

DISSERTATION

On

Monitoring Degradation in Concrete Filled Steel Tubular Section Using Guided Waves

Submitted in partial fulfilment of the requirement for the award of degree

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IN

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Submitted by

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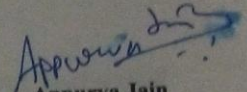
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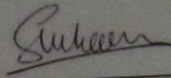
DECLARATION

I hereby declare that work done in this dissertation report entitled, "**Monitoring Degradation in Concrete Filled Steel Tubular Section Using Guided Waves**" submitted towards partial fulfilment of requirement for award of Master of Engineering degree in CAD/CAM Engineering in Mechanical Engineering Department of Thapar University, Patiala, is an authentic record of work carried out by me under the supervision and guidance of **Dr. Sandeep Kumar Sharma**, Assistant Professor of Mechanical Engineering Department, Thapar University, Patiala.

This 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.


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



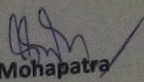
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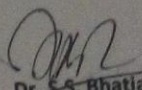
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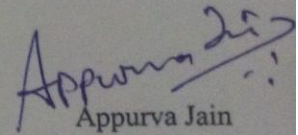
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ABSTRACT

Concrete filled steel tubes are extensively applied in engineering structures due to their resistance to high tensile and compressive load and convenience in construction. But one major flaw, their vulnerability to environmental attack, can severely reduce the strength and life of these structures. Degradation due to corrosion of steel confining the concrete is one of the major durability problems faced by engineers to maintain these structures. The problem accelerates as inner surface of steel tube is in contact with concrete which serves as electrolyte. If it remains unnoticed, it further accelerates and can be catastrophic. This work presents a non-destructive degradation monitoring technique for early detection corrosion in steel tubes in CFST members. Due to corrosion, damage in the form of debonding and pitting occurs in steel sections. Guided ultrasonic waves have been used for the detection and monitoring of corrosion damages in CFST sections. Guided waves have been utilized to monitor the effect of notch and debond defects in concrete filled steel tubes simulating pitting and delamination of steel tubes from surrounding concrete caused by corrosion. Pulse transmission has been used to monitor the healthy and simulated damaged specimens. A methodology is developed and successfully applied for the monitoring of concrete filled steel tubular sections undergoing accelerated chloride corrosion. The ultrasonic signals efficiently narrate the state of steel tube undergoing corrosion.

LIST OF ACRONYMS

DOF	Degree Of Freedom
DPR	Defect Reflection Peak
DRO	Digit Read Out
ML	Mass Loss
NDE	Non-Destructive Evaluation
PC	Pitch Catch
PE	Pulse Echo
PT	Pulse Transmission
SHM	Structural Health Monitoring

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CHAPTER 1

INTRODUCTION

1.1 BACKGROUND AND MOTIVATION

Concrete-filled steel tubular (CFST) structures have been progressively utilized as a part of elevated structures, spans, and other modern structures in view of their great seismic execution for example, high quality, high pliability, and huge vitality ingestion capacities. On account of their fabulous mechanical conduct and advantageous development process, steel- concrete composite frames have gained wide popularity in the modern building industry. They also exhibit good hysteresis under cyclic loading. Application of the CFST idea can prompt general investment funds of steel in correlation with routine basic steel structures [1]. The steel and the concrete element in a composite member provide structural strength which complements each other ideally.

In present practice with CFST concrete filled steel tubes, the member's individuals are normally steel supports acting with profiled steel sheeting or pre-cast partial thickness composite sections [2]. The vertical members planned for lateral load-resisting systems are generally divided into four categories as shown in **figure 1.1**:

- (i) The encased composite column
- (ii) The concrete-filled steel tubular (CFST) column.
- (iii) Reinforced concrete filled tubular steel (RCFT).
- (iv) Double skinned concrete-filled steel tubular (CFST) column [3].

Steel tube of CFST a member act as a permanent and integral formwork and supports several levels of construction proceeding to concrete being poured. It also provides external reinforcement and stiffness and higher strength compare to RC sections of the same materials properties. The main advantage of concrete is that it reduces the local buckling of the tube wall and the concrete itself. Composite members also used for the resisting outside pressure, in

seismic regions due to their excellence in earthquake-resistant properties like high strength, high ductility, and high energy absorption capacity. The beneficial composite action of these CFST members requires force transfer between the steel tube and the core concrete. The quality of concrete pumping and pouring, the change of temperature, the shrinkage and creep of the mass concrete core and so on may induce the interfacial debonding defect between the steel and inner concrete core of CFST. The interfacial debonding defect can weaken the confinement effect of steel tube on the concrete core resulting into the loss of load-carrying capacity and in the ductility of the CFST under earthquake and cyclic loadings. Unfortunately, such debonding damage and the voids cannot be visually identified. Actually, these are almost unavoidable in CFST structures but such damages are most unfavorable [4]. The second major flaw of structures made of CFST sections is their vulnerability to environmental attack. It can severely reduce the strength and life of these structures. Corrosion of steel confining the concrete is one of the major durability problems to maintain aging CFST structures. The problem accelerates since the inner surface of the steel tube is in contact with concrete which serves as an electrolyte for the initiation of corrosion. If the corrosion ingress starts, it further accelerates and can be catastrophic for the structures as it results in huge loss of life and property. The increased volume of the corrosion products induces stresses in the concrete that result in cracking and delamination of steel tube from the in filled concrete. As a result, it weakens the structure to a high degree. Also corrosion due to chloride ingress results in the occurrence of pits in the steel tube which reduce the cross-sectional area of tube drastically and can be catastrophic [5].

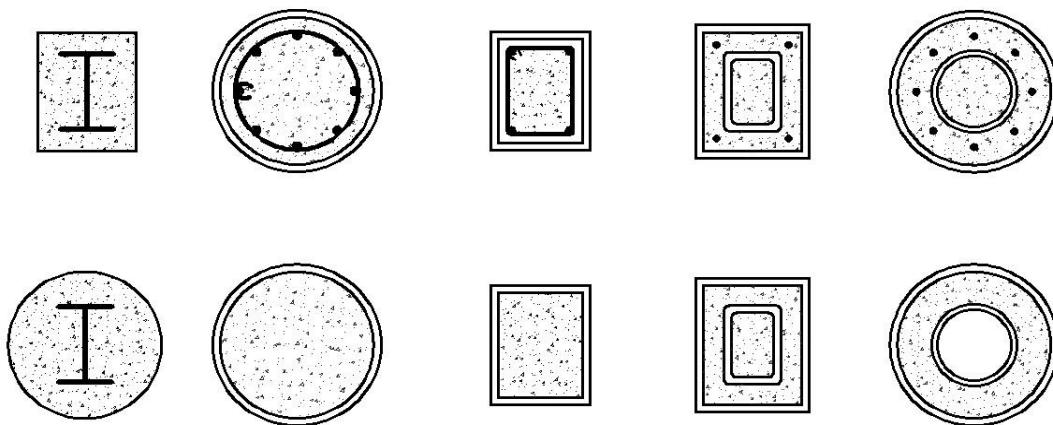


Figure 1.1: Composite Steel and Concrete columns

An extensive variety of systems has been accounted that might be appropriately utilized for the checking of consumption of steel in solid structures for evaluating the cause and degree of the corrosion. Be that as it may, the majority of the systems are electrochemical strategies which relate corrosion rate and degree through assessment on encompassing solid medium. None of the procedures concentrate on consumption observing through direct estimations on steel tube. The degradation due to corrosion accelerates and can be catastrophic unless early remedial action is taken. Therefore, it is necessary to develop a non intrusive technique for early detection of damages in the form of cracks, debonds and corrosion in steel tubes in CFST members [6].

1.2 DAMAGE/CORROSION MONITORING METHODOLOGIES

A in-situ and real-time health monitoring of specimen assemblies as in a case of concrete filled steel tube and other components for damage like cracks, dents and corrosion are very important to avoid any compromise to the integrity of these structures. Various non-destructive techniques to assess in- service damages and corrosion in concrete filled steel tube are listed below:

- Visual inspection
- Magnetic particle inspection
- Magnetic flux leakage technique
- Eddy current
- Pressure testing
- Magnetic resonance imagery
- Laser interferometer
- Acoustic emission technique
- Penetrating gamma and X-rays
- Thermographic imaging or time-resolved thermography
- Holographic interferometry
- Sensors such as galvanic thin film, electrochemical sensors, chemical sensor etc.

Hence, there is a need to develop a non-destructive damage monitoring technique for specimen in corroded conditions typically for corrosion induced damages that can replace or supplement the prevalent techniques. Present work is an attempt to develop a complete damage monitoring methodology for concrete filled steel tube structures using ultrasonic guided waves.

1.3 ULTRASONIC WAVES- A IMPENDING SOLUTION

Currently used methods for non-destructive testing and damage evaluation of concrete filled steel tube assemblies as discussed above are indirect indicators of the likelihood of damage or corrosion. These cannot be used for large structure either due to scale up problems or huge costs associated with their implantation and maintenance. Corrosion, if been accounted for in the inscription that might be appropriately utilized for observing of consumption in a common structure for diagnosing the cause and degree of consumption. But all these techniques suffer from various practical limitations. Therefore, it is imperative to develop a non-intrusive and a non-contact technique for monitoring state of health of CFST forming civil infrastructures.

Ultrasonic bulk waves have been used in the past as an effective method to monitor the health of various kinds of structures. Bulk wave's travel within the interior of a material away from any boundaries, exhibits a finite number of wave modes and have small wavelengths compared to the dimensions of the object being inspected. The state of health of structure is judged on the basis of parameters like transmission amplitudes, traveling time, and attenuation of received signals. Time of flight can also be used to locate the damage and quantify the amplitude of the reflected signal so as to assess the severity of the damage. But the bulk waves have limited scanning capabilities which are mainly attributed to a rapid loss of energy due to bulk material attenuation. Guided waves have come up as a promising option for effective and reliable monitoring of relatively larger domains. Guided waves exhibit solid entrance, quick spread, omnidirectional dispersal, an accommodation of enactment and securing, reasonable execution and in particular, high affect ability to auxiliary harm and material in-homogeneity notwithstanding when they are little in size or lie underneath the surface.. Due to these unique propagation characteristics, guided waves have been effectively used for damage detection in a variety of applications, involving plate, pipe and rod geometries. In most of these applications, the subject structure is placed in air and transducers are required to be in direct contact with the structure being monitored.

Guided waves in plates called lamb waves can be predominantly excited (while subduing other modes) by offering the longitudinal incident ultrasonic wave obliquely to the plate at a particular angle of incidence. This can be accomplished by using- 'Variable angle' and

‘Immersion Coupling’. Former technique is a contact type arrangement, in which a variable angle probe riding on lateral surface of a Perspex semi-cylinder transmits energy into the subject plate. Perspex block is coupled to the CFST by a thin layer of gel. But this contact system is not suitable for structure applications. Moreover, measurements are unreliable mainly due to the inadvertent variations in the contact pressure and couplant thickness. Owing to the several practical limitations in direct contact approach and to exploit mode-specific behavior of Lamb waves to advantage, some researchers have suggested using immersion coupling by employing local water column as an effective means to couple the structure with the transducer. However, in a case of CFST structure, presence of water makes the situation unique and challenging as it acts as a natural couplant. A quick, in-situ and noncontact health monitoring methodology for real-time damage assessment of concrete filled steel tube structure is not reported.

Present work is focused on developing a non-contact inspection technique utilizing ultrasonic guided waves for damage monitoring in CFST. The proposed technique has the potential to develop into real-time health monitoring and evaluation tool for CFST structure. A pair of mobile transducers placed in ‘pitch-catch’ orientation employing Immersion coupling has been used. The surrounding water acts as a carrier of incident ultrasonic energy from a probe to the plate. In order to excite a specific lamb wave mode, a transmitter probe inclined at a specific angle injects incident energy in the plate. The receiver is also placed in the same orientation as the transmitter. It makes the receiver most sensitive to the wavelength of the mode being input. It results in the highlighting the preferred mode and suppressing the others. This setup has been used to generate and acquire the propagating guided lamb wave through the healthy CFST. CFST. Subsequently, plates with damages in the form of machined notches of varying depths inflicted on them have been tested. Specific lamb wave modes sensitive to near surface and sub-surface damages have been identified. Experimental data captured using pulse transmission techniques has been used effectively in combination to identify, locate and quantify the various kinds of notch damages oriented in a different configuration, i.e. notches, notches of varying depths etc.

1.4 AIMS AND OBJECTIVE

The aim of present work is to develop a damage monitoring methodology for CFST as in civil structure using guided wave propagation. The developed technique should detect, localize

and finally quantify the extent of deterioration in CFST structures. A large number of specimens must be investigated with different amounts and rates of damage, different depths and locations of damages etc. and characterization of the same need to be done. Hence, objective of present work can be outlined as:-

- Investigation of propagation of guided lamb waves through healthy and damaged submerged plate specimen.
- Map the wave signature with the defects.
- Determination of sensitivity of waves to typical damages
- Post-processing of the data to develop defect maps
- Application of the developed methodology to plates undergoing corrosion
- Calibration of the ultrasonic signals with physical parameters and development of semi-empirical relationships.
- Recommend a non-invasive, noncontact and in-situ damage monitoring methodology for CFST sections.

1.5 LAYOUT OF THESIS

Form the study carried out in this work, the thesis is organized in the following chapters:

In **Chapter 1**, the significance and need for a non-invasive and in-situ damage monitoring technique for CFST structure assemblies is established by highlighting the drawbacks of the existing methods and introduction to ultrasonic guided waves is established.

Chapter 2, bring out the review of the latest works done till date in the use of Lamb waves for damage detection in CFST structures and corrosion monitoring in the structures have been compiled.

A detailed non-invasive and non-contact experimental set-up is developed for generation and propagation of guided waves in CFST structures and the experimental study on propagation characteristics of various ultrasonic guided wave modes in CFST structure is presented in **Chapter 4**.

Chapter 3 highlights the theory and background of ultrasonic guided waves in CFST structures called Lamb waves and discusses the key issues in the use of Lamb waves for damage detection

in infrastructures.

The investigated Lamb wave modes in CFST structure are utilized for damage detection using pulse transmission method of ultrasonic testing. The damages are inflicted in form of machined notches in the CFST structures and typical modes sensitive to surface and sub-surface damages are identified to develop a defect detection strategy in the CFST structures in **Chapter 5**.

In **Chapter 6**, damage detection methodology developed above is extended to CFST structures undergoing accelerated corrosion. Ultrasonic nondestructive testing data is calibrated with the destructive test parameters of flexural rigidity to facilitate correlation between compressive strength and rate of corrosion.

Chapter 7 summarizes the entire work and conclusions derived from the study are reported. Future scope of the work in the area is also highlighted.

CHAPTER 2

REVIEW OF LITERATURE

2.1 GENERAL

There is a developing pattern of the utilization of ultrasonic guided waves for damage identification in common, mechanical, off-shore and marine foundations. This part introduces a brief discussion of using guided waves for damage observing in CFST structures utilized as a part of different sorts of structures.

2.2 GUIDED WAVES FOR DAMAGE DETECTION IN CFST

Concrete filled steel tubular (CFST) column is an effective way to improve structural properties of concrete. Base on the accomplishment and exploration on the concrete filled steel tube (CFST), with four perspectives: research on major auxiliary conduct, dynamic property, holding hypothesis of interface and damage examination on the concrete filled square steel tube. It is well-accepted that the concrete filling is confined and protected by the steel tube enclosure, resulting in a tri-axial compression state that increases the compressive quality and twisting limit of the solid, whereas the concrete filling will prevents local buckling of the steel tube.

Cawley and Alleyne (1996) emphasized the importance of lamb wave for quick inspection of large structures. Authors discussed main limitation of lamb wave inspection like, multimode behavior and dispersive nature resulting into complicated received signals. Authors suggested appropriate choice of frequency-thickness range of exciting Lamb waves. The paper discussed the selection of an appropriate mode, its excitation and reception for detection of delaminations in composite materials and corrosion in pipes.

Hanagud et al. (1997) studied the effect of defects, impact damages and delamination on the structural dynamics characteristics of composite beams. Authors demonstrated that annoyances in natural frequency and mode of a bar, because of defects, can be utilized for health monitoring of structures.

Dalton et al. (2001) investigated the potential of guided waves for monitoring large areas

of metallic aircraft fuselage structures. The potential for long-range propagation of ultrasonic guided waves through metallic aircraft fuselage structure was investigated using dispersion analysis and numerical modeling, validated by experiments.

Schneider et al. (2004) done a trial and diagnostic study on the conduct of short concrete filled steel tube sections concentrically stacked in pressure to failure. Extreme quality results were figure to current detail supervision for the configuration of concrete filled steel tubular short segments. Nonlinear limited component model were create and confirming utilizing exploratory result. The systematic models were further used to research the obtained outline of a particular sample. Author also compared the results with the results obtained using different design codes. Tests were also conducted on 14 specimen tests under concentric axial load. d/t ratio in this study ranged from 17 to 50 . A solidify end top was joined at the base of all steel tube. Concrete was put in five layers.

Finally, the authors conclude that circular steel tube offers much more post yield axial ductility than the square and rectangular one. Measured parameter to longitudinal strains of steel tube suggests significant confinement is not present for most specimens until the axial load reaches almost. Local wall buckling for the circular occurred at an axial ductility of 10 or more where at 2 and 8 for square and rectangular one. They have observed that for small size CFST columns having smaller D/t ratio providing a significant increase in yield load compared to code.

Fam et al. (2005) Authors conducted a trial work and logical displaying for concrete filled steel tubes (CFSTs) subjected to concentric hub pressure and consolidated hub pressure and sidelong cyclic stacking. The target of the study is to assess the quality and pliability of CFST short segments and bar segment individuals under various bond and end stacking conditions. Both equipped and unbounded samples were tried, including utilization of the essential load to the composite steel-solid area and to the solid center as it were. Test results were contrasted and the accessible configuration determinations, which were observed to be moderate. The paper additionally shows an explanatory model fit for anticipating the flexural and hub load quality of CFST individuals. Test results were observed to be in great concurrence with the anticipated qualities.

Study with bounded and non-bounded specimen was the unique experiment of this paper. This brought out some interesting result that the bond and end stacking conditions did not influence the flexural quality of specimen segment individuals altogether. Then again, the

fundamental quality of the unbounded short segments was marginally expanded, contrasted with those of the reinforced ones, while the firmness of the unbounded examples was somewhat diminished.

