under existing corrosion deposits. It is the result of concentration of salts, acids and moisture which results in the formation of an occluded corrosion cell in such sheltered areas. A small anode is created in the crevice with the remainder of the body acting as a large cathode so corrosion at the crevice is highly accelerated as well as concentrated.

HIGH TEMPERATURE: Under very high temperature metals need only the presence of oxygen or other oxidizing gases to corrode. This type of corrosion is referred to as high temperature oxidation, scaling or tarnishing and requires neither moisture nor dissolved electrolytes (salts, acids) to proceed.

5.2.2. Effect of Corrosion on Bars

The corrosion of bars occur in various forms which results in loss of material which in turn decrease the area of bar and stress concentration increases and rod may undergo failure. The corrosion occurs mostly in the form of pitting and rods undergo deterioration. If the deterioration in the bars or shafts goes unnoticed, it can lead to catastrophic failures of the structures leading to large scale loss of life and property.

5.2.3. Mechanism of Corrosion

Corrosion is basically an electrochemical process where the anode and cathode are on the same steel bar. At the anode, iron atoms lose electrons to become iron ions (Fe^{++}) [Equation 5.1]. At the cathode oxygen in the presence of water accepts electrons to form hydroxyl ion (OH^-) [Equation 5.2].

Anodic reaction: $Fe \rightarrow Fe^{2+} + 2e^-$ .... (5.1)

Cathodic reaction: $2e^- + H_2O + O_2 \rightarrow 2OH^-$ .... (5.2)

Both the anodic and cathodic reactions are necessary for the corrosion to occur and they need to take place simultaneously. The hydroxyl ions combine with the ferrous ions to form ferrous hydroxide [Equation 5.3].

$Fe^{2+} + 2\,OH^{-} \rightarrow Fe(OH)_2$ .... (5.3)

In the presence of water and oxygen, the ferrous hydroxide is further oxidized to form Fe_2O_3. The reaction follows as

$4Fe(OH)_2 + O_2 + H_2O \rightarrow 4Fe(OH)_3$ .... (5.4)

(Ferric hydroxide)

$Fe(OH)_3 \rightarrow Fe_2O_3.2H_2O$ (Hydrated ferric oxide- rust)....... (5.5)

5.2.4. Method adopted for inducing corrosion

There are many methods of accelerated corrosion. They can be listed as below:

1) Dipping in acid solution
2) By impressed current (electrolysis) corrosion.
3) Alternate drying and wetting
4) Placing in salt mist chamber.

To corrode the specimens of different diameter, impressed current corrosion was used. It has following advantages over the other corrosion methods.

1. The corrosion rate could be accelerated or decelerated by changing the voltage.
2. It could be stopped or started without any delay.
3. It is the fastest method of corrosion.

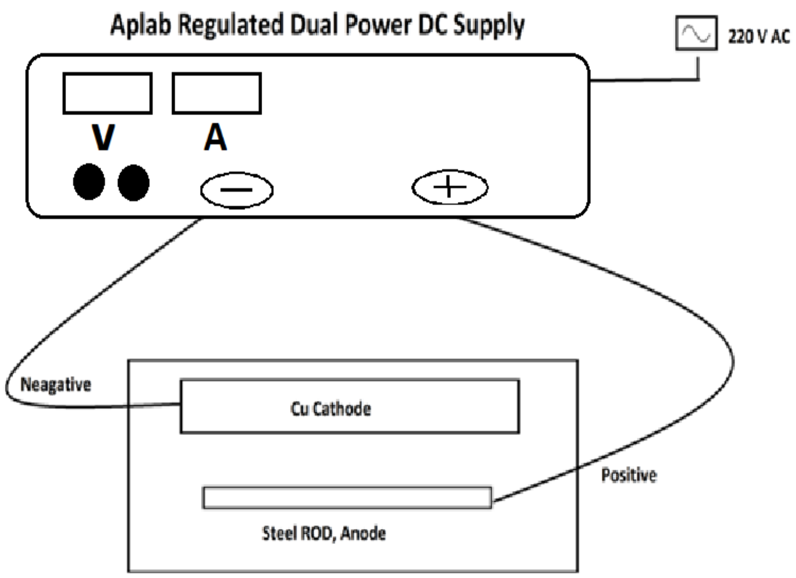

Fig. 5.1 Line diagram for Impressed Current Corrosion

In this technique, the positive terminal of a constant power supply was attached to the steel bar to be corroded which acts as anode. The negative terminal was attached to copper plate which acts as cathode. Both anode and cathode were dipped in 5% NaCl solution to accelerate the electrolysis process. **Fig. 5.1** shows line diagram for impressed current corrosion.

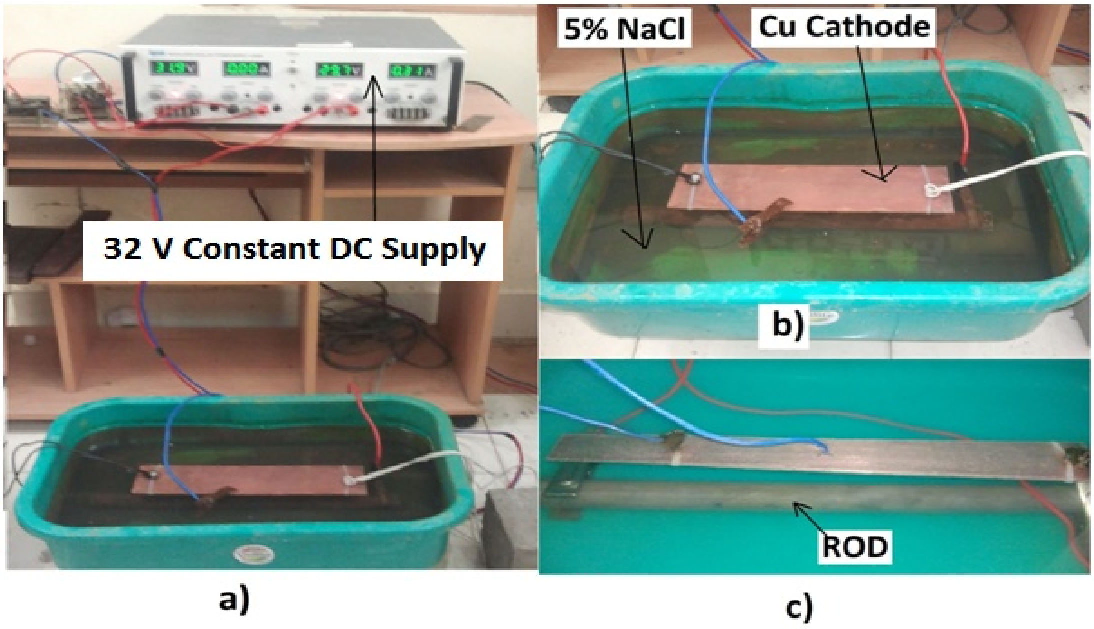

Fig. 5.2 Experimental Setup used for Impressed Current Corrosion

5.3 Ultrasonic Investigations

Ultrasonic Guided Waves have been used as damage detection tool for non destructive testing purposes.

5.3.1. Specimen Details and Test Matrices

The extruded mild steel bars of 12 mm and 25 mm diameter and 380 mm length were used for experiments as shown in **Fig. 5.3**. The damage in the form of number of days of corrosion of the specimen was introduced with impressed current corrosion as discussed above. Test matrix is shown in **Table 5.1**. Five specimens of 12 mm diameter for 0 Days, 5 Days, 9 Days, 14 Days, 20 Days of corrosion prepared. Four specimens of 25 mm diameter for 0 Days, 8 Days, 16 Days, 30 Days of corrosion prepared.