Vesmawala et al. (2008) applied modal curvature to various beam models. And numerical method is used to demonstrate the effectiveness in locating single and multiple damage. The difference between various curvatures and mode shape of intact and the damaged beam increases in the damage severity. These methods are based on alter with dynamic characteristics of damage in the structure.

Hanagud et al. (2009) emphasized analytical expression of a damage measure which relates the strain energy, to point out damage location and magnitude. The strain energy was calculated using modes and natural frequencies of damaged beams. Authors have done a different examination to check derived analytical expression for notch like non-spreading cracks with subjective boundary conditions.

Poddar et al. (2011) experimentally studied application of time reversibility of a Lamb wave for standard free damage detection in aluminum plate where in reconstruction of the original signal at the receiver and presence of damage in the path of the signal was ascertained by observing the change in reconstructed signal. Authors used PZT wafer transducers to explore the effect of frequency, pulse frequency band width, transducer size and the influence of tuning these parameters on the quality of a reconstructed of input signals for enhanced damage sensitivity. Time reversal process (TRP) was also implemented to detect various defects like block mass, notch and surface corrosion in an aluminum plate and these defects could be effectively discerned by quantification of reconstructed signals.

Leleux et al. (2013) used a low frequency, multi-element matrix probe driven by phased array principle for exciting and capturing pure Lamb wave modes in large plates. Selected modes propagating were launched and detected in specific directions for which phase and group velocities are collinear. Authors experimentally evaluated the directivity of the launched guided beams and the possibility of detecting, locating and sizing acoustic sources like placed at various positions around a receiving probes. Defects like 3D shaped delamination, impact damages in composites plates and corrosion-like defects in metallic plates were detected using the proposed setup prototype.

In case of CFST structures, In-situ damage monitoring is unique and challenging task.

Prominent works regarding the application of guided waves for monitoring structures (O). Although considerable progress has been made in understanding the propagation of ultrasonic Lamb wave modes sensitive to different kinds of damages and corrosion need to be identified. The technology needs to demonstrate in structures undergoing in progressive corrosion. Moreover, the ultrasonic readings must be calibrated with actual degradations for predicting residual strength. The objective of the present work is to study the propagation of ultrasonic guided waves through a CFST structure and develop a non-invasive, in-situ damage monitoring methodology.

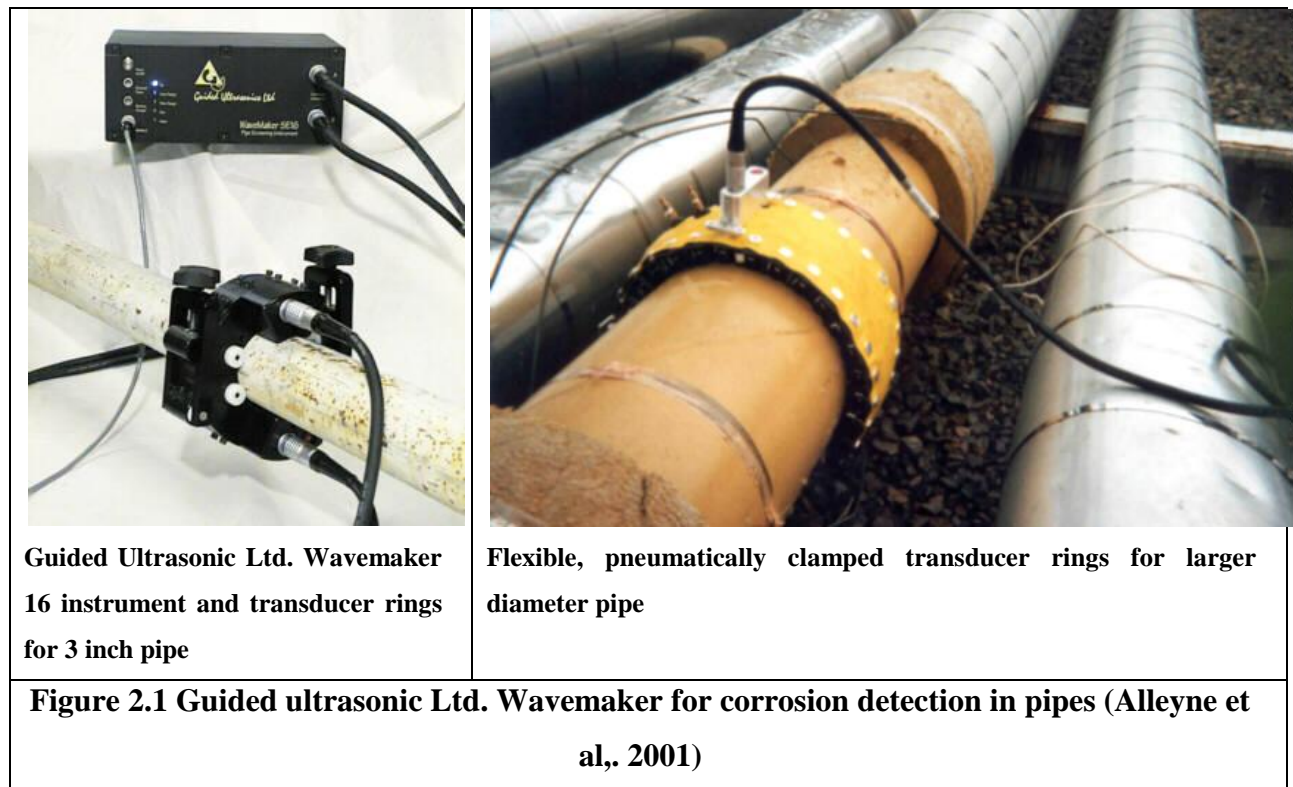
2.3 GUIDED WAVES FOR CORROSION MONITORING:

Corrosion in civil infrastructure is particularly challenging mainly due to factors viz; limited access for monitoring, relatively higher cost of corrosion damage and associated risk to human life and property. A variety of techniques has been developed and implemented to detect corrosion in civil structures. A lot of research effort is still on to develop an automatic system for data acquisition and interpretation for evaluating the health of the civil structure. Use of ultrasonic guided waves is one of the promising options that provide good penetration power as guided waves have long propagation distance. Some of the latest works related to application of guided waves detection of corrosion are presented below:

Lowe et al. (1998) use guided waves for corrosion detection in insulated pipes in chemical and oil industry. Presented method replaced the current practice of point by point investigations which necessitated removal of protective insulation at each point of testing. Authors used propagation of ultrasonic guided waves in pipe walls using pulse-echo configuration. Access to the pipe surface was provided by removing insulation at just one location. Signals were then transmitted and reflections from received using a single transducer unit. This work mainly focused on a selection of the optimum guided wave modes and the formulating the relationships between the reflection signal amplitude vis-à-vis the defect size. Dry coupled piezoelectric patches distributed around the circumference of a ring were employed to generate and receive an axially symmetric mode. Arrival times of reflections reveal the presence and axial location of defects. Authors reported that a span of 50-meter pipe length could be done in one setup. A key feature of this work was a generation of a selected single mode despite the possibility of a number of other modes within the used frequency

bandwidth. The reflection coefficient of L(0,2) and F(1,3) reflections from defects for any combination of a circumferential and radial extent and it was generalized for pipes of other sizes.

Alleyne et al. (2001) addressed the issues related to inspection of corrosion on pipe network in industrial and civil applications. The main problem in such situations is the accessibility of the structure for inspection and cost of inspection. Authors suggested a use of guide waves for quick investigation of a longer span of pipes. Guided waves were launched from one location on the pipes and reflections if any from the corrosion or other discontinuity were analyzed for its location. Authors used dry coupled piezoelectric transducer system and an inspection span of up to 25 meters on pipelines with 2 to 24 inches. Diameter was reported L(0,2) mode was employed due to factors viz. non-dissipative nature, particle motion largely in axial direction and uniform distribution of strain through pipe wall. Circumferential and radial extents of the depth were correlated with the reflection coefficients. The system yielding good field results also. Cross sectional area loss up to 8-10% could be detected at any given axial position (**Figure 2.1**).



Jenot et al. (2001) demonstrated the use of lamb waves for measurement for thickness of plate undergoing corrosion. In this work, researchers measured group velocity of s_0 mode propagation through plate. Variations in the measured group velocities were related to the progressively reduced thickness of the plate exposed to successive chemical attacks. Dispersive nature of lamb waves, which is otherwise considered to be an impediment in guided wave health monitoring applications, was used to advantages in this work. A pair of Perspex wedge was employed to excite desired lamb waves modes through a copper plate (0.45 mm thick) which was successively exposed to concentrated nitric acid. Experimental and numerical result indicated that the group velocity can be very sensitive to the reduction in thickness; however it depended upon the lamb wave mode used for monitoring. This technique yielded satisfactory results when the erosion of the surface was uniform and there were small variations in thickness. Results were found be independent of the side (corroded or on the un-corroded) on which the lamb wave generation and detection for group velocities measurements were made. Authors recommended wavelet signal processing to resolve the signals, when several modes overlap because of strong dispersion or limited propagation distance. Thus it was possible to track the desired lamb wave mode for which the variation in group velocity vis-à-vis thickness of plate was considered.

Tuzzeo and scalea (2001) used micro machined air coupled capacitive transducers nondestructive detection of thinning in aluminum plates due to corrosion. Author exploited dispersive nature of selected lamb waves. More cutoff, frequency shift, group velocity and time of flight measurements were used for estimating the severity and extent of material loss in the form of corrosion.

Saidarasamoot et al. (2003) presented a board review of the state of the art non-destructive evaluation techniques used for ensuring the integrity of the coatings on marine structures and meticulously examine the corrosion wastage. Authors compiled review of developments in important nondestructive techniques like electromagnetic wave sensors for eddy current, elastic wave sensor for advance ultrasonic practices, electrochemical sensors and time resolved thermography techniques etc. The authors emphasized the necessity of using methodologies for convenient and quick assessment of corrosion loss on coated marine structure despite tough spatial locations. Each one of the available nondestructive technologies was evaluated on the basis of a set of requirements obligatory to be a suitable marine corrosion

wastage testing tool.

Sicard et al. (2003) presented the possibility of using phase velocity variations in A_1 mode as airframe structure. For a corroded patch if the thinning is relatively constant in depth, the phase velocity curve of a lamb wave propagating through this area can be exploited to evaluate the residual thickness. In this work a comb array and a wedge transducer were employed as emitter and receiver respectively. Mode selection was based on the criteria: mode should be highly dispersive and should be isolated from other modes in phase velocity dispersion curves. 11.5% thinning was reported to be measured with an accuracy of 2%.

Sicard et al. (2004) presented lamb synthetic aperture focusing technique (L-SAFT) for detecting and obtaining images of corrosion defects with defect to wavelength ratio as small as 2/11. This technique proposed to overcome the limitation of lamb wave investigations like; low SNR due to dispersive nature, inaccuracy in time of flight measurement for long span inspections. L-SAFT algorithm generated defect images of corrosion pitting using pulse-echo data in frequency domain. Authors demonstrated the application of this in imaging of simulated defects (5 holes of diameter 1.5mm on 1.82mm thick stainless steel 304 plate) using 2 MHz transducer. Simulated defect was detected using A_1 and S_1 modes, whereas as corrosion defect was detected using S_1 mode.

Yeo and Fromme (2006) investigated pilot finite element (FE) study lamb wave propagation and reflection characteristics in plates resembling part of ship hull. The hull of ships is reinforced using longitudinal and transverse stiffeners, web frames. These zones are acknowledged to be safety sensitive area and prone to fatigue as well crevice and pitting stiffener on a plate. Corrosion damage introduced as localized thickness reduction at different locations relative to the stiffener and excitation and monitoring locations. Authors studied wave propagation, reflection, transmission and mode conversion characteristics with A_0 mode pulses and predicted sensitivity of defect detection. Reasonably good sensitivity for the detection of defect at a stiffener and lying masked behind a stiffener were predicted. Special emphasis was placed on the quantification of the A_0 mode pulses reflected back to the excitation location, which could be measured using a guided wave array monitoring approach. However, due to the large number of structural features, the authors concluded that the observed time signal was quite complicated and the exact determination of defect location and severity from a measured time trace would require further investigation.

Mazeika et al. (2007) investigated the lamb wave tomography for inspection of tank floors from corrosion deposits where circumferential access is available. Proposed technique did not require draining and cleaning of the tank, that ensuring in-service inspection. Authors presented the pilot study carried out a prototype small sized tank and results of in situ experiments were reported. Authors found that significantly losses are comparatively lesser for fundamental symmetric mode as compared to fundamental anti symmetric mode and hence this mode is not recommended for scanning longer spans. Authors proposed prediction technique of the informative signal which is considered propagation characteristics like attenuation, frequency dependent leakage losses and appropriate phase velocity dispersion, so as to improve the quality of transmission tomography.

Volker et al. (2008) presented a permanent corrosion monitoring system using guided waves with a focus on real time quantitative evaluation of ageing infrastructure in order to improve reliability. Authors presented a methodology for evaluating the wall thickness of a plate specimen with water loading on one side using two arrays of ultrasonic transducers. Transducers in the active array were excited sequentially to generate selected lamb wave modes in dispersive zone. All transducers in the receiver array recorded the signals transmitting transducers excited selective lamb wave modes that are highly dispersive. When these modes interacted with the section of plate having thin section due to corrosion, it took longer to propagate. Inversion algorithm was invoked to invert the measured time of flights to corresponding wall thickness.

Chen et al. (2010) emphasized on the early stage detection of corrosion to prevent massive degradation to the metallic structure embedded in corrosive environment. Authors presented corrosion detection technique in terms of pulse echo measurements in submerged structures by employing A_0 mode. This mode was preferred over S_0 mode due to factor like; ease of excitation, lower wavelengths and larger signal amplitude. But coupled fluid medium drastically modulated propagation characteristics of A_0 mode resulting in erroneous identification of the damages. Authors investigated and calibrated the effect of fluid coupling of varying extents on the A_0 mode. The proposed technique was corroborated analytically numerically by assessing through-thickness hole and chemical corrosion in submerged aluminum plates by using probability-based diagnostic imaging approach. Results proved the need to rectify and compensate medium loading effect in case of lamb-wave-based damage

identification.

Dutta et al. (2011) studied feasibility of non-contact guided wave system to detect delimitation in multi-layer composite component. This study in two phases conducted. In first phase, the technique was developed using PZT transducer mounted on surface of composite plate and out of plane velocity is measured in 1D using scanning laser Doppler vibrometer. From this scanning, wave field images are constructed and this image is used to study the interaction of lamb wave with delamination. In this study they produce additional signal and image processing techniques used to highlight the defect in the scanned area. The elastic wave propagation system image sequence created from non contact excitation system.

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

Sharma and Mukherjee (2013) reported non-destructive evaluation of reinforcing bars that are corroding in the presence and absence of chlorides utilizing ultrasonic guided waves. Ultrasonic guided wave observing using particular center and surface looking for modes to distinguish the sort, rate, and system of erosion in a fortifying bar in cement subjected to various presentation conditions was examined. The exploratory examination included observing of RC bars experiencing quickened awed current erosion. By and large, tremendous setting and non-uniform region misfortune was highlighted by extreme sign constriction marks chloride erosion, which was all around grabbed by center looking for mode. It started with de overlay appeared by sign ascent with surface looking for mode. In oxide consumption, the rate of erosion was moderate, restricted, and set apart by moderate security disintegration as portrayed by sign

quality ascent in surface looking for mode. Setting was immaterial in center looking for mode in OC. Subsequently, it was watched that through a prudent choice of ultrasonic modes, distinctive sorts of consumption in RC structures can be effectively distinguished. Bars at various phases of erosion were ultrasonically observed in both oxide and chloride situations to investigate the capacity of ultrasonic have to anticipate the level of decay of the bars. It was done effectively by connecting ultrasonic voltage proportion with dangerous parameters of mass misfortune, rigidity and bond quality in the two basic erosion situations. It was inferred that, in spite of the fact that the utilization of guided waves is powerful in recognizing the nearness of erosion in rebar's in generally changing situations, the strategy needs access to the finishes of rebar. At site, bars that are most defenseless to erosion should be uncovered at the finishes to play out the test. Likewise the sign to-clamor proportion ought to be over the ground commotion level.

2.4 SUMMARY

In this chapter a brief review on few selected literature on Concrete Filled Steel Tubular members (CFST) were made to understand the further need of future research. This literature has established the capability of Lamb wave for damage detection in the CFST structures with simulated damages in form of cracks, notches and corrosion defects. But rarely any study has been focused on site application to real time damage monitoring of CFST specimen undergoing actual corrosion. The objective of the present research effort is to develop a real time, non-invasive corrosion monitoring strategy for CFST structures using guided waves.

CHAPTER 3

ULTRASONIC GUIDED WAVES PROPAGATION

3.1 INTRODUCTION

A periodic disturbance in a medium or space by which energy is transferred from one place to another is called wave motion.

3.1.1 Wave motion

The wave motion is one of the most important means of transmitting energy from one place to another without the transfer of any material medium with it. The waves are of two sorts:

- (a) **Mechanical waves or Elastic waves:** The waves which compulsorily require material medium which possesses the properties of inertia and elasticity for their proliferation are called mechanical waves or elastic waves. These waves are also called progressive waves
- (b) **Non-mechanical waves or Electromagnetic Waves:** The waves which require no material medium for their proliferation are called non-mechanical waves or electromagnetic waves.

e.g. radio waves, Light waves, microwaves, X-rays etc.

3.1.2 Types of wave motion

The particle of a medium can execute vibrations in two possible ways, namely:

- (i) Vibrations at right angles to the direction of propagation of the wave.
- (ii) Vibrations along the direction of propagation of the wave.

Accordingly, there are two types of wave motions:

1. **Transverse wave motion:** It is that kind of wave movement in which the particle of the medium vibrates about their mean positions in a direction at right angles to the direction of propagation (motion) of the wave.

2. **Longitudinal wave motion:** It is that kind of wave movement in which the particle of the medium vibrate back and forth about their mean positions parallel to the direction of propagation (motion) of the wave.

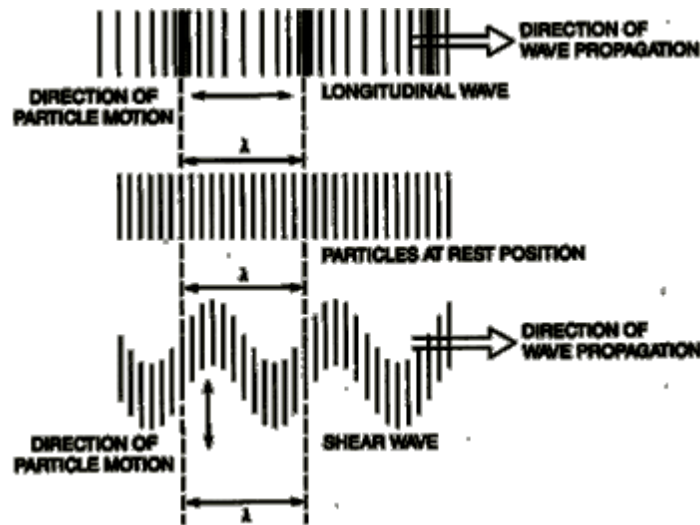


Figure 3.1: Transverse and Longitudinal Wave Propagation(www.ndt.net)

3.1.3 Range of frequencies

Depending upon audibility, the range of sound frequencies are classified as under:-

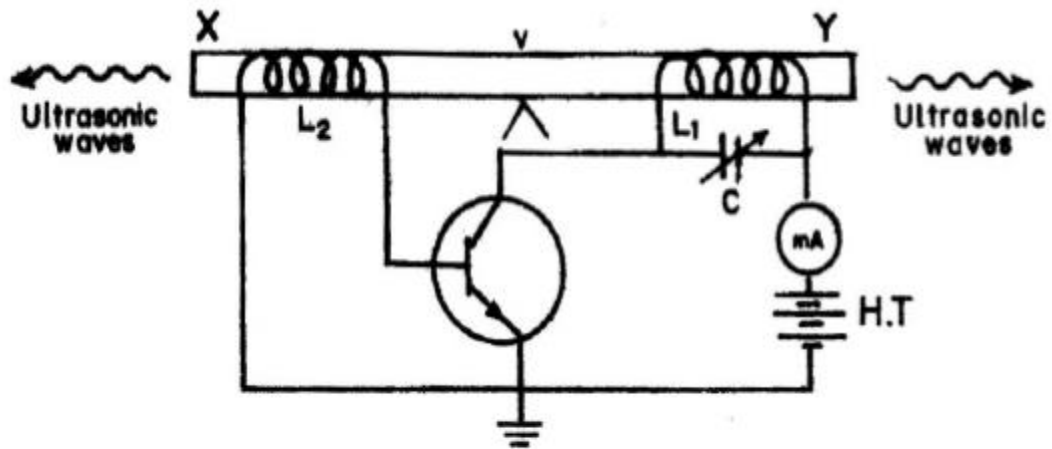
1. **Audible frequency range:** The sounds of frequency between 20 Hz and 20 KHz, which are audible to normal human is called audible frequency range. Human ears cannot hear sounds of frequency less than 20 Hz and more than 20 KHz.
2. **Inaudible frequency range:** The inaudible range of frequencies are classified as under:
 - (i) **Infrasonic:** Sounds of frequency below 20 Hz are called infrasonic.
 - (ii) **Ultrasonic:** Sounds wave of frequency more than 20 KHz are called ultrasonic's.

3.2 INTRODUCTION OF ULTRASONIC WAVES

The following are the most commonly used methods for the production of ultrasonic

- (i) **Magnetostriction Oscillator:-**The production of ultrasonic by this method is based upon magnetostriction effect. Magnetostriction effect, "when a rod of ferro-

magnetic material such as Nickel or Invar is suddenly magnetized, it undergoes a slight change in its length." **Figure 3.2.**

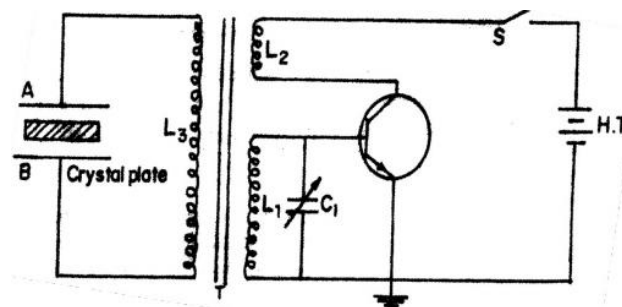


Magnetostriction oscillator

Figure 3.2: Magnetostriction oscillator

- (ii) **Piezo-electric Oscillator:-**The production of ultrasonic waves by this method is based on the **piezoelectric effect**. According to *piezo-electric* effect when crystal of salts like quartz, zinc blended, barium titanate, Rochelle salts etc .cut with their optical axis normal to the faces are subjected to high mechanical pressure on one pair of opposite faces, the other pair of faces develop equal and opposite electrical charges on them. If the crystal is subjected to tension, the sign of the charge is reserved.

Figure 3.3



Piezo electric oscillator

Figure 3.3: Piezo electric oscillator

3.2.1 Terms related to Sound wave propagation

- 1. Reflection and Transmission of Sound Waves:** When ultrasonic waves travelling in one medium strikes the surface of rigid body, they are sent back to the same medium. This phenomenon is known as *Reflection of Sound waves*. This occurs due to difference in acoustic impedances (Z) of the materials on each side of boundary. This difference in (Z) is commonly called impedance mismatch. Reflection of ultrasonic waves obeys snell's law of reflection as obeyed by light, but some of the properties of sound waves may change depending upon the shape of reflecting surface or nature of medium.
- 2. Wave velocity (v):-** The distance travelled by the wave (Transverse or longitudinal) per unit time is called *wave velocity*. Sound waves travels at different velocities in different mediums.
- 3. Wavelength (λ):-** In case of transverse waves, it is the distance between two consecutive troughs or crests and In case of longitudinal waves, it is the distance between nearest compressions or two nearest rarefactions. Wavelength is related o frequency and velocity by the simple equation wavelength (λ) = velocity (v)/frequency (f).
- 4. Time period:** -The time taken by a vibrating body to complete one vibration is called *time period*. It is generally denoted by T. it is also the time in which the wave motion advances by one complete wavelength.
- 5. Frequency:** - The number of vibrations made by a vibrating body in one second is called *frequency*. It is denoted by n.
- 6. Attenuation:** -At the point when sound goes through a medium, its force lessens with separation. In idealized materials, sound pressure (signal amplitude) is just diminished by the spreading of the wave. Normal materials, be that as it may, all deliver an impact which further debilitates the sound. This further debilitating results from scrambling and assimilation. Scrambling is the impression of the sound in bearings other than its unique course of engendering. Ingestion is the transformation of the sound vitality to different types of vitality. The consolidated impact of scrambling and ingestion is called *attenuation*.

3.2.2 PROPERTIES OF ULTRASONIC WAVES

- 1.** They have very high frequency i.e., beyond 20 KHz.

2. They are highly energetic.
3. Wavelength of ultrasonic wave is very small.
4. They have many modes of vibration.
5. In homogeneous medium they possess constant velocity.
6. Velocity of ultrasonic waves increases with increase in frequency.
7. They produce physical and chemical effects when passed through a liquid.
8. They obey law of reflection.

3.3 ULTRASONIC TESTING

3.3.1 Basic Principle

Ultrasonic NDT utilizes short length, low vitality; high recurrence stress pulse that is brought into a test object so as to acquire data about the auxiliary reliability of the specimen without modifying or harming it in any capacity. Typical Ultrasonic Testing (UT) system include several function units like pulse/receiver system, piezoelectric patches or transducers, data acquisition and display devices etc. in this function of transducer is to convert energy one form to another form of energy and it is injected to structural member which is being investigated. Interaction of propagating energy with flaws/defects results in reflection, dispersion of the energy. The reflected energy is picked by other transducer and converts into electrical signal.

Two essential parameters measured during ultrasonic testing are: - time of flight of signal through the sample, and amplitude of received signal. Measurement and analysis of these parameters can effectively give information about size, location and orientation of the flaw.

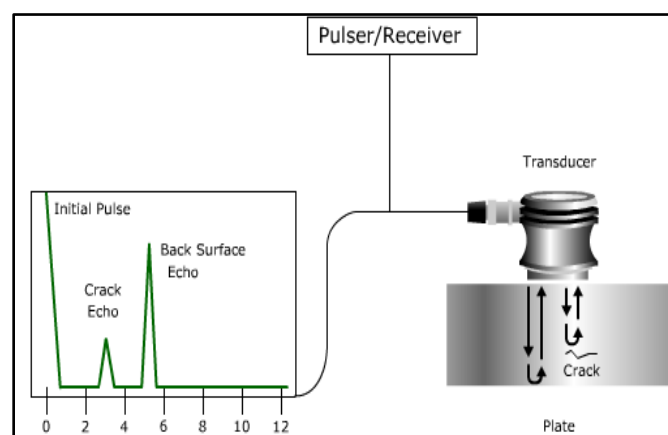


Figure 3.4: General ultrasonic inspection principle (www.nde.net)

3.3.2 Method of Ultrasonic Testing

Commonly used ultrasonic testing methods are:

- Pulse Echo method
- Pulse transmission/ Through Transmission method
- Pitch Catch method
- Pulse Echo (PE)

In this method only one piezoelectric transducer is utilized that acts as both active as well as passive transducer. Transducer is kept normal to the surface and mounted on or close to subjected specimen (**Figure 3.5**). It transmits ultrasonic energy to the specimen. These ultrasonic waves were reflected through different interface of the specimen. This interface is formed by different materials or by discontinuities, layers, debris or voids etc. in the specimen. Waves reflected from different interfaces are captured by same transducer (acting as receiver) and is converted into electrical signal, which is further used for monitoring and analyzing. Various parameters like thickness of the specimen, location of defect etc. may be disclosed using time of flight information from PE data.

The pulse echo method permits testing when access to only one side of the material is conceivable.

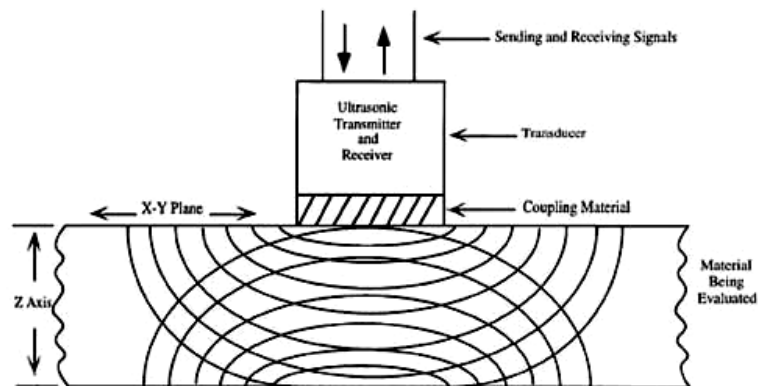


Figure 3.5: Pulse echo method of ultrasonic testing

(Source: NASA Guidelines for Ultrasonic testing of Aerospace Materials)

- **Pulse Transmission (PT)/ Through Transmission method**

In PT method two transducers were used and they were placed on opposite sides of the specimen. One transducer acts as transmitter (T) while other transducer act as receiver (R) **Figure 3.6.** PE is generally used for detecting and localizing the defect in specimen. PT is employed for sizing defect. By correlating the change in amplitude of input and the received signals, the relative severity of the flaw can be assessed.

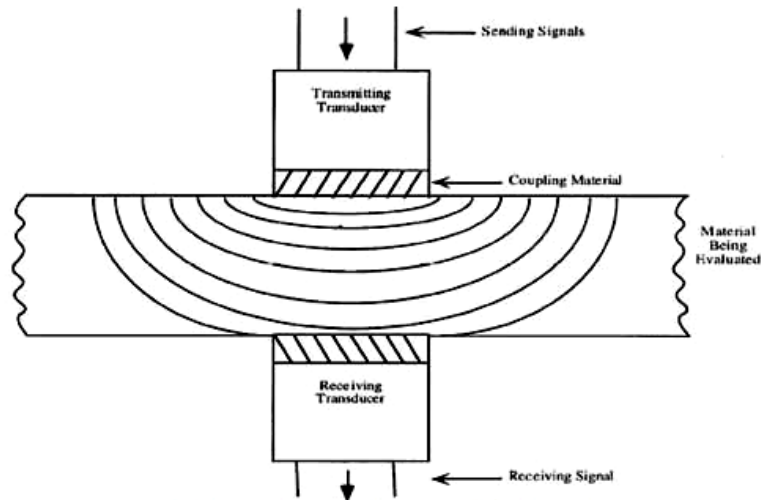


Figure 3.6: Pulse Transmission method of testing

(Source: NASA Guidelines for Ultrasonic testing of Aerospace Materials)

- **Pitch Catch (PC) method**

Like PT method, this method also employs two transducers. However, in this case the transducers are placed on one side of specimen only. In PE and PT methods transducers are generally oriented normally to the specimen surface. But, in PC method, ultrasonic energy may be transmitted at an angle and received as reflected energy returning at reflected angle. PC method is usually employed for specimen where only one side is accessible **Figure 3.7.**

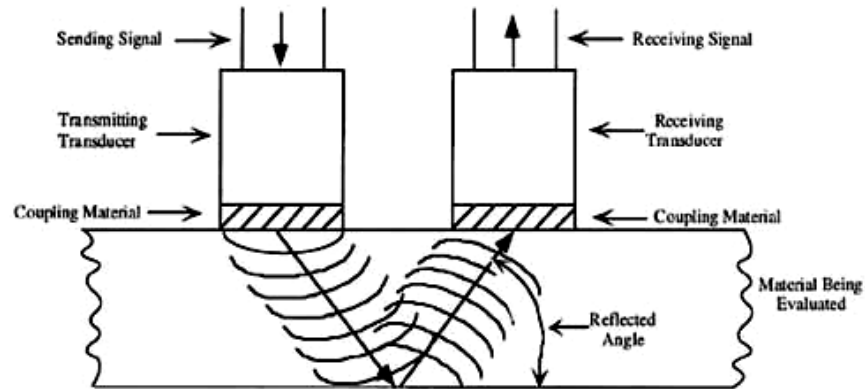


Figure 3.7: Pitch-catch Method of ultrasonic testing

(Source: NASA Guidelines for Ultrasonic testing of Aerospace Materials)

3.4 SUMMARY

Active wave propagation is high frequency external excitation. The state of health of structure is evaluate by injecting a very low energy level, high frequency ‘stress pulse’ or ‘wave packet’ into structure and its wave parameter (like reflection, transmission, attenuation etc.) are observed. The waves are generated due to piezoelectric effect. Passive wave propagation health monitoring technique does not require any external excitation. Passive wave propagate fairly large distances through the structure under investigation and can be detected by a structure mounted sensor. Presence, extent and location of damage in the structure can be analyzed by receiving signal.

In above section, the basics of ultrasonic waves and the principal associated with NDT tool for engineering purpose have been discussed. Ultrasonic waves are guided waves and can be used for health monitoring purpose. They have normally applied as guided wave since bulk waves are more complicated to use in NDT technique.

CHAPTER 4

ULTRASONIC WAVE PROPAGATION IN CFST STRUCTURES

4.1 GENERAL

A thorough exploratory study on propagation of ultrasonic guided waves modes at specific frequencies in CFST is discussed in this section. Motivation behind this study is to effectively use ultrasonic guided waves for through health monitoring of the CFST. Guided ultrasonic waves are known for their unique characteristics like long propagation distance, frequency dependent wave structure and lower attenuation as compared to bulk waves. UGW in the present case have been generated by obliquely exposing the CFST to the incident longitudinal waves. The transducer rides on the back of the semi cylindrical Perspex block and interacts with CFST at desired angle generating the required mode. Appropriate guided waves modes with ideal examining capacities have been distinguished in CFST structure framework. Finally, the propagation of the selected modes through CFST structure would be further used for defect identification in civil structures.

4.2 EXPERIMENTAL INVESTIGATIONS

4.2.1 Set-Up and specimen details

The square empty steel tubes affirming to IS 4923 - 1997 and IS 1161-1998 having a cross-segment of 72mm x 72mm have been used in this as a part of the study. The thickness and length of the square empty steel tubes is 3.2mm and 600mm respectively. These empty steel tubes were filled with regularly utilized M-25 grade concrete with configuration blend extents of bond, sand and stone totals as 1:1.375 (FA):1.539 (20mm CA) :1.510 (10mm CA) by weight arranged with water bond proportion of 0.44 percent. For holding and curing purpose the steel tube was left unfilled by 25 mm on each side of the segment. The CFST specimens were cured for 28 days.