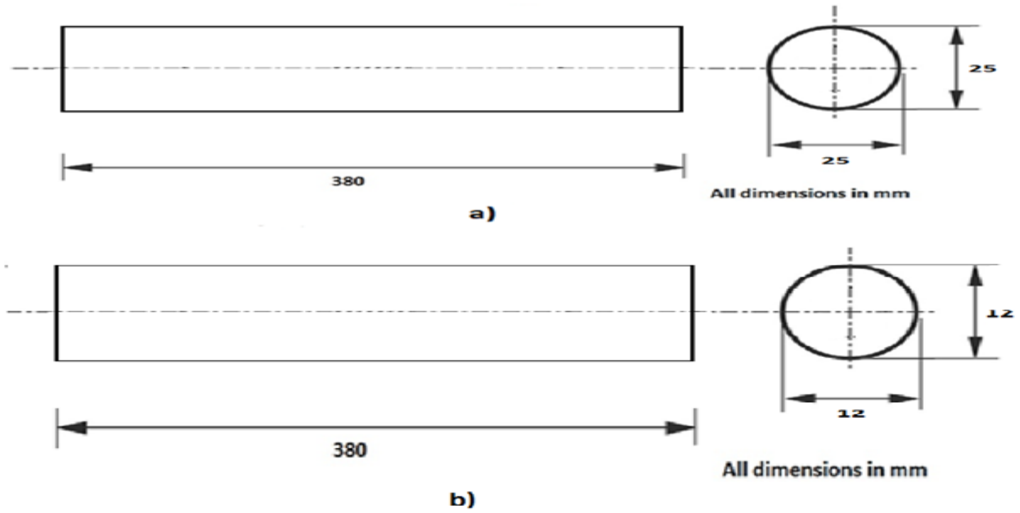

Fig. 5.3 Test Specimen dimensions a) 25 mm Dia. b) 12 mm Dia.

Table 5.1 Test Matrices

Matrices of number of specimen for different Days of Corrosion are shown here.

12 mm Diameter Rod	
Specimen No.	**No. of Days of Corrosion**
S1	20 Days
S2	14 Days
S3	9 Days
S4	5 Days
S5	0 Days
25 mm Diameter Rod	
Specimen No.	**No. of Days of Corrosion**
S1	30 Days
S2	16 Days
S3	8 Days
S4	0 Days

5.3.2. Mode of Excitation

Dispersion curves for 12 mm diameter rod are shown in **Fig. 5.4** for steel properties shown in Table 4.2. The modes L(0,4) at 1 MHz and L(0,7) at 2 MHz were chosen for 12 mm bar. The phase velocity as obtained from dispersion curve at this frequency is 5.9 km/s. Similarly, for

25 mm bar at 1 MHz frequency, L(0,7) mode was chosen as shown in chapter 4. The group velocity obtained from group velocity dispersion curve at 1 MHz frequency is 4.58 km/s.

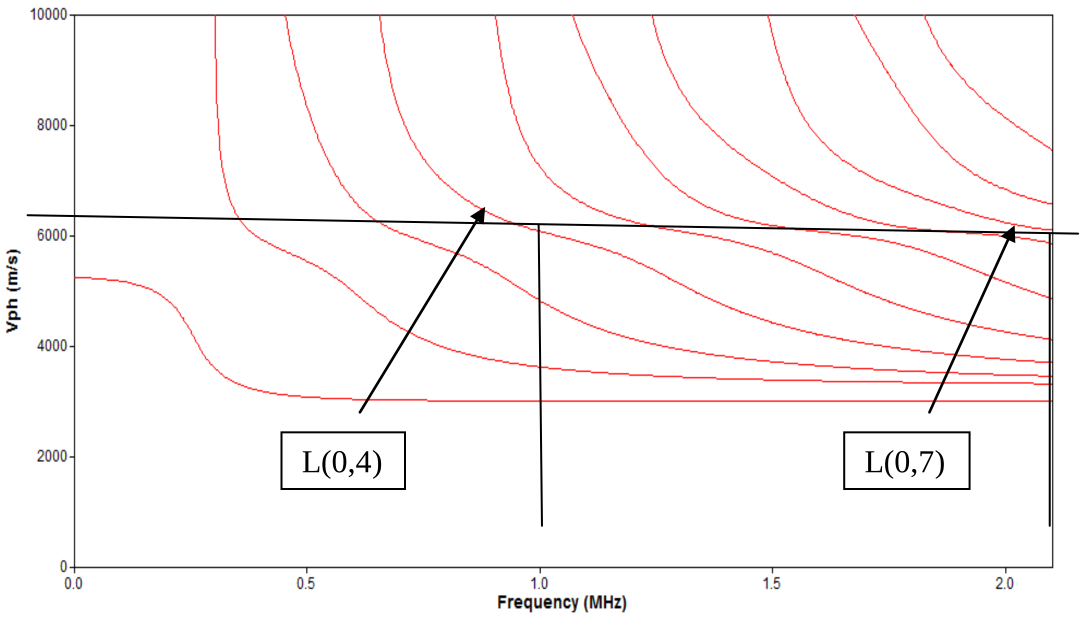

Fig. 5.4 Phase velocity vs. Frequency for 12 mm rod in air

5.3.3. Ultrasonic Testing and Results

Pulse Echo signatures were taken for nine different specimens subjected to corrosion for various numbers of days. For every specimen first healthy ultrasonic signatures taken with help of setup shown in **Fig. 5.5** then specimen was corroded to particular number of days with help of impressed current corrosion and corresponding ultrasonic signature was taken of corroded specimen called back wall echo (BWE) after every 24 hours for 12 mm rod. Similarly, 25 mm rod tested for ultrasonic testing. The voltage was read corresponding to peak at calculated Time of flight. All the corroded and healthy specimens were retained for destructive purposes.

Calculation of Time of Flight

From Pulse Echo Method

D= (V*t)/2

V= Phase velocity or group velocity from dispersion curve

D= Length of Rod (380 mm)

t= Time of flight to be calculated

For 12 mm Rod

V= 5.9 km/s (from phase velocity dispersion curve)

Thus, t= 130 us

For 20 mm Rod

V= 4.58 km/s (from group velocity dispersion curve)

Thus, t= 165 us.

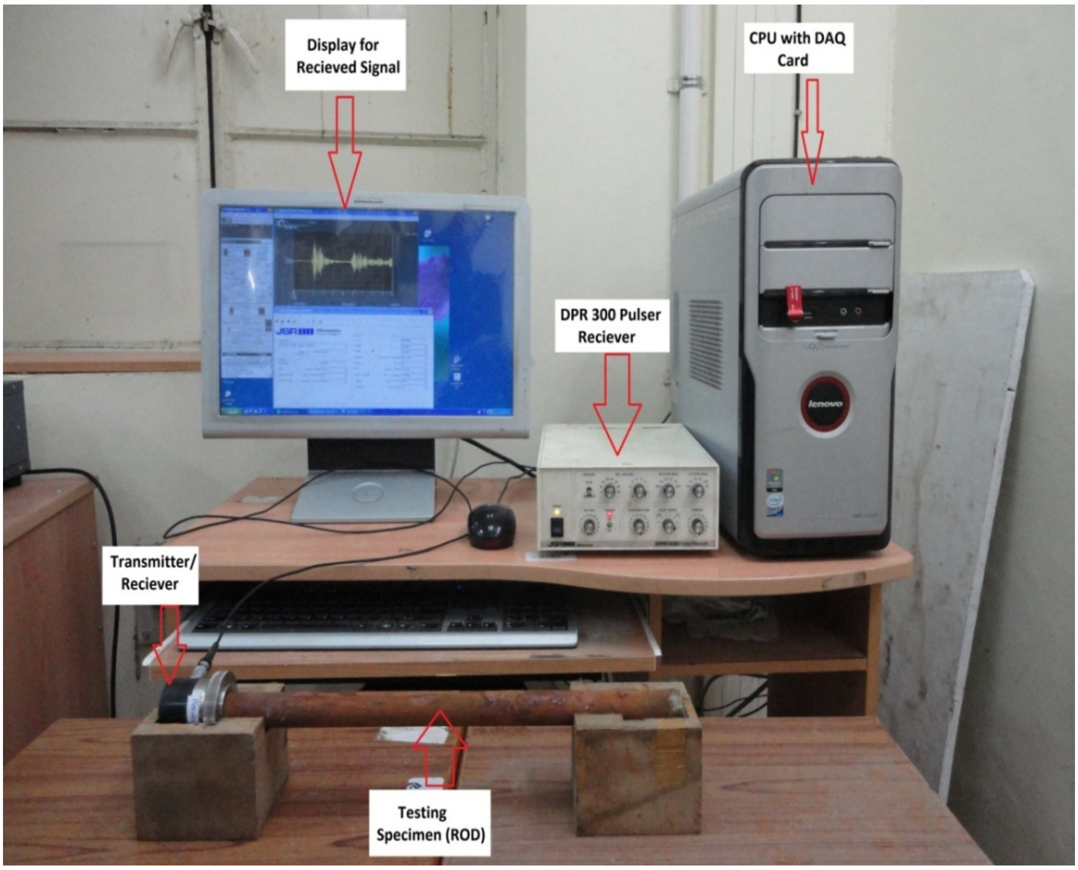

Fig. 5.5 Experimental Set up for Ultrasonic Testing of Corroded Bars

Ultrasonic Signatures and Results for 12 mm Bar

Pulse echo signatures obtained for corroded 12 mm bar are shown below:

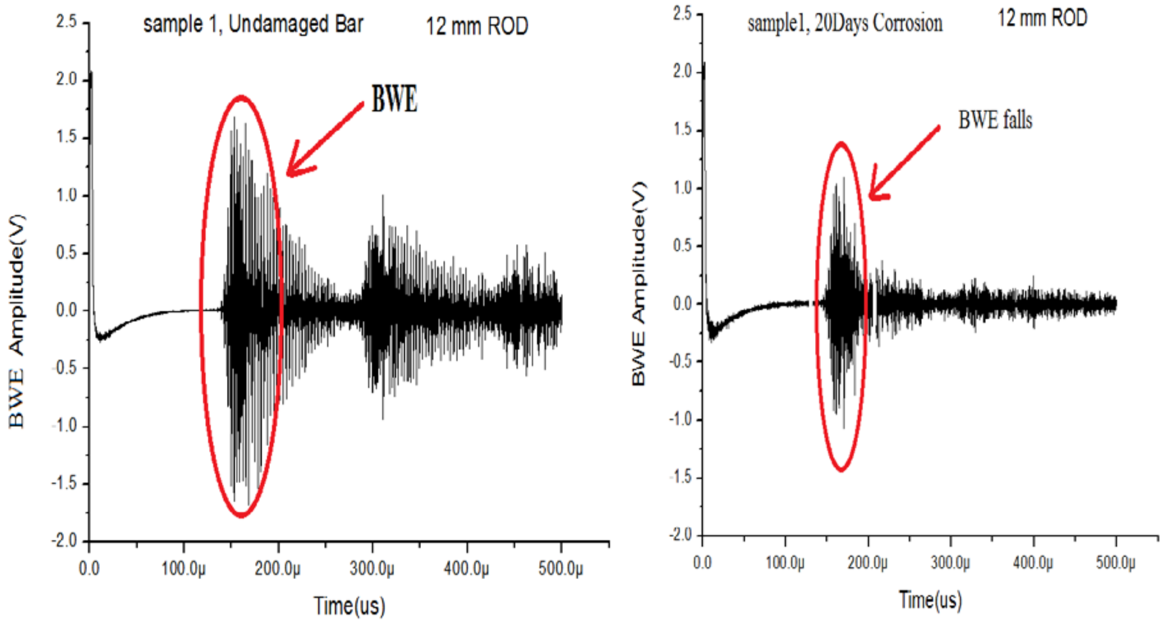

Fig. 5.6 Pulse echo through 12mm Dia. Rod a) Healthy b) 20 Days Corrosion at 2 MHz frequency

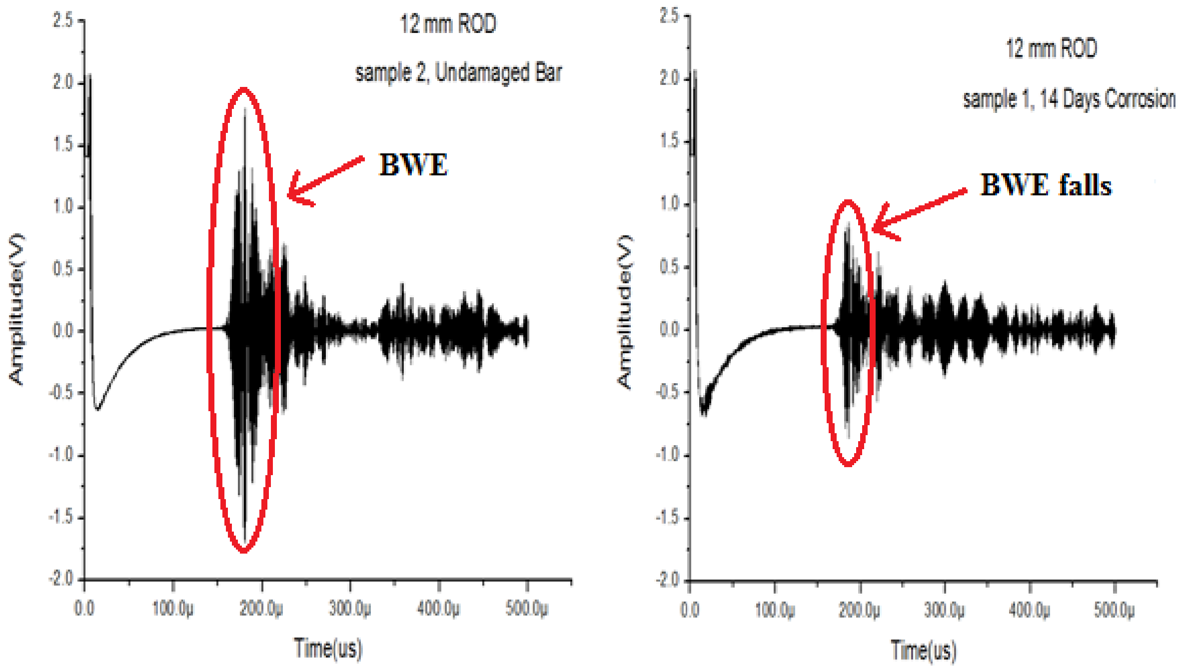

Fig. 5.7 Pulse echo through 12mm Dia. Rod a) Healthy b) 14 Days Corrosion at 1 MHz frequency