Figure 4.1: Actual CFST specimens

4.2.2 Ultrasonic Testing System and Set up details

The ultrasonic testing (UT) setup comprises of DPR500Pulser/Receiver (PR) transducer (Karl Dutsch Make), transducers (Olympus NDTTContact), and the data acquisition card and display device. The pressure transducers are driven by the PR which creates ultrasonic pulse through the concrete container of CFST segment. The ultra-sonic excitation is a wave got when PR is at most extreme information voltage of 900 Volt. The ultrasonic waves created by the transmitter transducer go through the encompassing steel and concrete in the container of CFST point to produce the comparing Lamb wave mode. The tests are to be put at a fitting partition from the plate illustration which is termed as wave travelling way. It is the separation went in Perspex before the wave hits the top surface of the CFST segment. Transmitter transducer sends the ultrasonic wave through a coupling medium (Perspex) and is received by the receiving transducer. The propagating waves are the wave transmission signals showed as Voltage-time (V-t) graph. In this study, transducers of 0.5 MHz are utilized **Figure 4.2.**

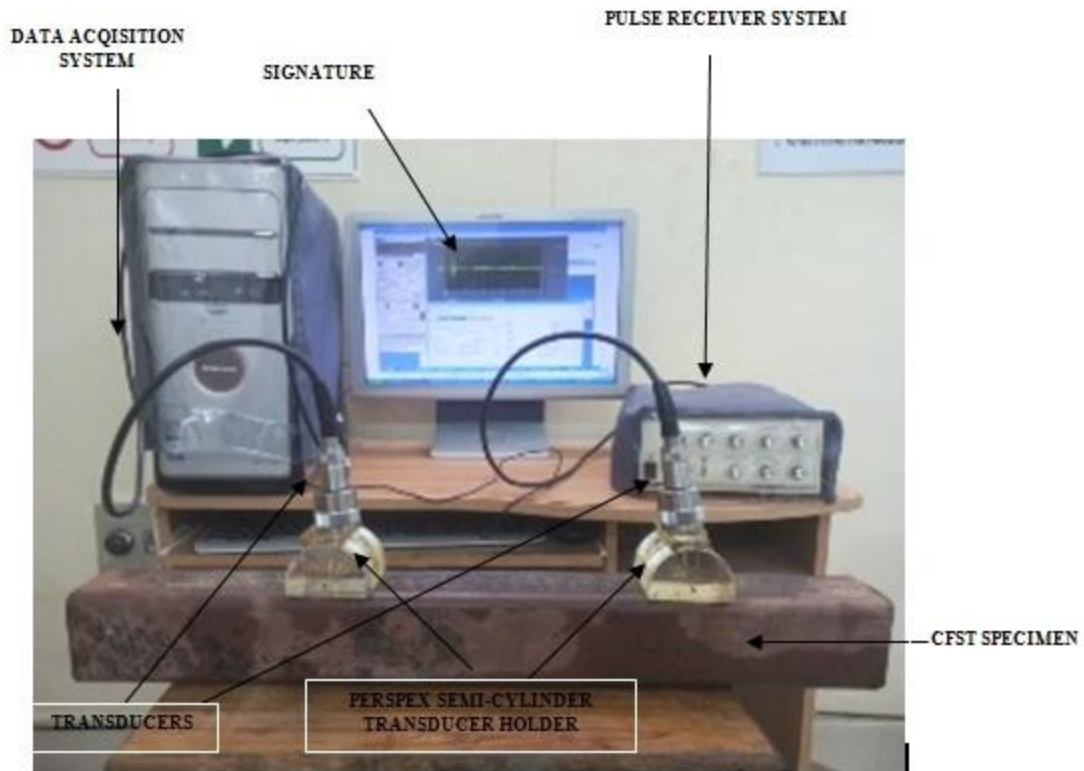


Figure 4.2: Actual Ultrasonic Testing set-up

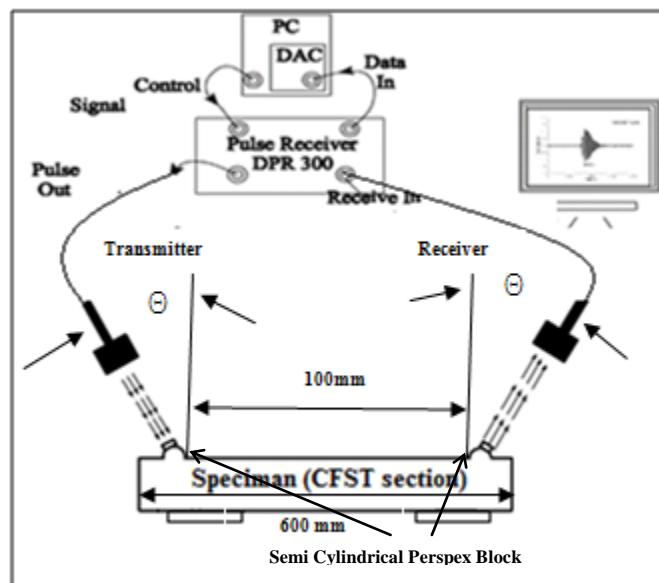


Figure 4.3: Schematic of Ultrasonic Testing set-up

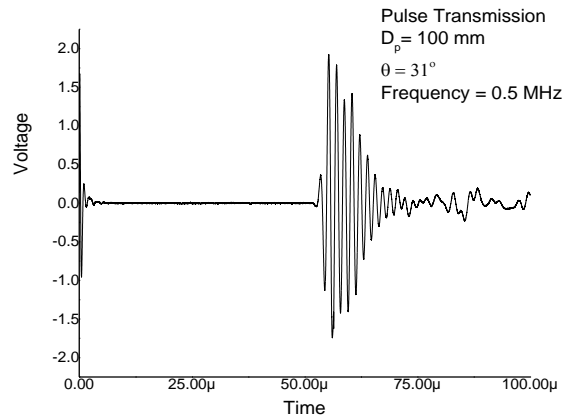
4.2.3 Ultrasonic wave propagation in CFST

The present study focuses on the propagation of ultrasonic waves through the CFST for developing a health monitoring strategy. For this purpose, ultrasonic transducer are mounted on Perspex semi-cylinder in pitch catch orientation, separated by a distance of 40 mm and making equal angle with respect to surface of CFST. The longitudinal ultrasonic waves generated by the transducers interacts the Perspex-steel interface obliquely. This input energy is partly reflected and is partly transmitted into the CFST structure.

In the pulse echo (PE) mode, reflected waves are received by the same transmitter probe itself. The distance travelled by the wave before hitting the steel interface is termed here as *wave travelled path* (D_w) because it is the distance travelled by longitudinal wave in the Perspex medium.

In this study the D_w has been kept as radius of Semi cylinder Perspex block = 40 Too large Perspex path results in loss of incident energy. On the other hand, if the transducers are placed too close then near field reflections from the solid interface overlaps with the initial pulse of transducer leading to complex and irresolvable signal. A number of trial were undertaken to obtain the suitable wave travelled path. The time base in this experiment is in the range of 100 μ s gives satisfactory results in term of signal fidelity and repeatability. Thus, in the entire experimental investigation is kept at 100 μ s for both transducers.

Ultrasonic testing of CFST in pulse transmission mode comprises of mounting the probes on cylindrical Perspex blokes (of radii equal to $D_w=40$ mm) in pitch catch orientation separated by suitable distance , The input energy is transmitted into the steel structure and is guided by the structure geometry to propagate further along the steel concrete interface n solid media. Guided waves propagating through the concrete (largely heterogeneous medium) are continuously loose energy to concrete due to material attenuation. These leaky guided waves travelling through the steel are captured by the receiver probe. These pulses are further conditioned by the PR unit and are displayed on the screen. The distance transverse by the guided wave through the structure is termed here as propagation distance (D_p). **Figure 4.4** show the PT signatures obtained using 0.5 MHz has only one clear peak.



(a)PT signatures at 0.5 MHz frequency

Figure 4.4: Pulse Transmission signature at $\theta=31^\circ$

Form studying effect of incident angle on lamb wave Propagation. We can conclude that when transducer probes kept on semi cylindrical Perspex block with 31° angle, the signal strength is maximum.

4.3 EFFECT OF INCIDENT ANGLE ON LAMB WAVE PROPAGATION

4.3.1 Experimental details

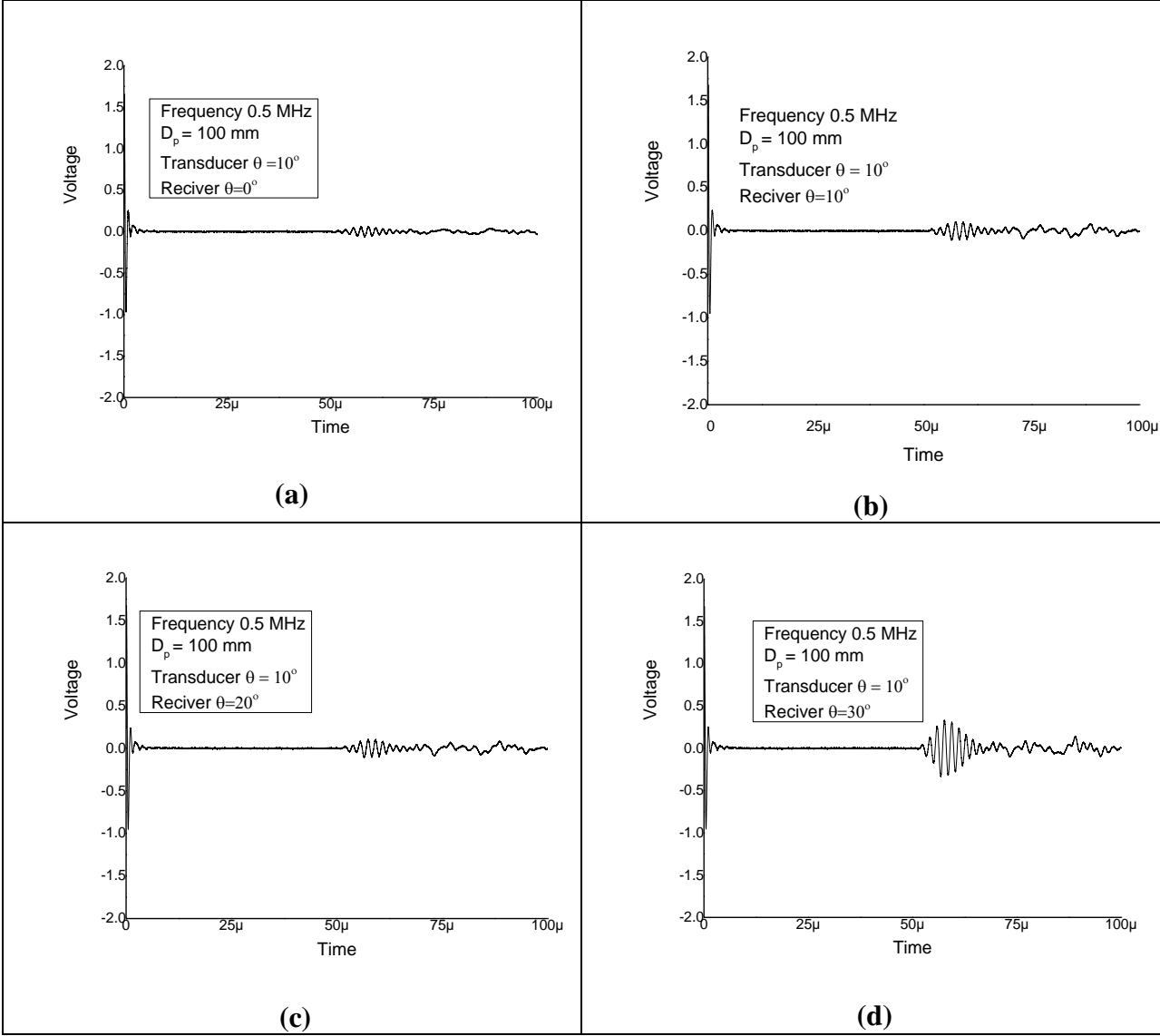
For a selected frequency and CFST thickness combination, a number of lamb wave modes can exist in geometry, each one having its unique propagation characteristics like- phase velocity, group velocity and attenuation. Particular modes can be selectively excited by keeping the transmitter and receiver transducers at a specified angle of incidence. Objective of this study is to experimentally investigate the variation in propagation characteristics of the transmitted pulse with respect to the angle of incidence (θ) and determine suitable angles of incidence for damage monitoring in given specimen.

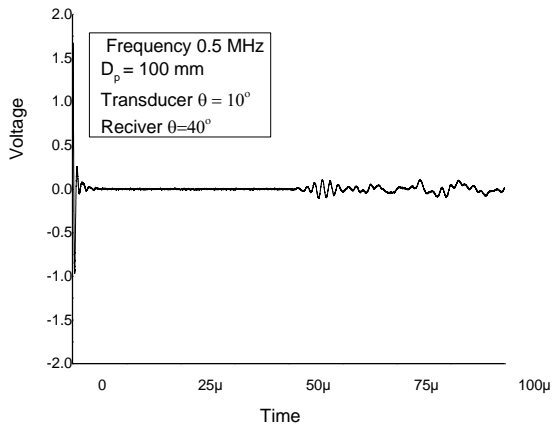
In this study, angle of incidence for both transmitter and receiver transducer are varied simultaneously from 10° to 50° in step of 10° . Corresponding PT signature are recorded using frequencies of 0.5 MHz during entire experimentation, Propagation distance (D_p) has been kept 100 mm. Propagation distances (D_p) of 100 mm has been used for frequencies 0.5 MHz PT

signature have been recorded at different locations on the CFST specimen in order to ensure consistency and repeatability of the results.