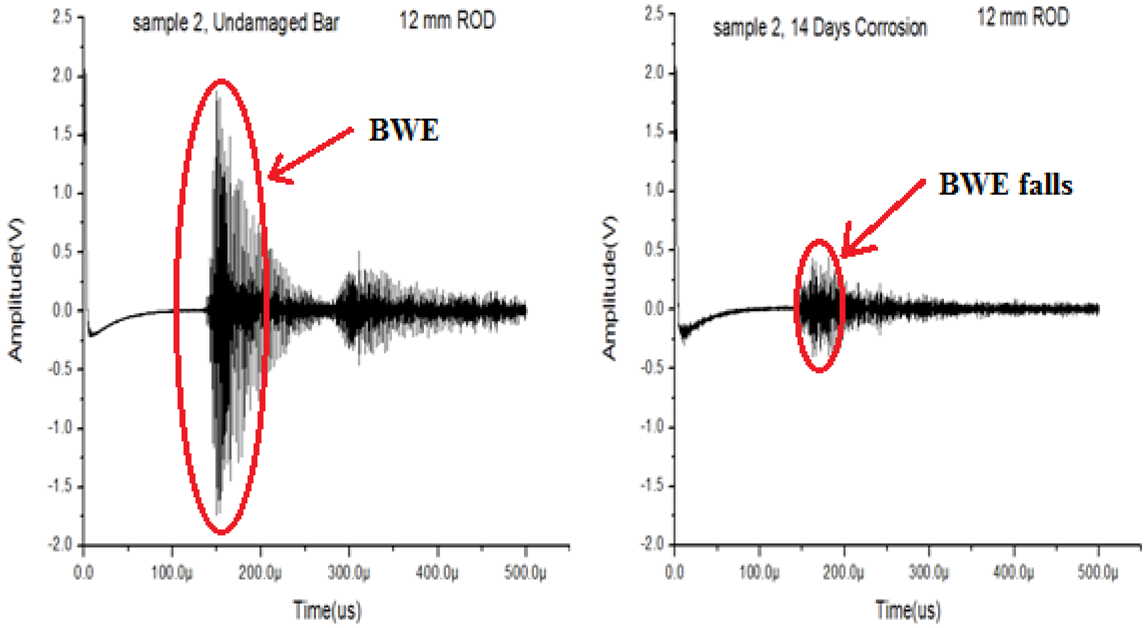

Fig. 5.8 Pulse echo through 12mm Dia. Rod a) healthy b) 14 Days Corrosion at 2 MHz frequency

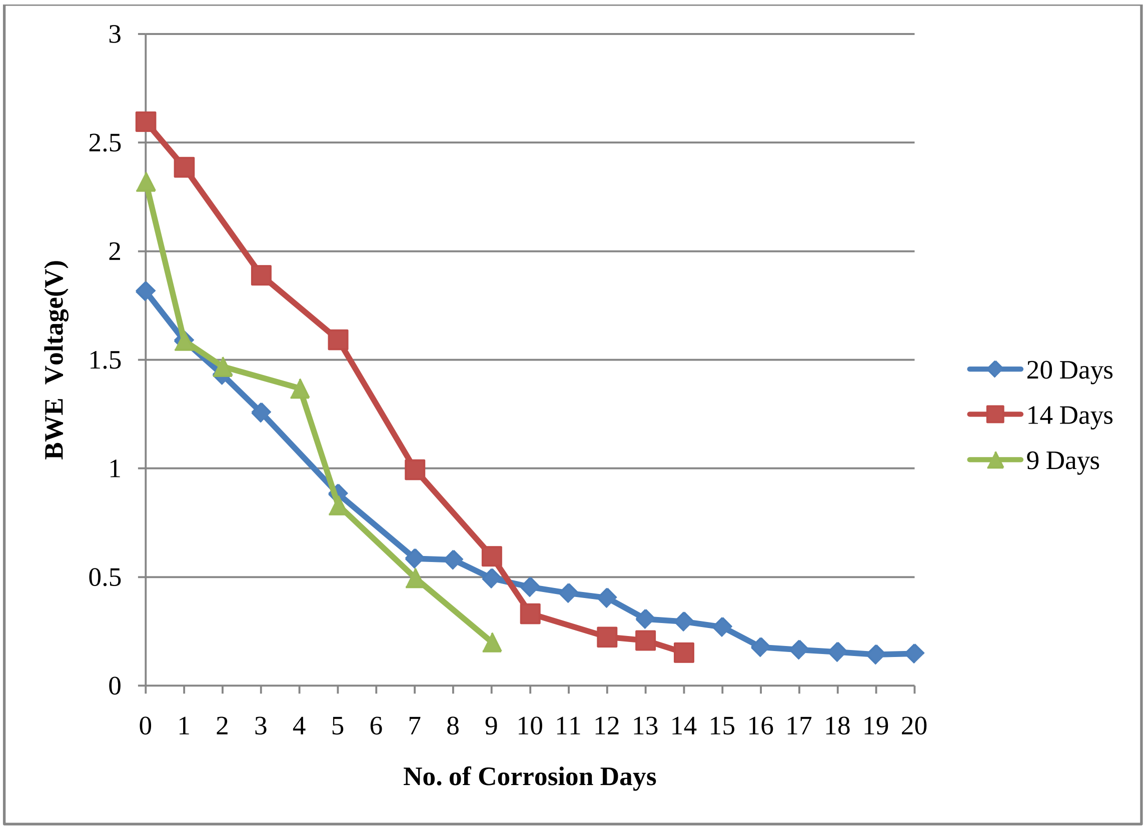

Fig. 5.9 a) BWE voltage vs. No. of days of corrosion for 1 MHz

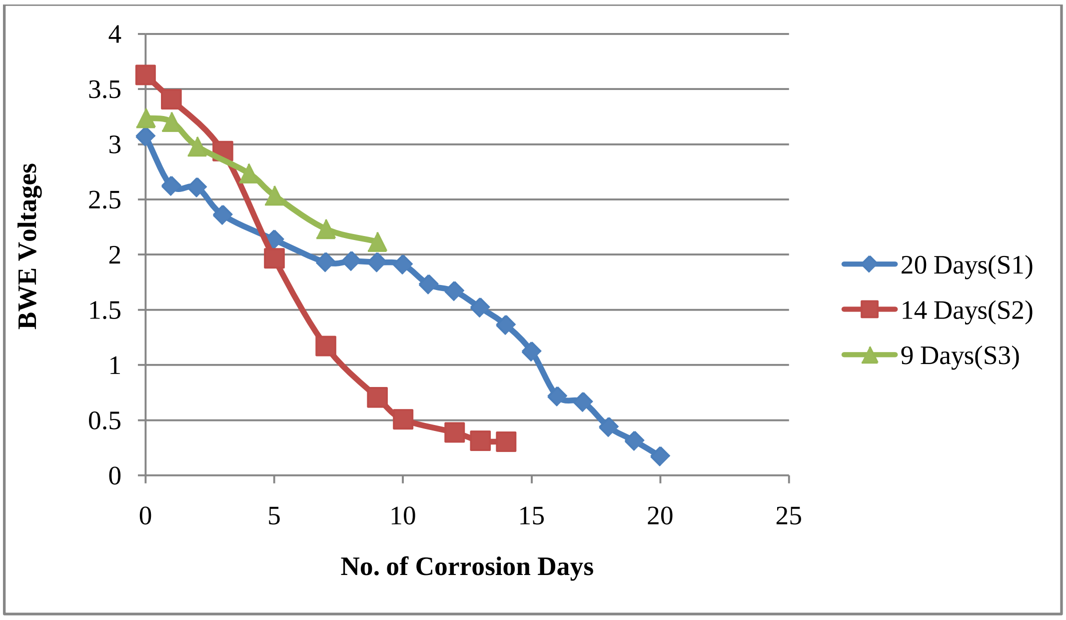

Fig. 5.9 b) BWE voltage vs. No. of days of corrosion for 2 MHz

From ultrasonic signatures of 12 mm Bar of 1MHz and 2 MHz frequency following observations were made:

As the number of days of corrosion increases, BWE voltage decreases for both 1MHz and 2 MHz frequency. **Fig. 5.9** show BWE voltage drops as number of corrosion day increase. Thus, it can be concluded that ultrasonic can pick up degradation due to corrosion.

Ultrasonic Signatures and Results for 25 mm Bar

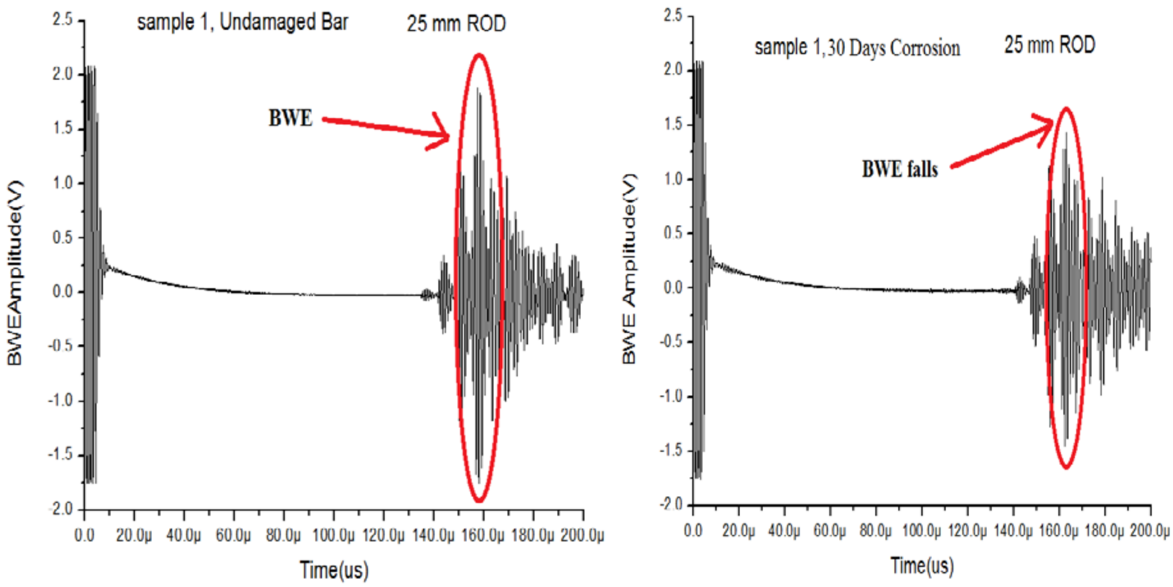

Fig. 5.10 Pulse echo through 25mm Dia. Rod a) Healthy b) 30 Days Corrosion at 1 MHz frequency

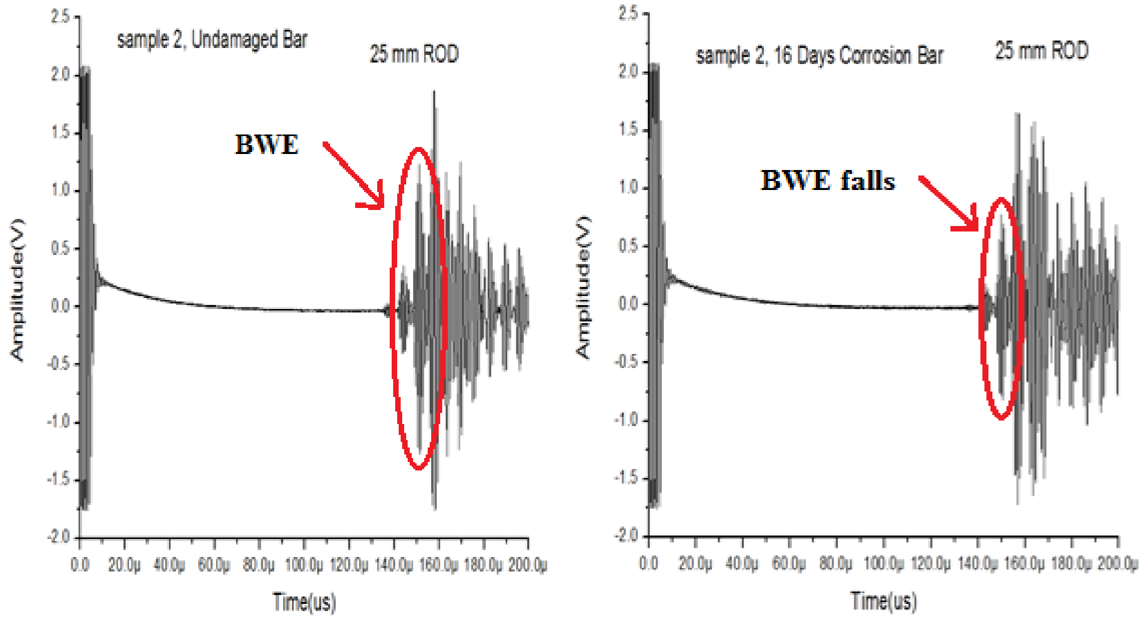

Fig. 5.11 Pulse echo through 25mm Dia. Rod a) Healthy b) 16 Days Corrosion at 1 MHz frequency

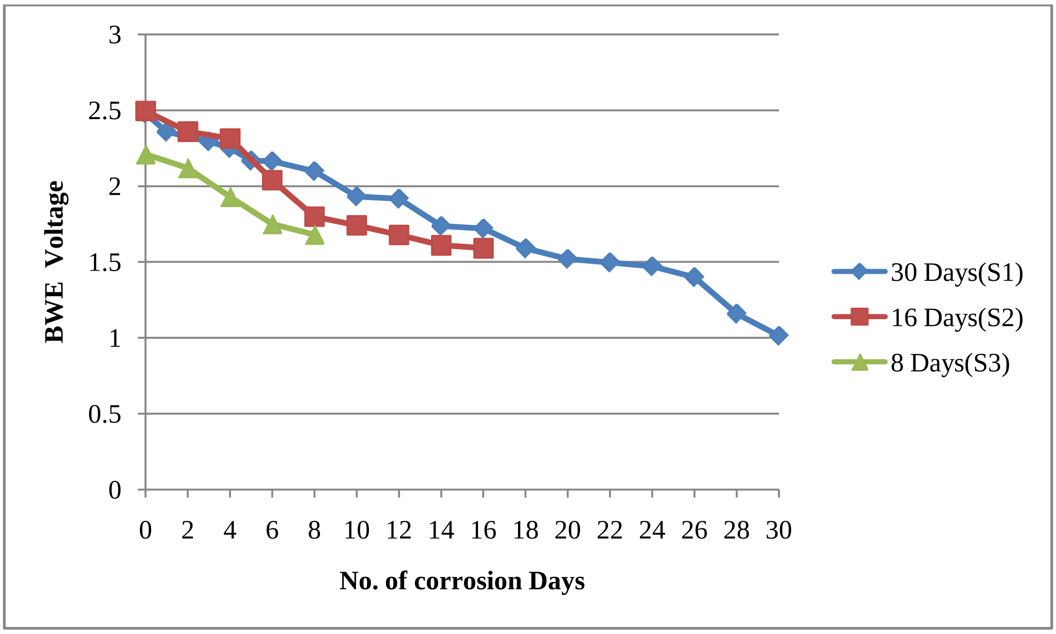

Fig. 5.12 BWE voltage vs. No. of Corrosion Days for 25 mm bar

From ultrasonic signatures of 25 mm Bar of 1MHz and 2 MHz frequency following observations were made:

As the number of days of corrosion increases, BWE voltage decreases for 1MHz frequency. **Fig. 5.12** show BWE voltage drops as number of corrosion day increase. Hence Ultrasonic Testing Technique can be applied for pick up degradation due to corrosion in bars.