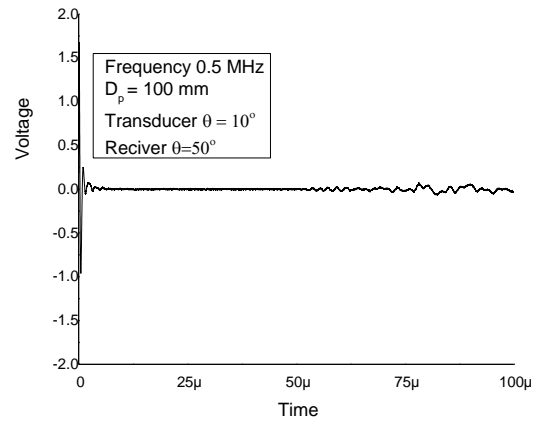
4.3.2 Observation and Discussion

4.3.2.1 Effect of varying angle

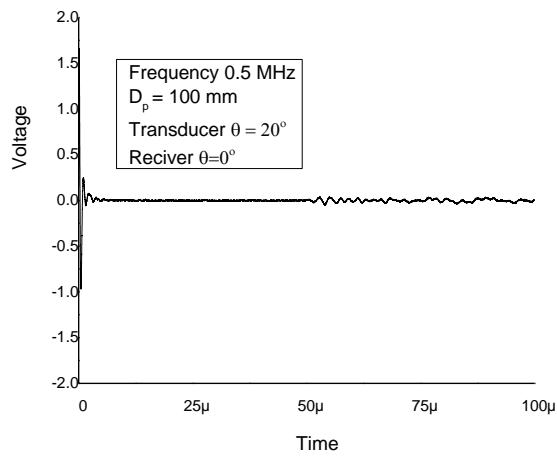




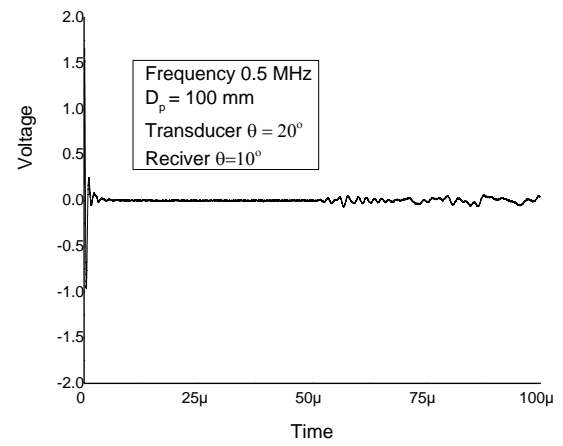
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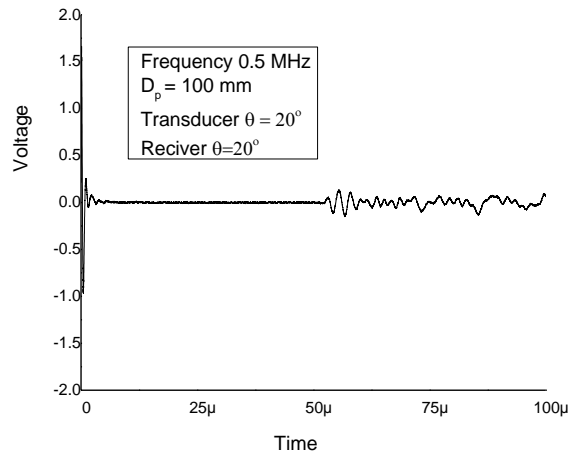
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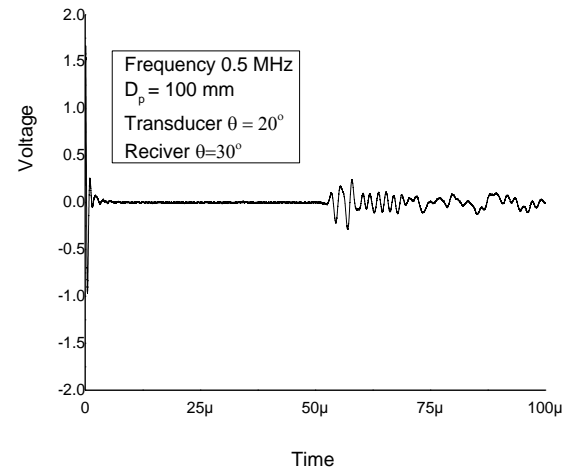
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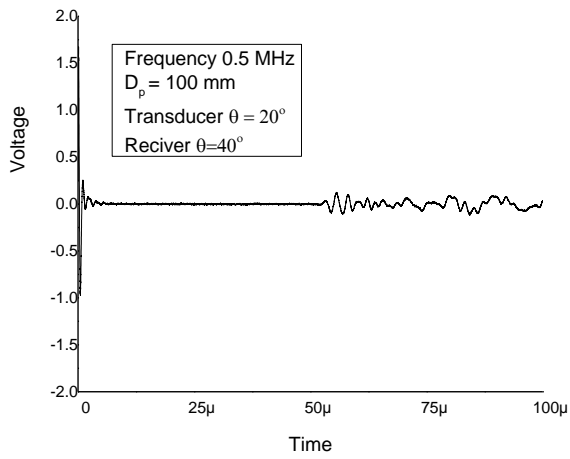
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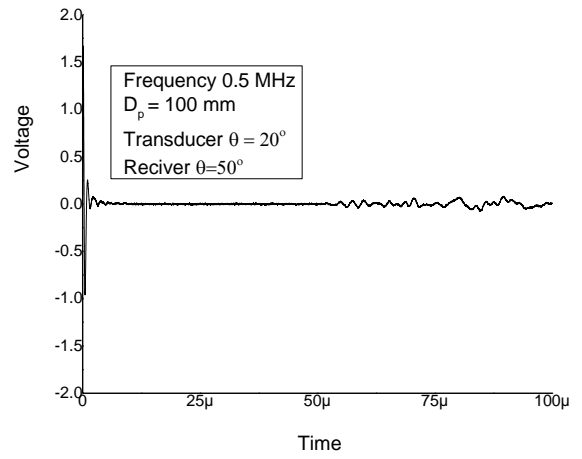
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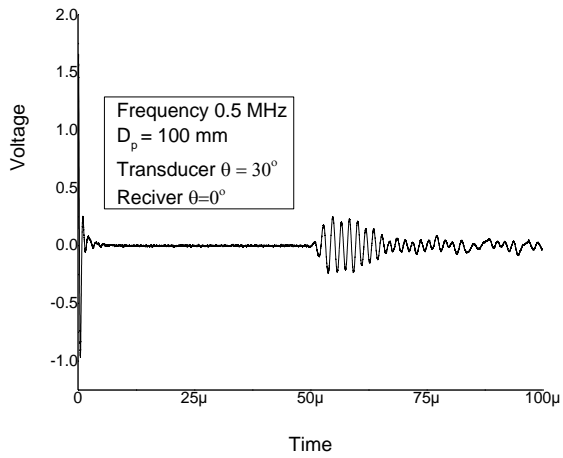
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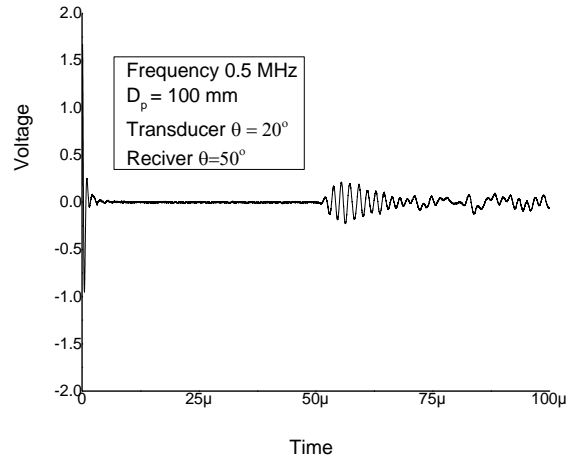
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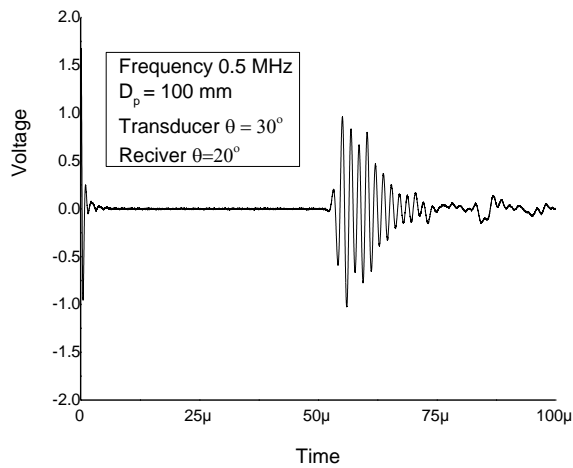
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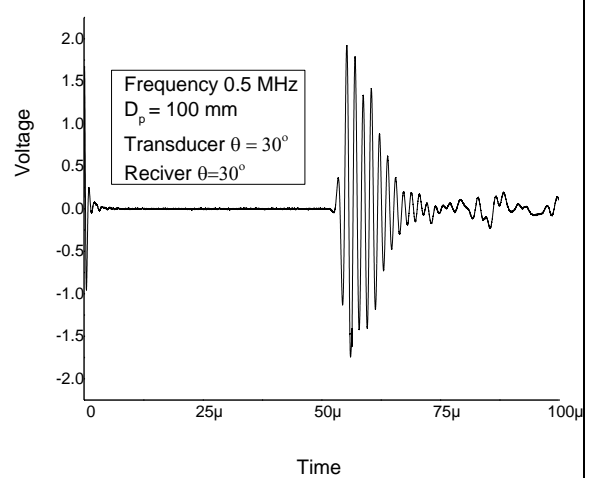
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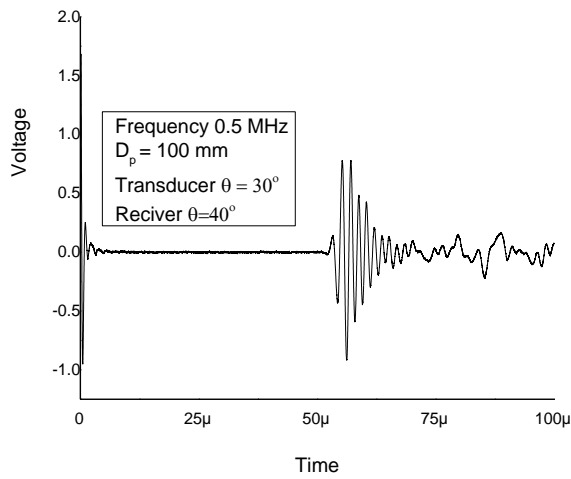
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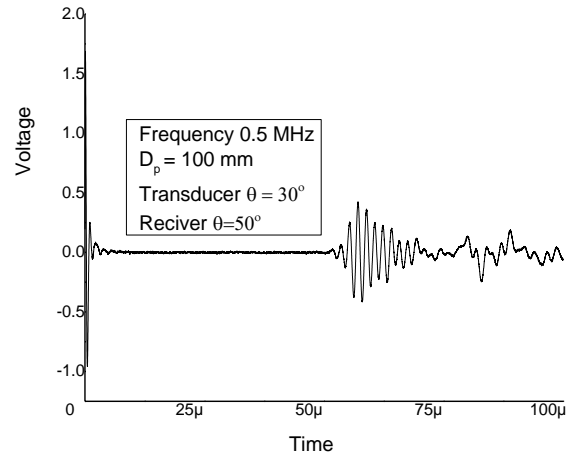
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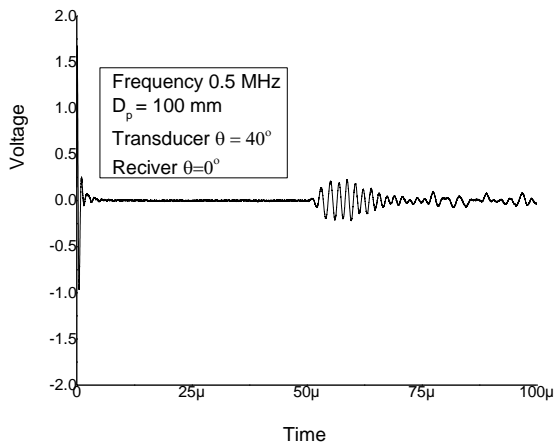
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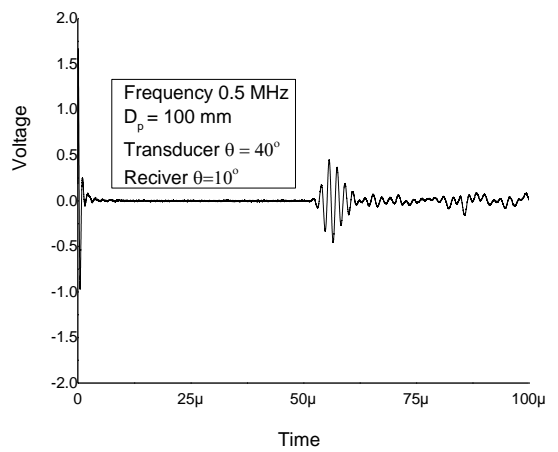
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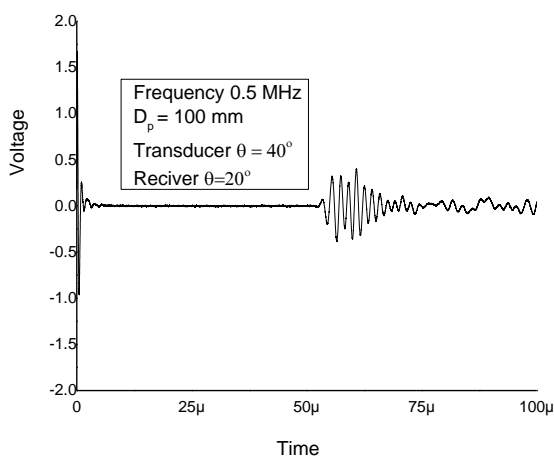
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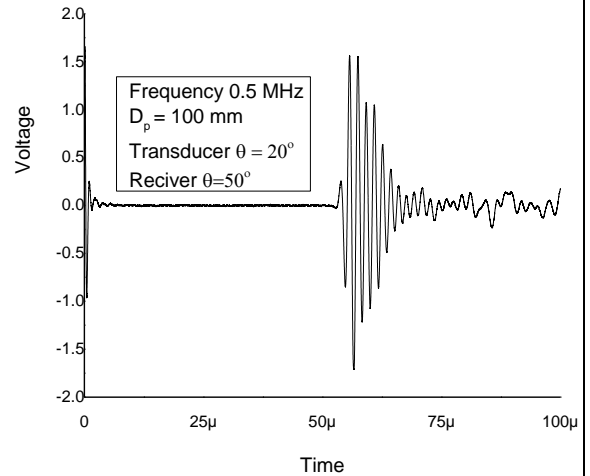
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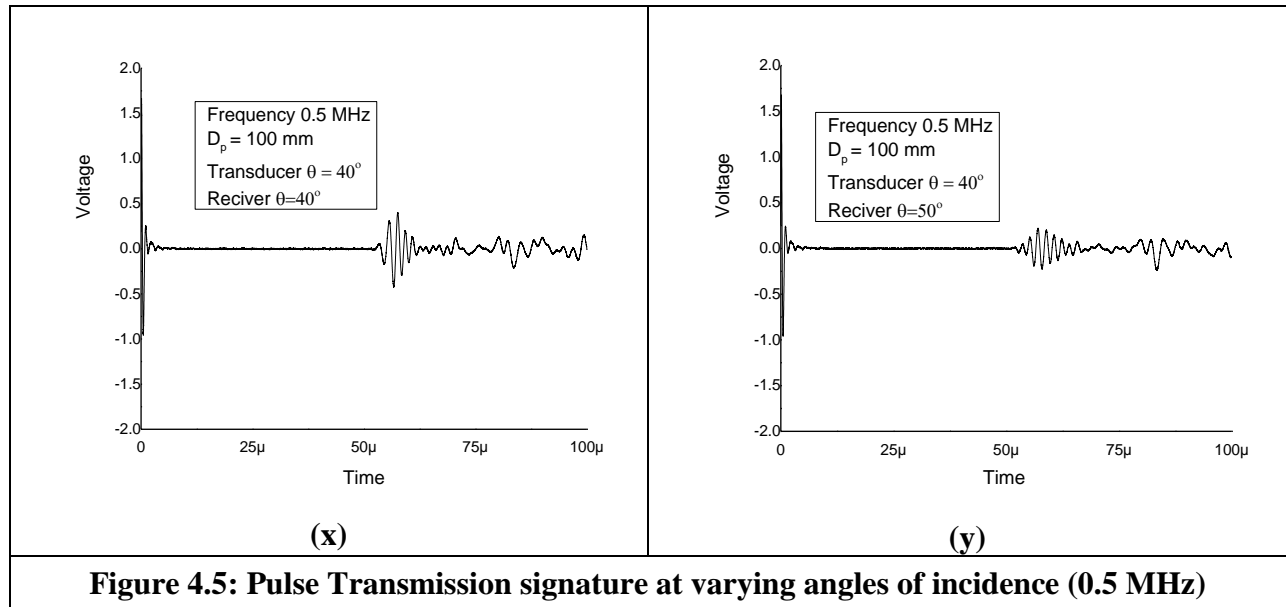


Figure 4.5 show the PT signatures obtained at different at different angle of incidence using 0.5 MHz frequency. At 0.5 MHz frequency, when angle of incidence is in the range of 0° to 20° (**Figure 4.5 a-i**), a weak signal is obtained. At 30° (**Figure 4.5 p**) a sharp peak is obtained at $52\mu\text{s}$. For 30° and 31° angles, this peak becomes even sharper and appears at $57\mu\text{s}$ and $68\mu\text{s}$ respectively. Additionally, traces of smaller amplitude peak on the left side can be seen at $51\mu\text{s}$. as θ increases to 40° , 50° and 60° , the peak on the left side gets stronger and appear around $70\mu\text{s}$, whereas the peak on the right side gets fainter and finally disappears. With further increase in θ (30° and beyond) all peaks gradually diminish (**Figure 4.5 t-v**).

Variations in the PT signature clearly indicate that for a selected frequency of excitation and CFST structure, the propagation characteristics like signal shape and its amplitude and time of arrival of the transmitted pulse are substantially influenced by varying the angle of incidence.

Figure 4.6 shows the plot of peak-peak voltage (v_p) of the received signal at different angles of incidence from 0.5 MHz It clearly indicates distinctive bands in v_p - θ plots where signal fidelity is best and this range can be further exploited for investigation of CFST structures. At 0.5 MHz frequency (**Figure 4.6**) range of 30° and 31° at which v_p of the transmitted pulse is distinctively higher.

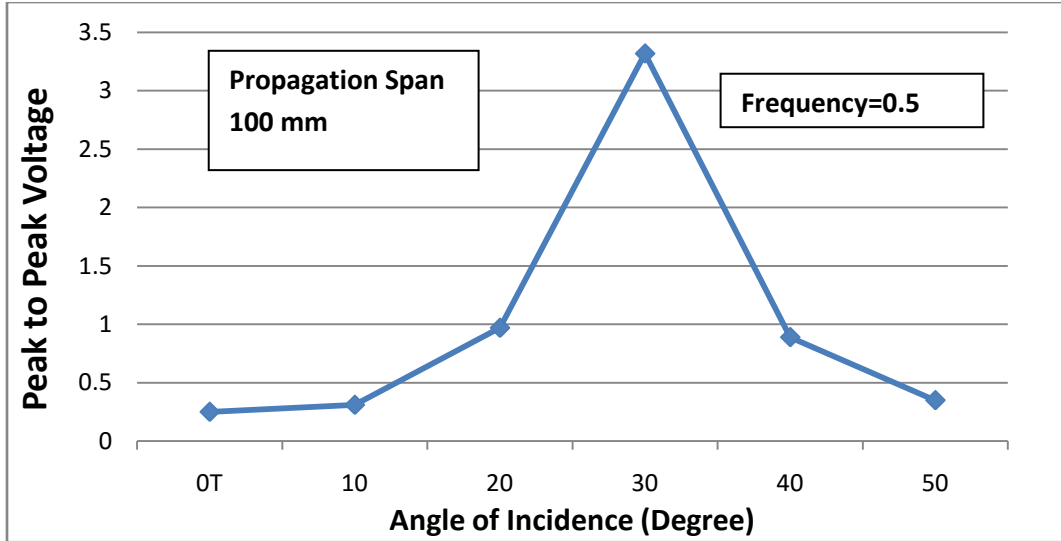


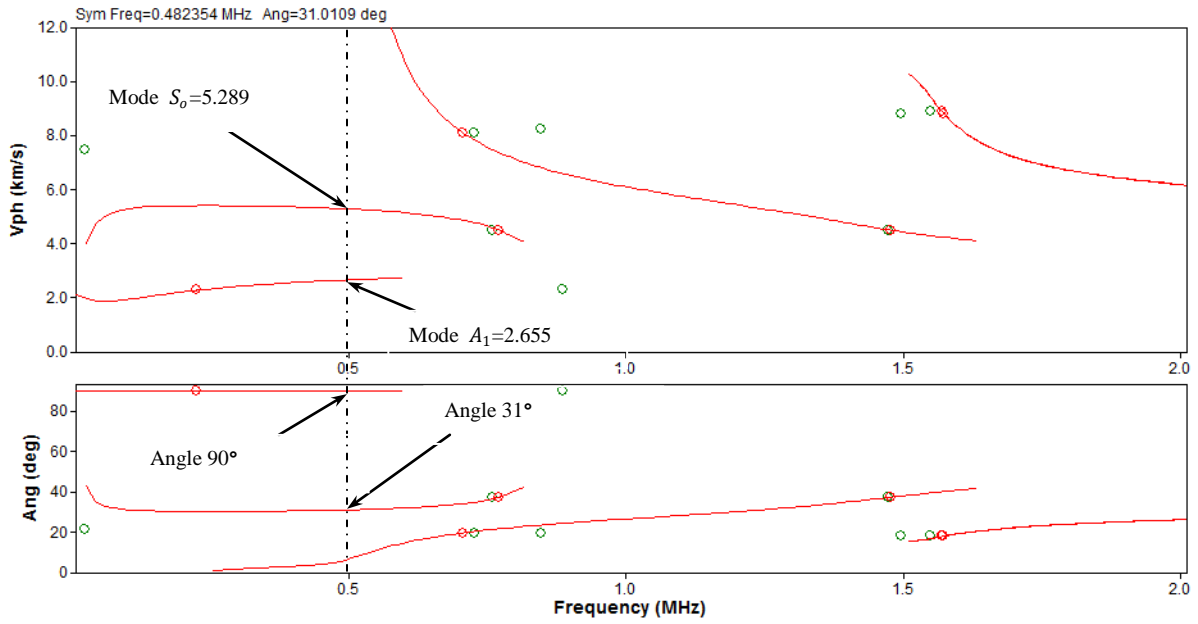
Figure 4.6: Angle of Incidence (θ) vs. V_p of transmitted pulse

4.3.2.2 Mode identification using Dispersion Curves

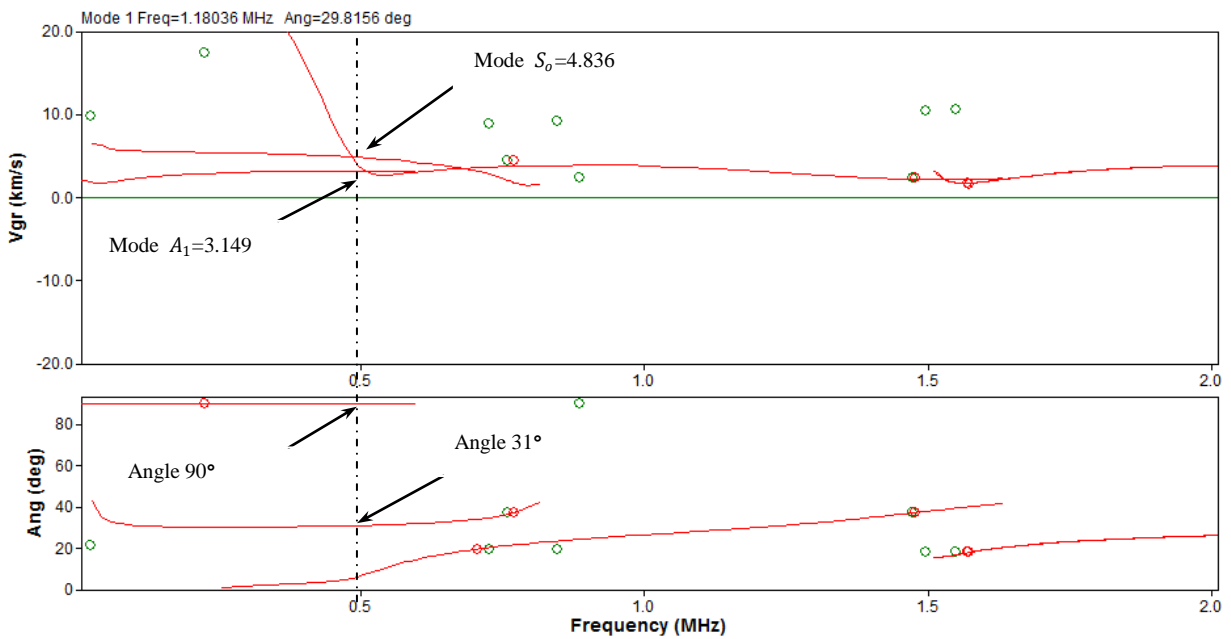
The variation in v_p with incidence angle can be explained theoretically by plotting dispersion curves for the CFST structures. This dispersion curves showing the variation of phase velocities (km/s), group velocities (km/s) and attenuation characteristics (dB/m) with respect frequency (MHz) for 3.2 mm thick square cross-section 72 mm x72 mm with concrete filled have been plotted using disperse software (Pavlakovic and Cawley, 2000) (**figure 4.7**). From the phase velocity dispersion curves (**Figure 4.7**), at 0.5MHz, two lamb wave modes S_0 and A_1 exist with phase velocities of 5.2591 km/s and 2.66236 km/s respectively. Any of these desired lamb wave modes can be selectively excited by impinging longitudinal waves from transmitter at an appropriate angle of incidence.