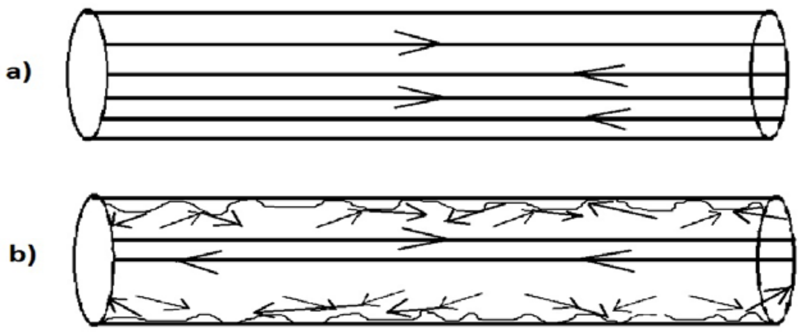

Fig. 5.13 Effect of corrosion on guided wave: (a) undamaged bar, (b) corroded bar [20]

The reason for BWE fall can be explained below:

In healthy rod, the diameter is uniform throughout the length. Thus, a smooth waveguide forms. As the bar corrodes, the diameter of bar reduces due to dissolution of metal irregularly. Thus, the waveguide is disturbed and scattering take place from rough surface. This cause drops in received BWE voltage.

5.4 Correlation of Corrosion Loss with Ultrasonic

To correlate corrosion, percentage weight loss of specimen with ultrasonic voltage, graph between percentage weight loss and number of corrosion days plotted and further an attempt has made to correlate with BWE voltage. **Fig. 5.14** shows various corroded specimens for different number of days of corrosion. **Fig. 5.15** shows specimen S1 before and after corrosion.

Fig. 5.14 Corroded Rods having different number of days of corrosion

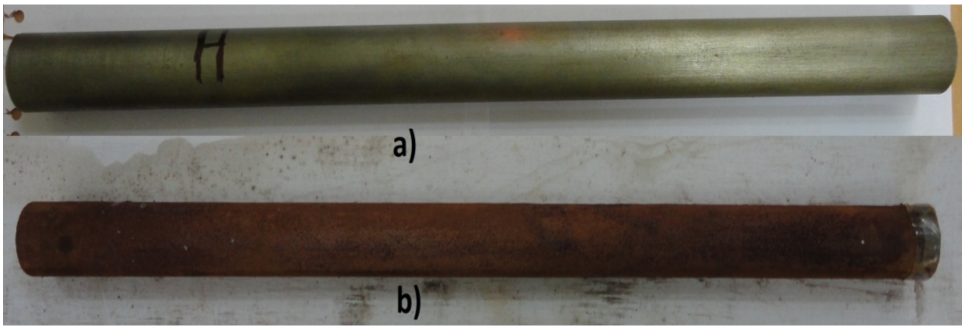

Fig. 5.15 specimen S1(25 mm bar) a) Healthy b) 30 Days corroded

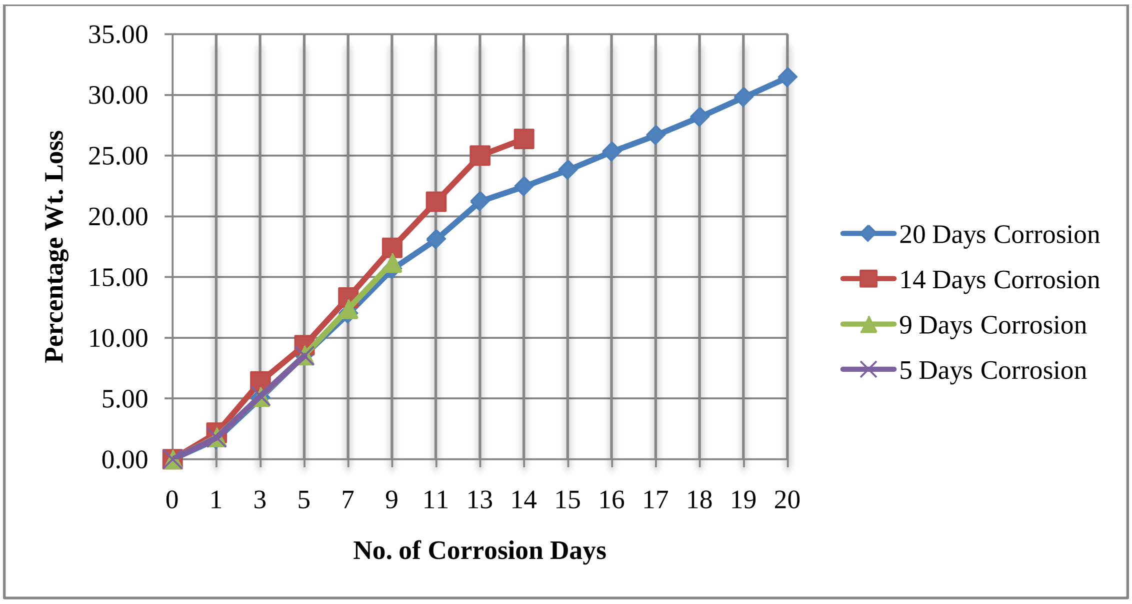

Fig. 5.16 Percentage Weight Loss vs. Number of Corrosion Days for 12 mm rod

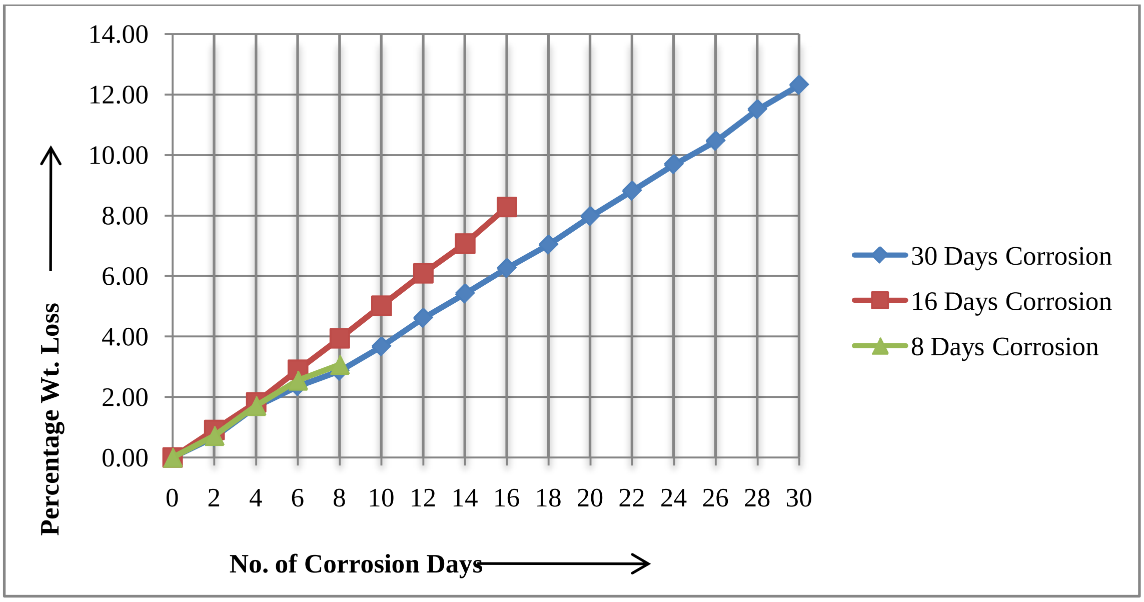

Fig. 5.17 Percentage Weight Loss vs. Number of Corrosion Days for 25 mm rod

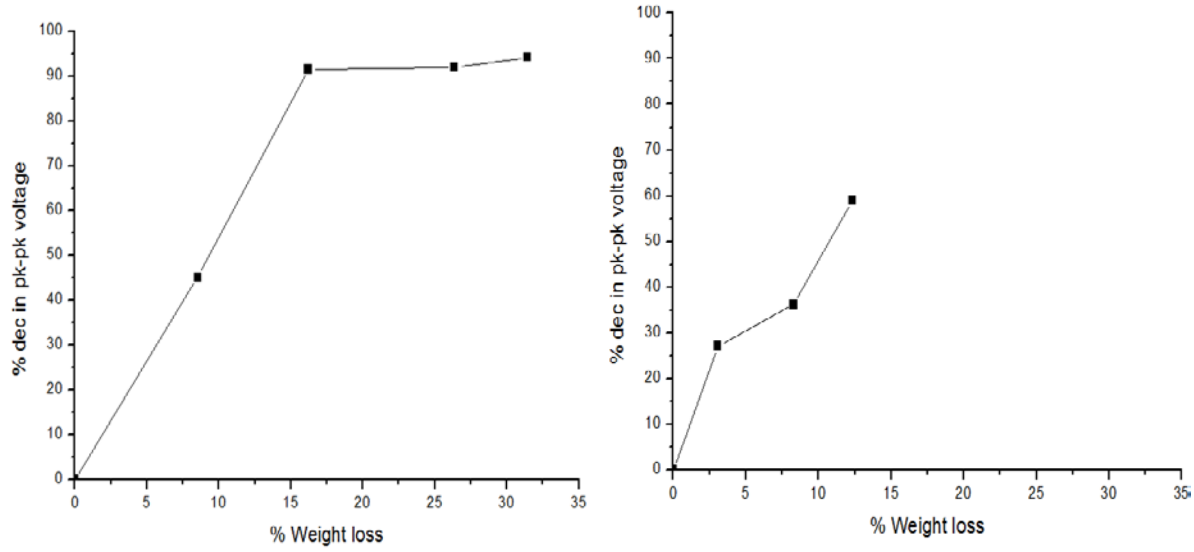

Fig. 5.18 Percentage decrease in peak to peak ultrasonic voltage and percentage weight loss a) for 12mm Dia. rod b) for 25 mm bar

From **Fig. 5.16** and **Fig. 5.17** shows that as the number of days of corrosion increase, the percent weight loss increases for both 12 mm and 25 mm rods. **Fig.5.18** a) and b) shows as the weight loss increases, BWE voltage decreases.

From the **Fig.5.16**, **Fig. 5.17** and **Fig. 5.18** following observations were made

1) As the number of days of corrosion for a specimen increases, percentage weight loss of the specimen also increases. This observation for all the specimens is same.
2) As the percentage weight loss of the specimen increases, percentage decrease in BWE voltage also increase.

5.5 Destructive Testing and Results

To establish a correlation between ultrasonic voltages and a destructive parameter, destructive testing has been done on rods of different number of days corroded and tensile testing was chosen. First healthy rod was subjected to tensile testing in UTM shown in Chapter 4 and ultimate tensile load was calculated. Then rest of rods having different no. of days of corrosion are subjected to tensile load and results are shown in **Table 5.2**. Tensile testing was performed on 12 mm and 25 mm diameter rods.

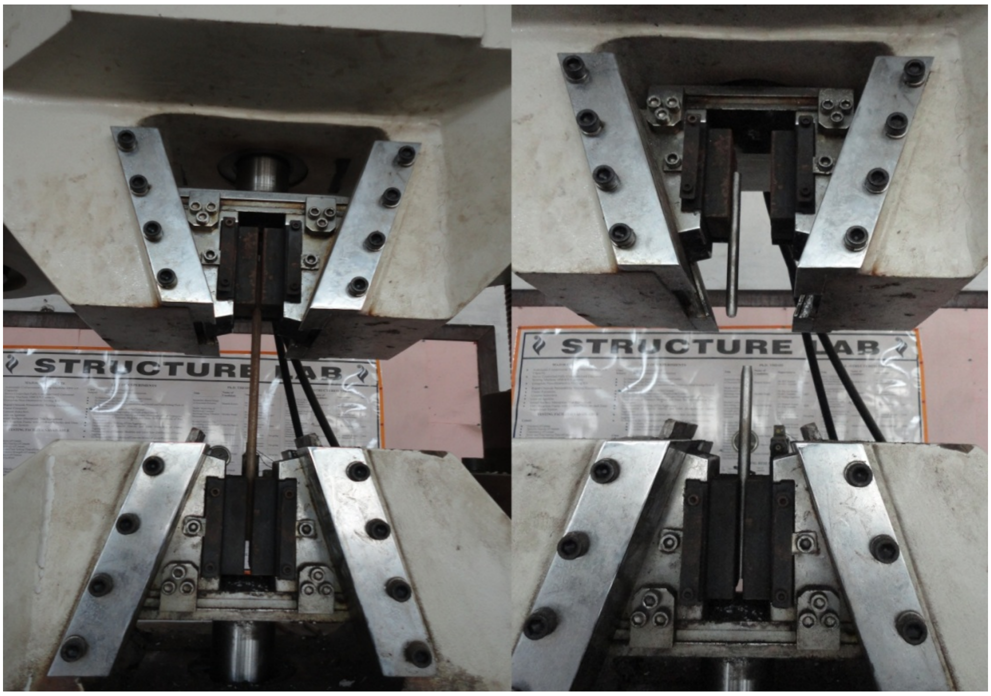

Fig. 5.19 1) Gripped Specimen 2) Destructed Specimen in UTM during Tensile Testing

Table 5.2 Tensile Test Results

12 mm Diameter Rod Tensile Test Results			
Specimen No.	**No. of Corrosion Days**	**Tensile Load (kN)**	**Tensile Strength(N/mm^2)**
S5	0	90.240	199.57
S4	5	79.995	176.91
S3	9	74.170	164.03
S2	14	68.360	151.18
S1	20	63.460	140.34
25 mm Diameter Rod Tensile Test Results			
Specimen No.	**No. of Corrosion Days**	**Tensile Load (kN)**	**Tensile Strength(N/mm^2)**
S4	0	313.245	159.61
S3	8	298.445	152.07
S2	16	286.370	145.92
S1	30	260.000	132.48

Table 5.2 shows the tensile strength of all corroded specimens to failure. From the table following observations were made

1) It is observed that as number of days of corrosion increases, the ultimate tensile strength falls. This observation is true for both 12 mm and 25 mm diameter rods as shown in **Fig. 5.20** for 12 mm and **Fig. 5.21** for 25 mm.
2) A correlation between BWE amplitude and tensile strength is attempted and as shown in **Fig. 5.22** a) for 12 mm rod and b) for 25mm rod.