In experimental studies, at 0.5 MHz frequency, when the angle of incidence is range of 30° and 31° (**Figure 4.5p**), is the sharp peaks appearing at $57\mu\text{s}$ and $44\mu\text{s}$ indicate the dominance of A_1 mode in this range. Theoretical arrival time of the transmitted pulse (T_t) in PT signature, comprise of two components namely- t_w at both transmitter (left transducer) and receiver. With further increase in θ (31° - 50°), the peak corresponding to A_1 vanishes and peak corresponding to S_0 mode grows in amplitude. At (30° - 34°), there is a single sharp peak. Presence of S_0 mode appearing at $57\mu\text{s}$ in the signature can also be verified by matching with the theoretical arrival

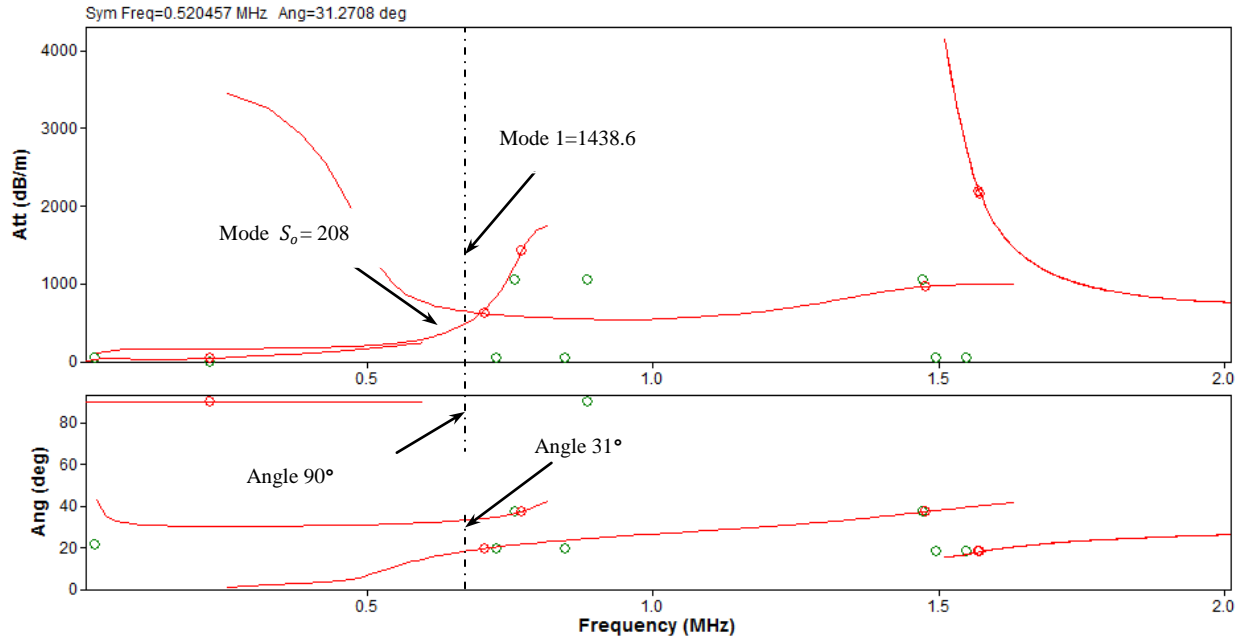
time of the mode. At higher values of θ (30° - 34°) this peak vanishes which is also supported by the dispersion curves that no lamb wave mode is feasible beyond 50° .



(a) Phase Velocity, angle vs. Frequency



(b) Group velocity, angle and Frequency



(c) Attenuation, angle and Frequency

Figure 4.7: Dispersion curves for 3.2 mm steel tube with Perspex.

In experimental studies, at 0.5 MHz frequency, when the angle of incidence is range of 30° and 31° (**Figure 4.5p**), is the sharp peaks appearing at $57\mu\text{s}$ and $44\mu\text{s}$ indicate the dominance of A_1 mode in this range. Theoretical arrival time of the transmitted pulse (T_t) in PT signature, comprise of two components namely- t_w at both transmitter (left transducer) and receiver. With further increase in θ (31° - 50°), the peak corresponding to A_1 vanishes and peak corresponding to S_0 mode grows in amplitude. At (30° - 34°), there is a single sharp peak. Presence of S_0 mode appearing at $57\mu\text{s}$ in the signature can also be verified by matching with the theoretical arrival time of the mode. At higher values of θ (30° - 34°) this peak vanishes which is also supported by the dispersion curves that no lamb wave mode is feasible beyond 50° .

Response of S_0 mode at 0.5MHz with varying transducer angle is plotted in **figure 4.5** as peak to peak voltage amplitude in the PT signature (**figure 4.5**) at corresponding time of arrival ($48\mu\text{s}$ and $107\mu\text{s}$) of the S_0 modes respectively it clearly highlights the regions of dominance of these modes at 0.5MHz. It is clear that **Figure 4.5** is the envelope curve encompassing the effect of all the feasible modes at 0.5MHz.

Further, at 40° there is appearance of a weaker peak at $65 \mu\text{s}$ which continuously shifts leftward with increasing values of θ . This exhibits highest amplitude at 41° and corresponding arrival time is $57 \mu\text{s}$. This peak is attributed to the S_0 mode as indicated by its time of arrival in PT.

Voltage amplitude of the received signals (**Figure 4.6**) corresponding to the arrival time of S_0 mode ($58 \mu\text{s}$) at 0.5 MHz have been plotted in **figure 4.6**. This plot shows the regions of dominance of these modes in the v - θ plot. It is also clear that the curve in **Figure 4.6** is the envelope curve of all the modal responses.

4.3.2.3 Criteria for guided wave mode selection

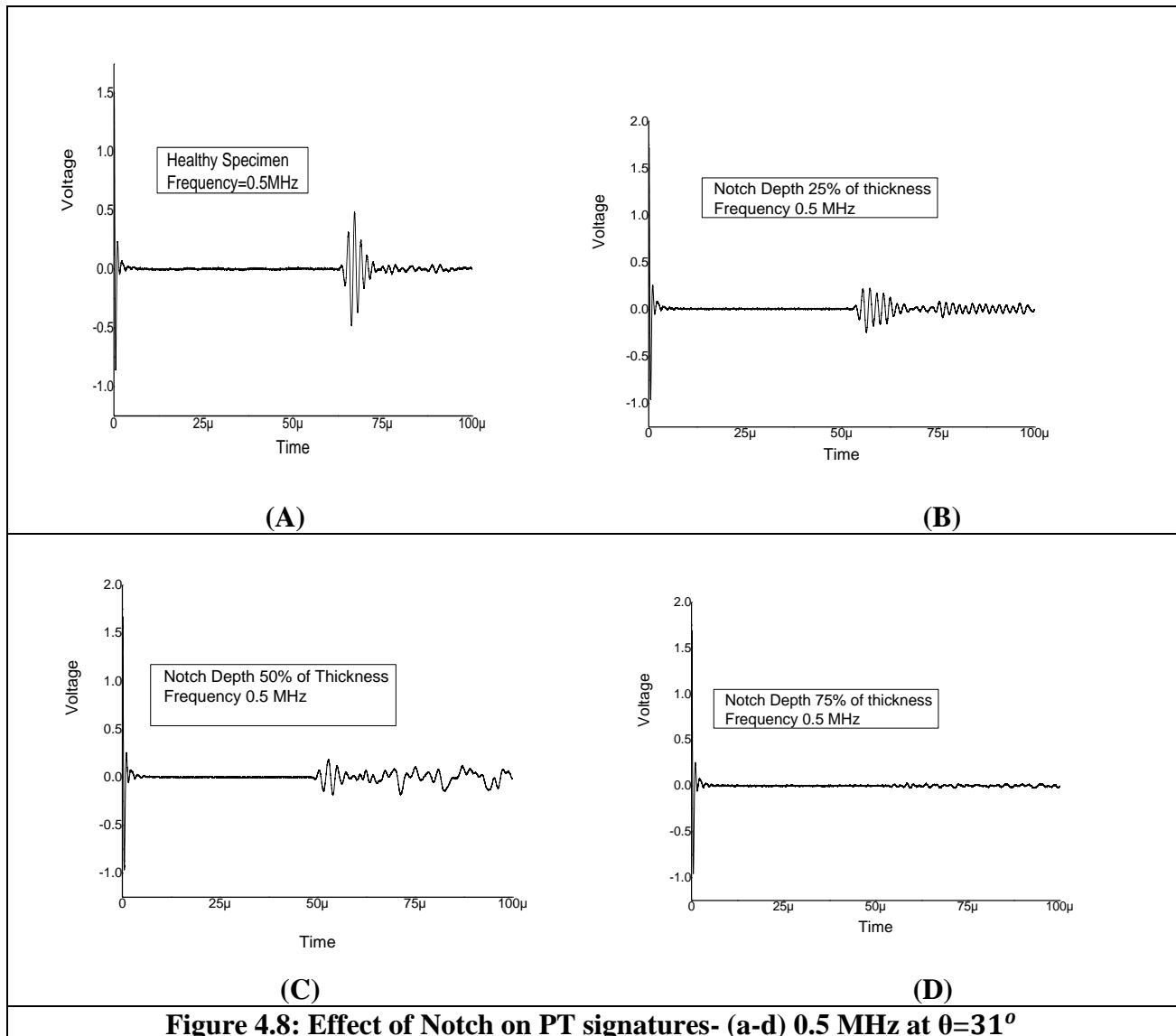
Selection of a particular mode is based on the consideration of minimum attenuation for maximizing scanning distance, good signal fidelity and the energy distribution profile across the plate thickness for maximizing the sensitivity of a mode for detection of a typical flaw/damage. In view of this, desired Lamb wave mode should exhibit well defined sharp peak, suffer minimum attenuation and there should be ease of excitation and successful capturing of the signal.

In the present work, at 0.5 MHz , the two available modes namely symmetric mode S_0 and anti-symmetric mode A_1 have well separated phase velocities (**Figure 4.7**) relatively lower attenuation (**Figure 4.7**). But S_0 mode exhibits a well-defined sharp peak in comparison to A_1 mode. In symmetric modes should be preferred over anti-symmetric modes because of their higher group velocities (**Figure 4.7**) resulting in lesser dispersion. Hence, S_0 is the preferred mode for damage monitoring at 0.5 MHz .

4.4 SIMULATED DEFECTS STUDY:

PT signature is likely to get affected in the presence of damage in the structure in the form of the interface modifications or loss of material due to ageing or corrosion. To investigate the feasibility and efficacy of the guided waves to detect damages in the CFST structure utilizing PT, notch damages of varying depths were inflicted on the steel encasing the CFST structure and PT signatures in the notched plates were compared with healthy CFST structure signals. **Figure 4.8** shows the results of primitive study to understand the effect of varying the notch increases the peak to peak voltage amplitude of the received signal drops. Hence, PT technique can successfully identify the notches and possibly quantify the extents. Hence, pulse transmission

testing of CFST structure obtained by using transducer exhibit a great potential as a non-destructive investigation tool. The following section describes the effect of the other experimental variables like angle of inclination (θ) and propagation distance (D_p) on the transmitted wave signal. The effect of external physical obstruction on the lamb wave propagation is also investigated.



4.5 EFFECT OF PROPAGATION DISTANCE

4.5.1 Signal fidelity vis-à-vis propagation distance

In this section, the effect of propagation distance on the transmitted signal strength is studied. At different angles of incidence, D_p has been varied from 120 mm to 40 mm. during this experiment, operating parameters like dB setting, Low pass Filter (LPF), High Pass Filter (HPF) settings etc. for the PR unit are kept at the same level in order to avoid any external biasing. It has been observed that for some values of angles on incidence, lamb waves are too weak to traverse through the given span. In such cases signal is too weak or undetectable. **Figure 4.8** shows V_p of transmitted pulse corresponding to the different angles of incidence at variable propagation distances. For a given angle of incidence, the amplitude of the transmitted pulse decreases with increase in the propagation distance. This can be primarily attributed to the more leakage of energy into surrounding water and increased material attenuation due to increased propagation distance. It clearly, suggests that change in the propagation distance has no effect on the trends of transmitted pulse amplitudes (**figure 4.8**).

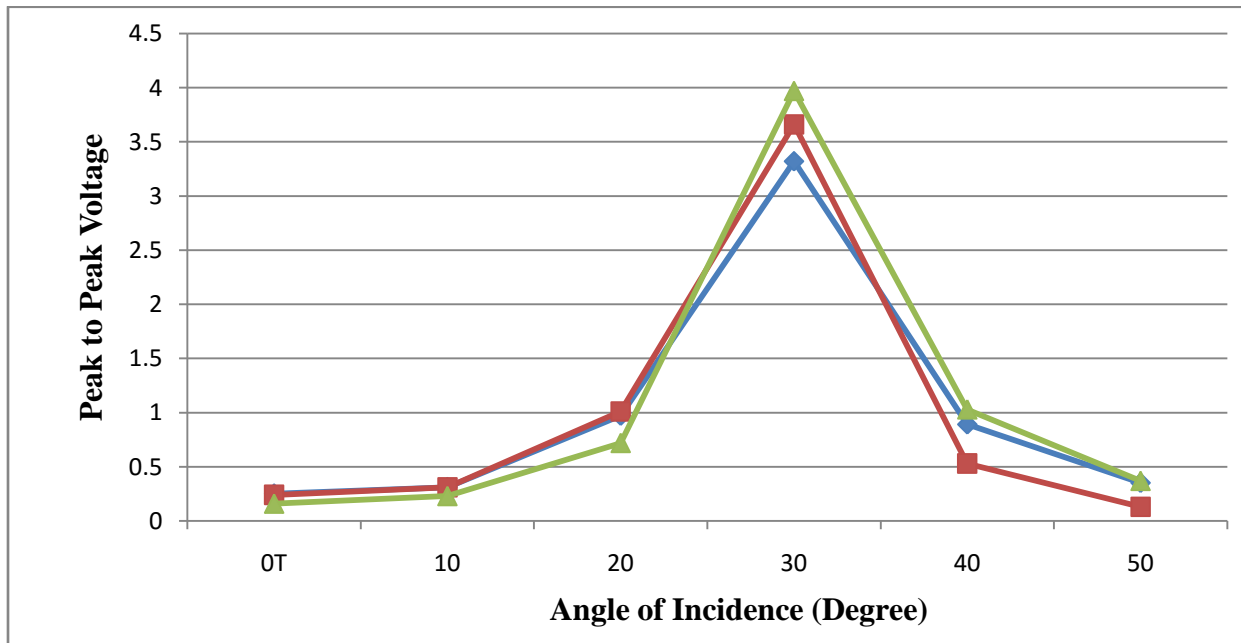


Figure 4.9: Angle of incidence (θ) vs. Transmitted Pulse Amplitude at Varying Propagation Spans.

4.5.2 Effect of Propagation distance on Selected Modes.

To investigate the optimum scanning capabilities of the selected symmetric lamb wave modes (S_o at 0.5 MHz), the transmitter and receiver transducer are set at respective angles in pitch catch configuration. Initially, the probes are set to have a propagation distance (D_p) of 100 mm and the PT signature are recorded. Subsequently, D_p increased in steps of 20 mm and the PT signature are recorded at each incremental position.

The variation in the arrival time and the normalized voltage amplitude of the transmitted pulse with increasing propagation distance for S_o mode at 0.5 MHz (**Figure 4.8**) is plotted.

4.6 SUMMARY

In this chapter we investigated the propagation characteristics of different guided lamb waves in CFST structure which would be further used to develop an in-situ and non-invasive health monitoring strategy for CFST structures. In such large structures, where the principal motive is detection of defect, the propagation characteristics of different guided wave modes would eventually help to develop a damage detection strategy for structure wherein a pair of immersion mobile transducers can collect the information about health of CFST structure. Specific ultrasonic guided wave modes with unique scanning capabilities have been identified experimentally. The different guided wave modes were generated and excited by keeping the transmitter and receiver transducer at suitable pitch catch configuration. The selected lamb wave would be further investigated for optimum scanning capabilities in CFST structure with different types of damages.

CHAPTER 5

MONITORING OF CFST WITH DEFECTS AND DAMAGES

5.1 INTRODUCTION

In previous chapter, we have discussed about ultrasonic guided wave propagation in CFST and it will further utilized to develop damage detection methodology. At frequency 0.5 MHz different lamb wave mode can be used to obtain PT signatures of the healthy and damage CFST specimen. The variation in PT signature with increasing damage in form of notches in specimen will guide to development of health monitoring strategy for the CFST specimen. Particular guided wave mode is selected to identification of notches and subsequently used for damage detection and identifying its location. Main focus of this chapter is to develop a in-situ methodology for rapid assessment of the health of a CFST specimen.