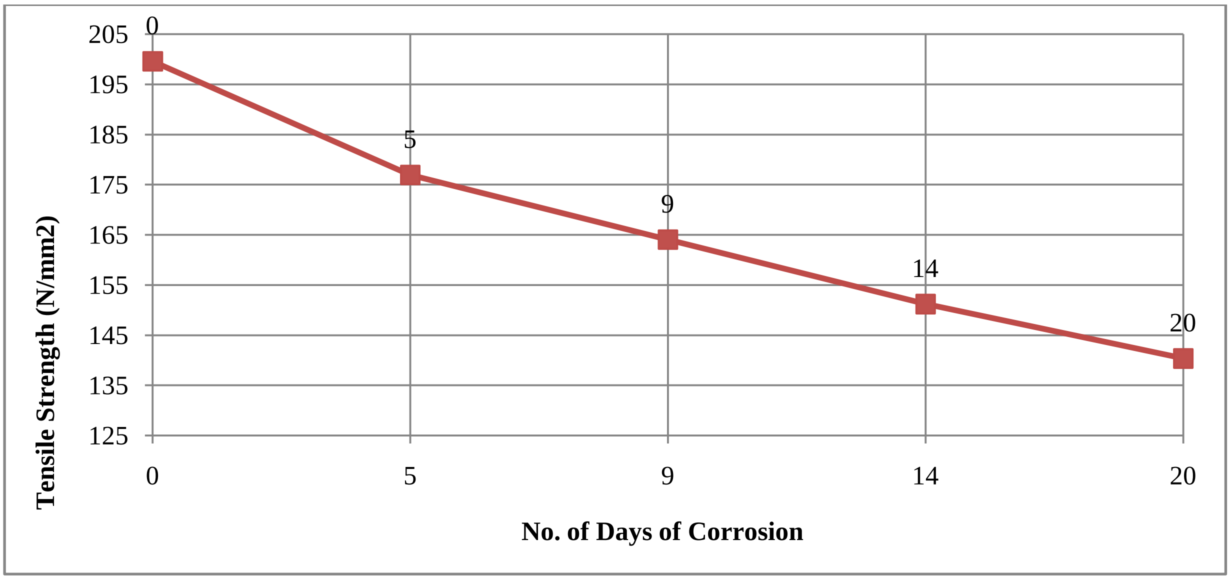

Fig. 5.20 Tensile Strength vs. No. of Corrosion Days for 12 mm Diameter Rod

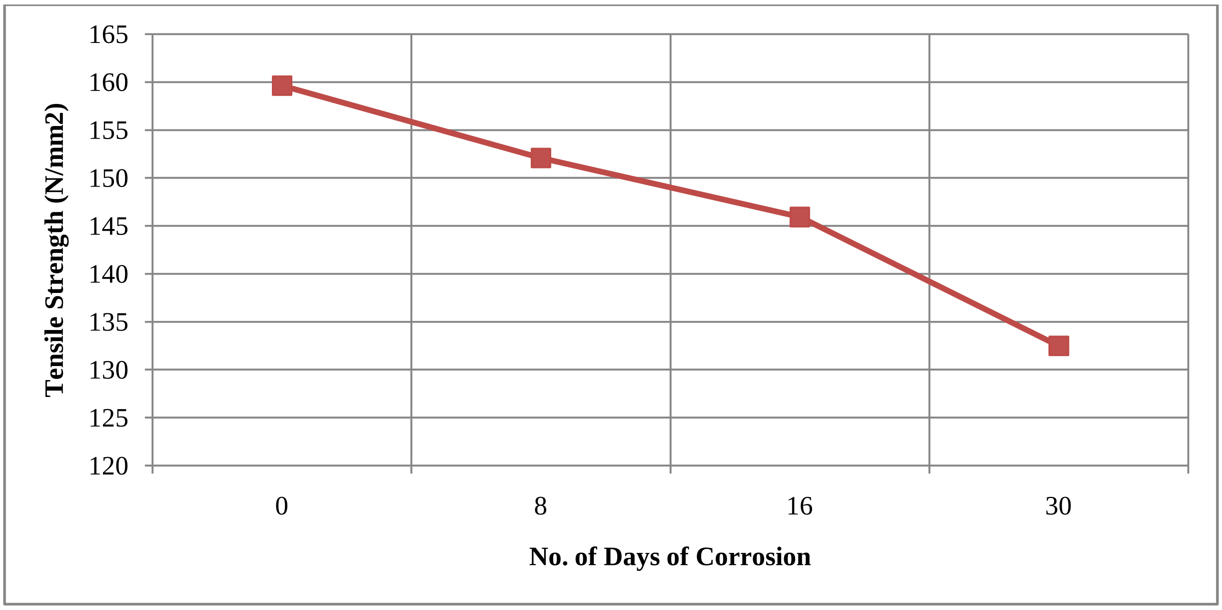

Fig. 5.21 Tensile Strength vs. No. of Corrosion Days for 25 mm Diameter Rod

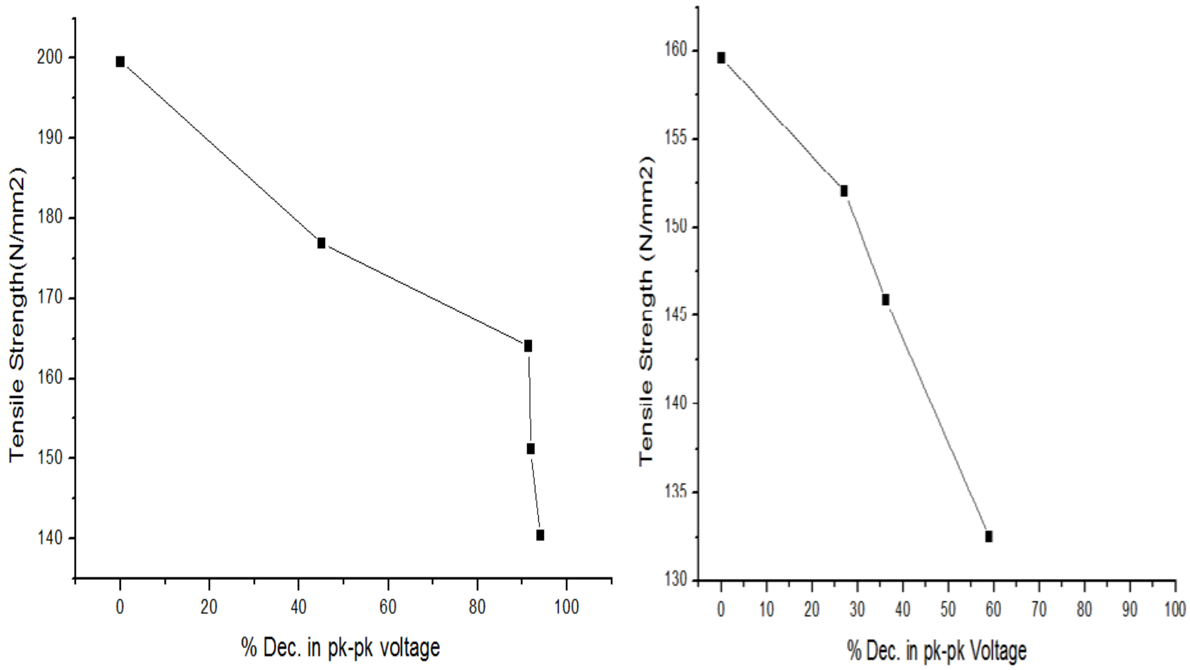

Fig. 5.22 Tensile Strength vs. Percentage Decrease in Ultrasonic Voltage a) for 12 mm dia. rod b) for 25 mm rod

5.6 Closing Remarks

From the experimental ultrasonic and destructive investigation, it can be concluded that UGW can be used as damage detection tool for picking up corrosion damage. Successful correlation between PE amplitude, percentage of weight loss and in-situ strength in the form of Tensile strength can be established. Thus guided waves can be successful be used for damages in bar due to corrosion.

Chapter 6 Conclusions

Conclusions from Torsion Study

From the experimental ultrasonic and destructive investigation, it can be concluded that

- Ultrasonic guided wave can be used as damage detection tool for picking up torsion damage.
- Successful correlation between angle of twist, pulse echo amplitude and in-situ strength in the form of tensile strength has been successfully established.
- Guided waves can be successfully be used for damages in bars due to torsion.

Conclusion from Corrosion Study

From the experimental and destructive testing, following conclusions were made

- Ultrasonic damage detection technique can successfully be applied for the detection of corrosion damages in steel bars.
- Successful correlation between BWE voltage, weight loss and in-situ strength has been established.

Future Scope of Work

The area of non destructive testing and damage detection constitutes the extremely important and challenging area of study where wave propagation provides an efficient means of characterizing defects in structures. As the topic of wave propagation is very wide spread and has utilities in many areas of human endeavour, there is much scope for future work.
The experimentation carried out can be extended for:

- To detect effect of excessive loads on bars or shafts.
- To detect effect of both corrosion and torsion on bars simultaneously using Ultrasonic Guided Waves.
- Damage detection in bar subjected to dynamic loads.
- Detection of fatigue cracks in bars.
- Embedded pipes inspections.

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