5.2 EXPERIMENTAL INVESTIGATION

5.2.1 Excitation Frequencies and Modes

The complexity of guided waves over bulk waves is their interpretation of correct signal used for healthy monitoring purpose. The complexity is because guided waves are dispersive in nature, multimode behavior and frequency dependent energy distribution profile of these modes. So it is difficult to judge optimum frequency lamb wave mode to evaluate presence of damage. Previous chapter discuss about selecting particular lamb wave modes by varying angle of transducer in pitch-catch orientation. PT signature obtained at 0.5 MHz is likely to get affected due to damage in specimen. So, PT signature involves great potential of non-destructive damage detection testing tool.

This chapter discusses about contact of Lamb wave modes with replicated damage and studies about the suitability of these modes to productively distinguish the degree of the damage. For detection of simulated damages, notches are made with varying depth on specimen with thickness of 3.2 mm. Dispersion curve showing group velocity (**Figure 4.7a**), phase velocity (**Figure 4.7b**) and attenuation (**Figure 4.7b**) characteristics of selected Lamb wave modes in (pavlakovic and cawley, 2000). Some essential parameter of guided wave propagation behavior of distinct mode is detailed in the **Table 5.1**. Lower frequency transducer is used to inspect

longer spans. A pair of 0.5 MHz rated frequency transducer have been used to develop methodology of damage detection in CFST specimen.

Table 5.1: Propagation characteristics of modes from dispersion curves

S. No.	Frequency (MHz)	Mode	V _{ph} (km/s)	Angle (θ)	V _{gr} (km/s)	Attenuation
1	0.5	A_1	2.6623	90°	3.14805	158.95
2		S_o	5.3105	31°	4.832	0

S_o Mode at frequency 0.5 MHz will be further used for experimental validation of specimen with varying depths of machined notches to develop a damage detection methodology.

5.2.2 Experimental setup and methodology

The 0.5 MHz frequency transducer at S_o mode is used for developing damage detection methodology in pulse transmission mode (PT). Firstly scanning of specimen is done to obtain the standard baseline signature. Then the specimen is seeded with machined notch of depth of 25% of thickness (0.5 mm) and PT signatures are again noted. After this the notch is depth gradually increased up to 75 % (3 mm deep) of thickness of specimen in steps of 25% (0.5 mm incremental depth) of plate thickness each and PT signatures are recorded for each depth of notch (**Figure 5.1**). During experiment parameters like propagation distance (D_p), PR settings (gain, HPF, LPF) are kept constant.

For experimental study on CFST specimen with and without notches, the experimental setup and transducer and ultrasonic transmission system kept same as in chapter4. For generating particular mode, the transducers are placed at particular an angle on Perspex semi cylinder with pitch catch orientation (**Figure 5.2**). Both transducers are at same angle (θ). The Ultrasonic excitation is a skewer pulse got when PR is set at the most extreme voltage amplitude of 900V. The ultrasonic energy in the form of longitudinal wave's generated by the transducers travels through the Perspex and hits the specimen at an inclined angle. Some part of this energy is transmitted in the specimen in the form of Lamb waves and left part of energy is reflected back. Receiving transducer receives reflected part of energy and forms PT signature.

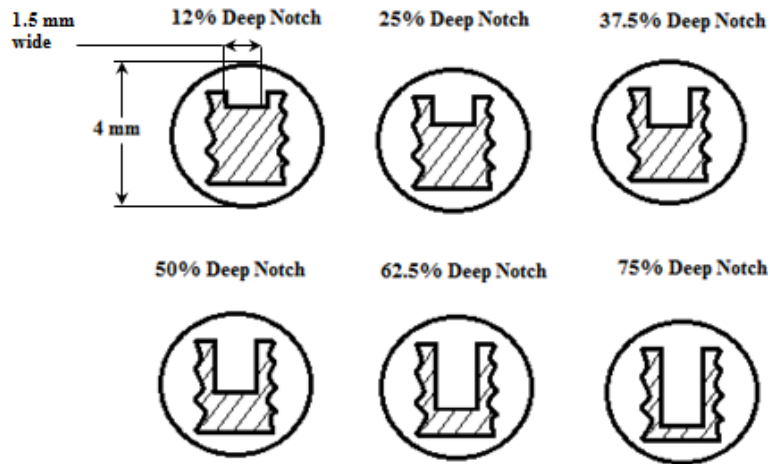
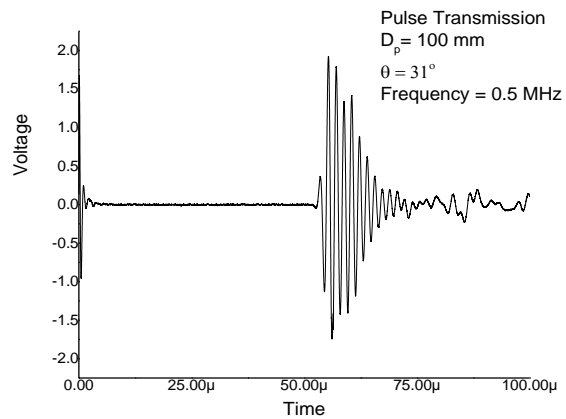


Figure 5.1: Notch Geometry Details (1.5 wide and depths varying from 0.5 mm to 3 mm with 0.5 increments)



Figure 5.2: Transducers are placed at 31° angle on Perspex semi cylinder with pitch catch orientation

The specimens were tested in PT mode after setting the transducer. PT signatures with healthy specimen are recorded with S_0 Mode at frequency 0.5 MHz rated transducer. A specific mode can be obtained by placing transducer at a particular angle of incidence (**Table 4.1**). **Figure 5.3** shows PT signature in healthy specimen with S_0 Mode at frequency 0.5 MHz rated transducer.



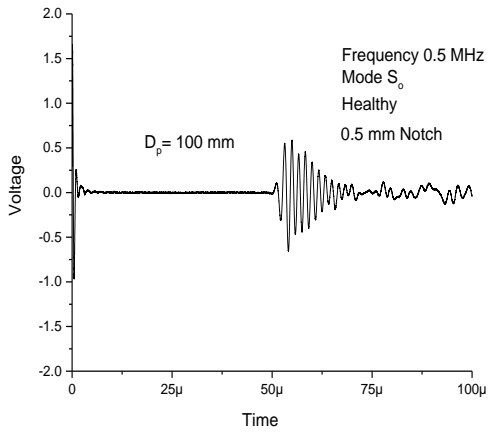
PT signatures at 0.5 MHz frequency

Figure 5.3: Pulse Transmission signature at $\theta=31^\circ$

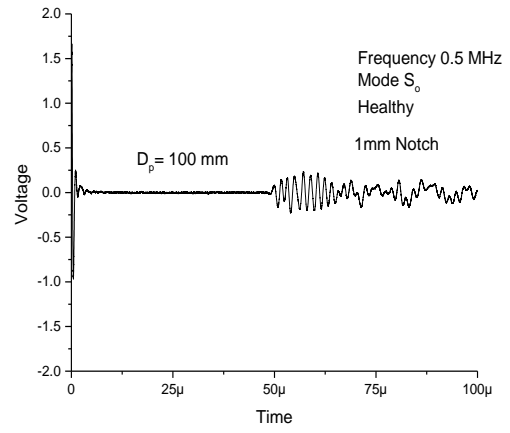
The experimental methodology comprises of scanning the specimen with varying defects in PT to detect the damaged areas in the specimen. Correlation of the received PT signatures in the notched specimen vis-à-vis the healthy specimen would prompt to finding damage.

5.2.3 Ultrasonic Pulse Transmission Investigations

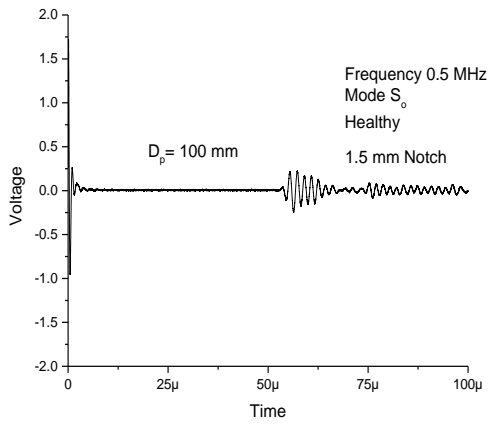
PT signals are likely to change due to presence of damage on the specimen. PT signals have unique signal distribution across the specimen thickness, each signal formed due to unique response of ultrasonic wave to notches of varying depths. In order to exploit the lamb wave mode is expected NDE tool, it is important to select those modes which are more sensitive to the type of defects being investigated. Modes which can exhibits to largest variations in signal amplitude of the transmitted pulse for a notched specimen vis-à-vis healthy specimen are most suitable and are preferred.



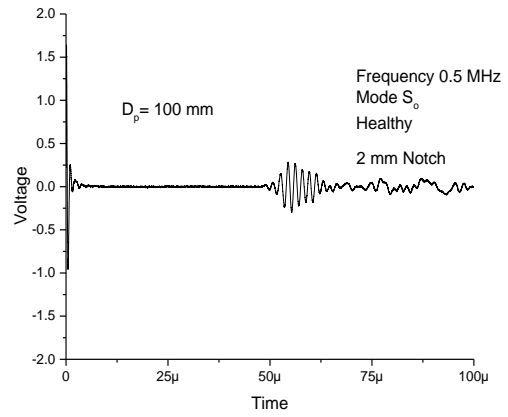
(a)



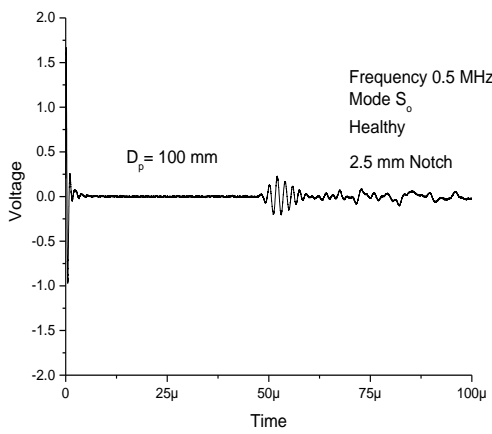
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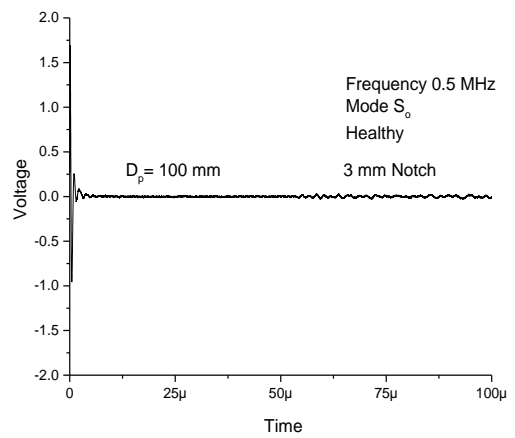
(c)



(d)



(e)



(f)

Figure 5.4: Pulse Transmission signature with varying depth of Notches

Figure 5.4(a-f) shows PT signatures recorded using with S_0 Mode at frequency 0.5 MHz for CFST specimen having changing depth of notches. As the notch depth increases, the signal amplitude of the received signal decreases. Hence, as the depth of notch increases then more energy reflected back from notch and less energy transmitted to the receiver (**Figure 5.4**). So, this methodology can successfully detect the presence of notch and possibly quantify their extent.

5.3 CFST WITH DEBONDS/DELAMINATION

For debond/delamination investigation, another set of CFST specimens with increasing length of debond between tube and concrete was prepared. Debonding/delamination between steel and concrete was created by pasting square sized PVC sheets of various sizes 40mm x 40mm (S1), 60mm x 60mm (S2) to inner surface of hollow pipe in the middle portion of steel tube prior to filling the concrete inside (**Figure. 5.5**). This indicated increasing debonds between steel tube and concrete of CFST section. The PT signatures were also taken on these simulated debond samples and compared with healthy signal to study the effect of delamination on PT signals.

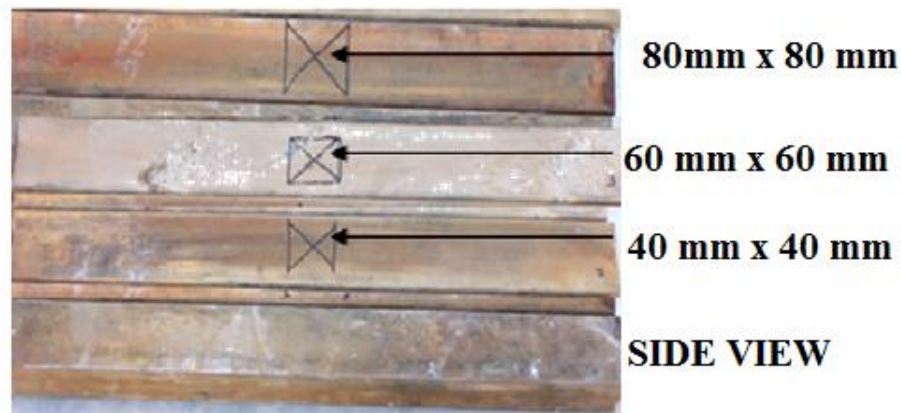
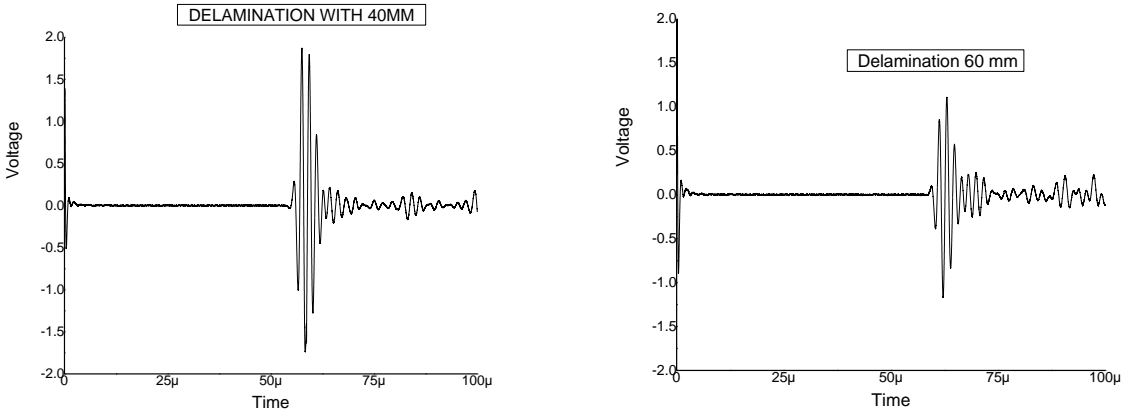


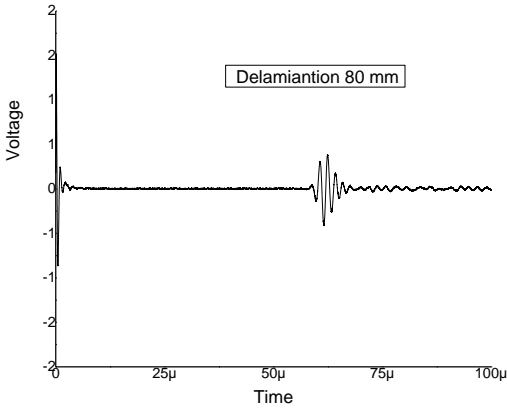
Figure. 5.5 Simulated debond specimens

Ultrasonic pulse transmission signatures were recorded in healthy CFST specimens **Figure 5.3** and compared with the signatures obtained with increased debonding using S_0 mode at 0.5 MHz. PT signatures recorded using S_0 mode at 0.5 MHz with increasing debond are shown in **Figure 5.5**. It is observed that there is increase in the ultrasonic signal as the area of

delamination increases. As the debond increases, there is a rise of 38.4 % in S1, 56.8% in S2 and 94.3% in S3 as compared to healthy signal. This is due to reduction in leakage of signal with increase in delamination causing rise in signal strength. Hence, increase in signal strength points towards delamination of the tube from surrounding concrete. Quantitative change in signal amplitude can be used to correlate with the extent of delamination. Hence, increase in debond is marked by rise in signal strength is well picked up by the low frequency mode. The investigation using the 0.5MHz low frequency modes are further used for picking up actual corrosion in CFST sections.



(a) Specimen with Delamination 40 mm and (b) Specimen with Delamination 60 mm



(c) Specimen with Delamination 80 mm

Figure. 5.6 PT signatures with increasing delamination (S₀ mode at 0.5 MHz frequency).

5.4 SUMMARY

This chapter brief about a in-situ damage detection (monitoring) methodology in form of simulated notches and debonds/delamination. Pair of ultrasonic transducer is used to quantifying and detecting the defects in CFST specimen. The application of this methodology is to compare healthy specimen with varying depth of notched specimen to identify the damage in specimen. For identifying delaminataion in CFST, increasing length of debonds were used. S_0 Mode at frequency 0.5 MHz is used in this methodology. This methodology is successfully applied to healthy specimen compare with notched specimen and delamination specimen and corresponding damage/defects can be identify on the specimen.

CHAPTER 6

CFST UNDERGOING ACCELERATED CORROSION

6.1 INTRODUCTION

Degradation due to environmental attack to steel confining the concrete (CFST) is one of the major durability problems faced by engineers to maintain these structures. There are many techniques available for early stage corrosion detection like Radiography, infrared thermograph, Half-cell potential etc. but they have limitations of high cost, complicated, highly skilled operator. Hence there is a need to develop a technique which has real-time monitoring and mass loss assessment for CFST structure.

In this chapter, methodology is developed for corrosion monitoring in CFST structures undergoing actual accelerated corrosion. Proposed methodology also attempts to predict the flexural strength of the corroded structure. Pulse transmission method is used to monitor corrosion with respect to day. The Destructive testing of CFST has also done to measure compressive strength after corrosion.

6.2 COMMON CORROSION TYPES IN CFST STRUCTURE

Generally CFST structure experience uniform and pitting corrosion beside of corrosion like crevice corrosion, galvanic corrosion, in restricted degrees (**Titcomb, 1982**). In CFST structure inside concrete serves as electrolyte so there is many chance of having corrosion inner surface as well as outer surface. CFST structure is also used for offshore or marine structures. Generally corrosion occurs in stationary or flowing seawater around a rate of 2-12 microns per year on mild and low-alloy steels. The corroded CFST structure loses strength and it cannot withstand the structural loads. The rust generally has a steady thickness and correspondingly constant over the surface.

Another form of corrosion which is boundless in a specific area in CFST structures is pitting. It is another type of corrosion that leads the process of pitting into presence of small pores into the metal. This form of corrosion is self-generating, i.e. autocatalytic, beginning from irregularity on the metal surfaces, under scale, then again from a few in-homogeneities in the

metal. This kind of corrosion is extremely gradual and causes mass loss of material with little impact on its surface, while it damage the deep structure of the metal leading to catastrophic failures. The pits at the surface are frequently concealed by corrosion products this chapter discusses the concept to detect corrosion in CFST structures. .

6.3 GUIDED WAVE MODES FOR CORROSION MONITORING

The methodology includes the application of ultrasonic guided wave approach for monitoring corrosion in CFST structure. This chapter presents the comparative study of the damages inflicted by machined notches and the actual corrosion. Two transducers with rated frequency of 0.5MHz have been used for monitoring corrosion. In previous chapter, the viability of utilizing the particular guided wave mode of S_0 at 0.5 MHz frequency for identifying notches in CFST has been illustrated. It has been established that each lamb wave mode interfaces exclusively with the notch defects. S_0 Mode at 0.5 MHz is relatively insensitive to the notches that are not deep and is better suited for identifying deeper notches.

The performance of S_0 mode at 0.5 MHz is responsive to wide range of pitting corrosion due to its wave structure that has more vitality accumulated at the mid plane of specimen. This S_0 mode is referred to as *core sensitive mode*. In this work, the S_0 mode is investigated for their appropriateness for detecting surface and pitting corrosion in CFST structure.

For developing corrosion monitoring strategy, a comparative study has been done by scanning healthy CFST specimen and corroded CFST specimen in pulse transmission mode (PT). By comparison of both specimens the standard signature has been developed. Hence, this healthy signature has been used to evaluate the extent of corrosion in the CFST.

6.4 ACCELERATED CORROSION STUDIES

As mentioned previously, the corrosion in CFST structures remains on the surface while pitting goes to deeper into material. The appearance of correlation of S_0 modes differently with shallow and deep notches gives a possibility of perceptive the two types of corrosion monitoring by applying the S_0 modes. This section discusses the experimental details of guided wave monitoring in CFST component corrosion undergoing in the chloride environment. Structure has been subjected to accelerated corrosion and corresponding changes have been observed by the present technique utilizing selected lamb wave modes.

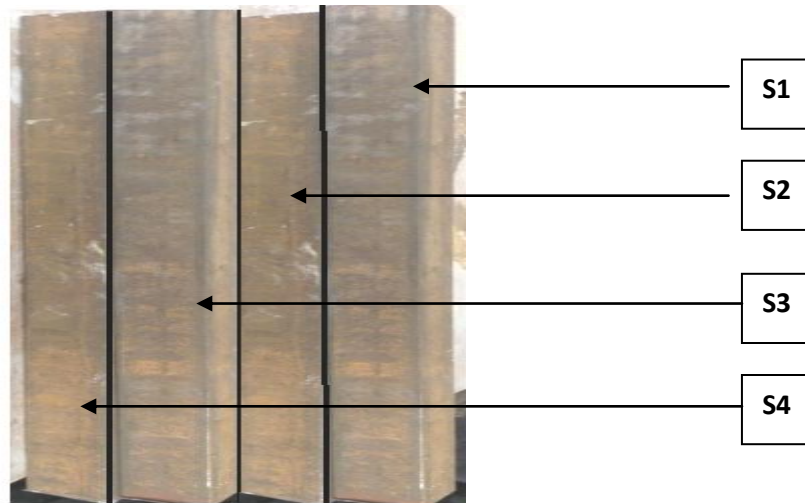


Figure 6.1: Actual CFST specimens used in accelerated corrosion monitoring Experiment

6.4.1 Experimental Set-up Details

Usually corrosion is a slow process and it takes long time to develop. In this study corrosion has been accelerated by using impressed current technique. Healthy CFST specimen (600mm x 72mm x 72 mm) is scanned by PT method using S_o mode at marked areas. The mass of healthy specimen is also recorded. The specimen is subjected with immersed current corrosion technique. An acrylic tank filled with 3.5% brine water with dimensions (40mm x 60 mm x 50mm) without base is placed on top face of CFST structure for selective exposure of the specimen to corrosive environment. A copper strip is made as cathode and dipped into brine solution while specimen made as anode to complete the circuit. A consistent voltage of 24.6V was connected between the two terminals by the method of a fixed power supply (**Figure 6.2**). An external resistance (R) in series generated a current of 0.28 Amperes in the circuit.

The acrylic tank is dismounted after every 24 hours of exposure to accelerated chloride corrosion. Ultrasonic scanning of the specimen in corroded condition using S_o mode is done to observe the changes in PT signatures. Mass of specimen is also recorded in each cycle to find out loss in mass due to corrosion after every day. After the ultrasonic scanning, the tank is remounted on the specimen and the process of accelerated chloride corrosion is continued. This procedure has been repeated till PT signature vanished or the CFST gave way.

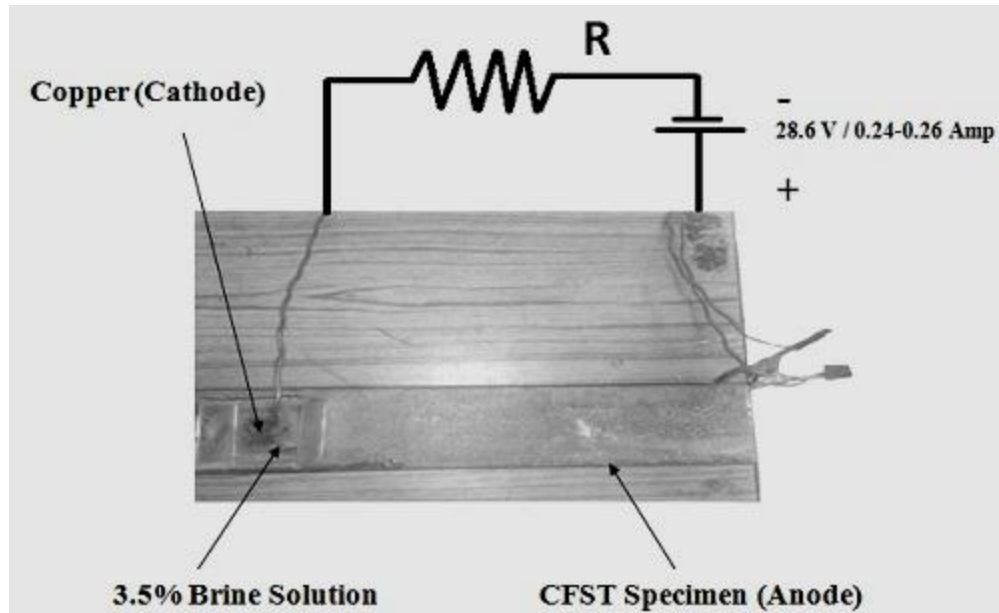


Figure 6.2: Accelerated Corrosion Set-Up

6.4.2 Results and discussion

6.4.2.1 Visual observations

CFST specimen expose to accelerated corrosion shows brownish corrosion debris volatile suspended in the acrylic tank in first 6 hours of exposure to corrosion. The brine solution turns into red-brown solution and it was refilled after every 12 hours to insure constant current in the corrosion circuit. Corrosion patches containing of small pits were noticed on the specimen after 40 hours of exposure to accelerated corrosive environment. The pits enhance and increase on the surface of the specimen with growing corrosion. After 3 days, extensive corrosion field were noticed (**Figure6.3a**).

At a constant rate of corrosion, consistent mass loss is observed every day. The process continued till 8 days and was stopped when pits was transformed to holes in the specimen (**Figure6.3b**). After this stage, corrosion exposure couldn't be preceded because brine solution starts spillage and PT signature almost disappears.

Marked locations for Recording PT Diagrams

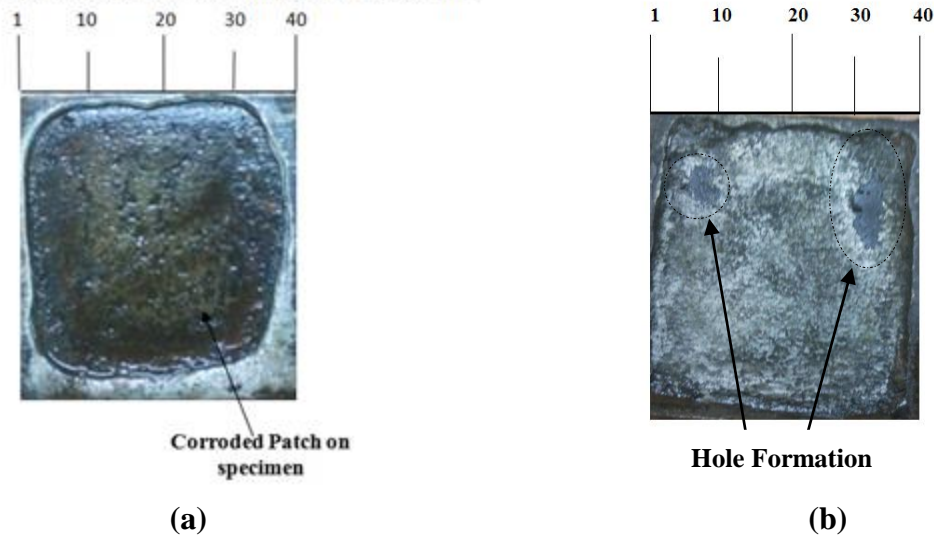
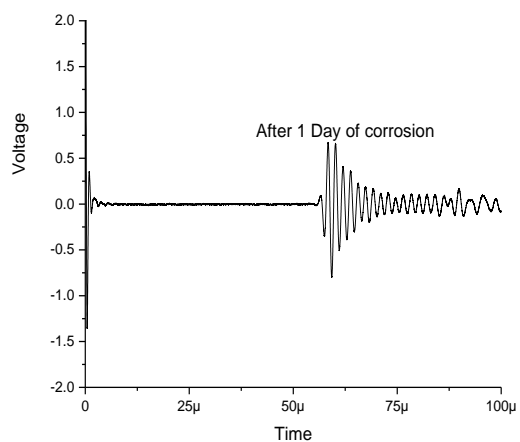


Fig. 6.3 Accelerated corrosion in the plate (a) after 5 days (b) after 8 days

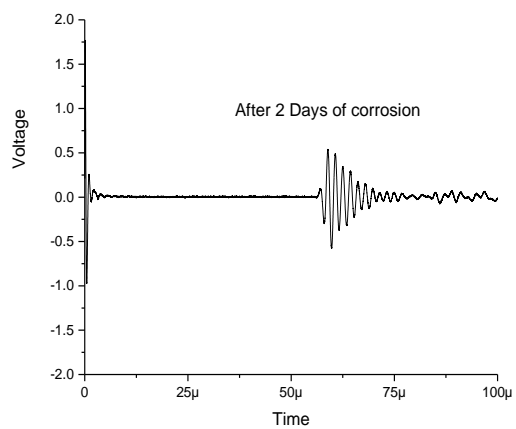
6.4.2.2 Monitoring with core sensitive mode (S_o mode at 0.5 MHz)

Ultrasonic PT signature was recorded repeatedly for the noted locations on the specimen using S_o mode at 0.5 MHz (**Figure 6.4a**) after every 24 hours of exposure. Due to corrosion, at location 10 material losses was maximum and PT signature was noticed shown in **Figure 6.4**. Initially for healthy specimen, the signature is recorded at middle location of specimen. With exposure to corrosion, changes are observed in PT signature.

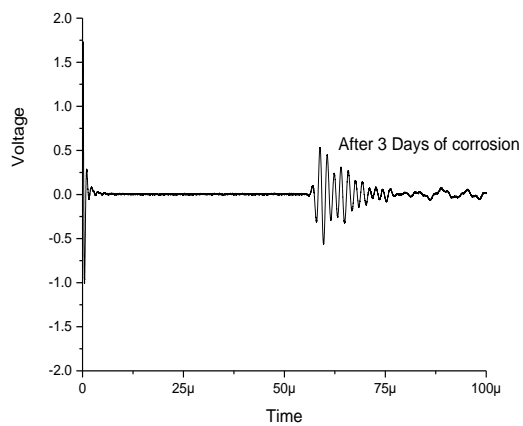
Sharp peak representing S_o mode at 0.5 MHz is fading rapidly with the increasing experience of corrosion. The decline in the signal amplitude is sharp in initial 6 days indicating its suitability to detect on set and initial phase of surface corrosion effectively. Further from 6-8 days, the signal drop was not very significant.



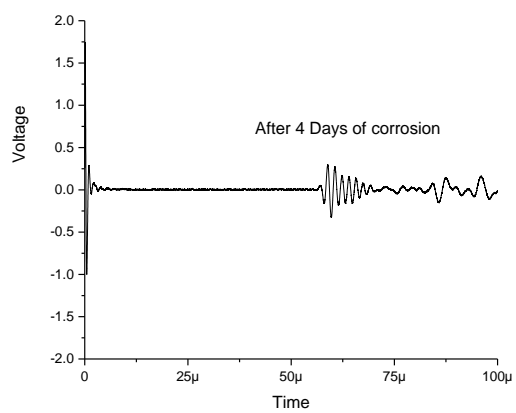
(a)



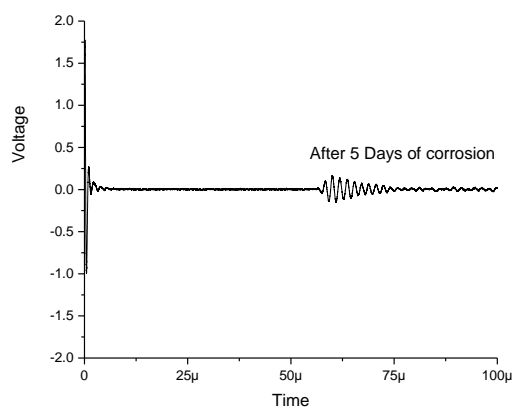
(b)



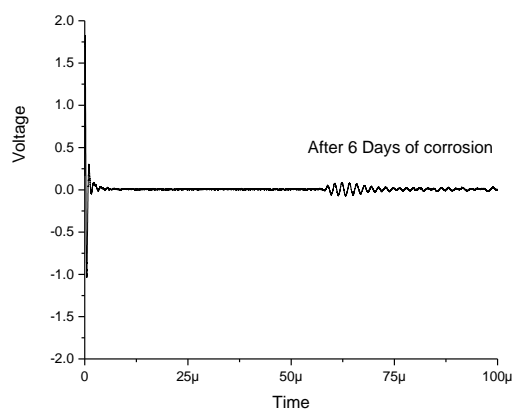
(c)



(d)



(e)



(f)

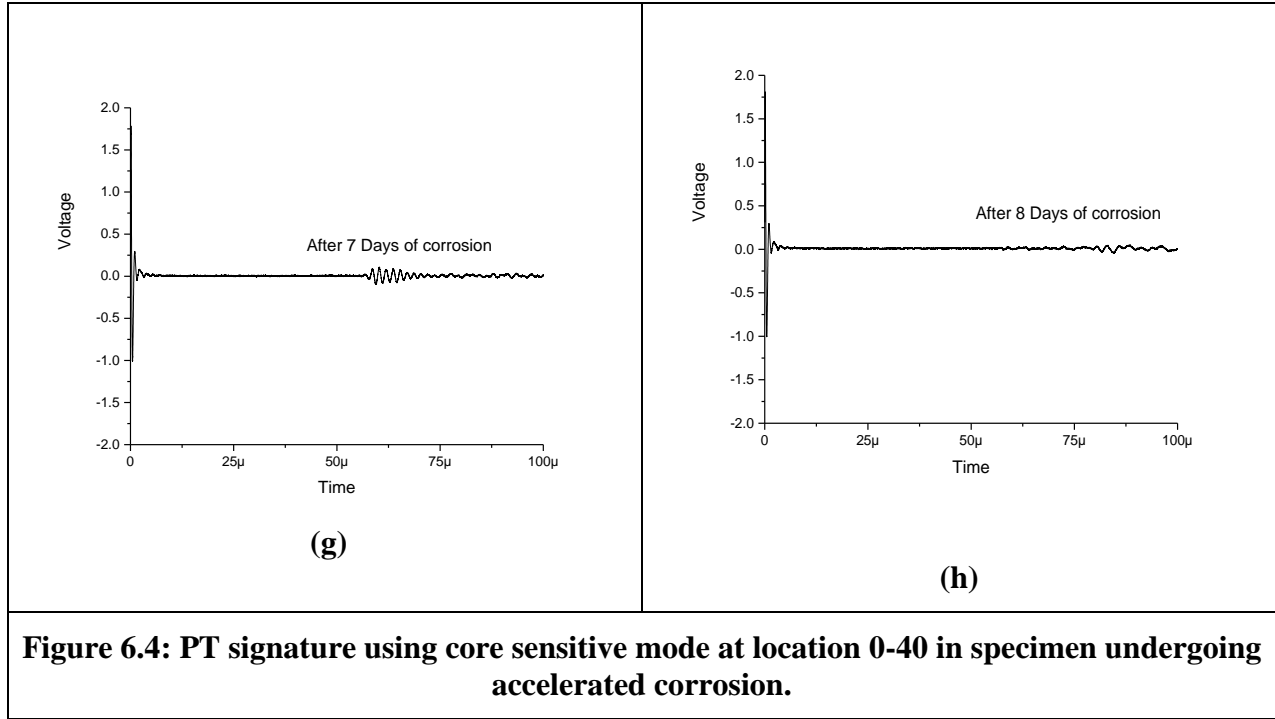


Figure 6.4: PT signature using core sensitive mode at location 0-40 in specimen undergoing accelerated corrosion.

V_n is referred as received peak to peak voltage amplitude of the transmitted pulse in the corroded specimen is normalized with respect to the corresponding peak to peak voltage in the healthy specimen. Through V_n it is possible to compare different signature on the same scale.

Figure 6.5 shows V_n at different area on the specimen using the S_o mode with progressive days of corrosion. The transmitted signature weakens with increasing exposure to corrosive environment showing material loss due to corrosion. Most extreme drop in voltage amplitude is seen at area marked 10-20 on the specimen. (**Figure6.3b**)

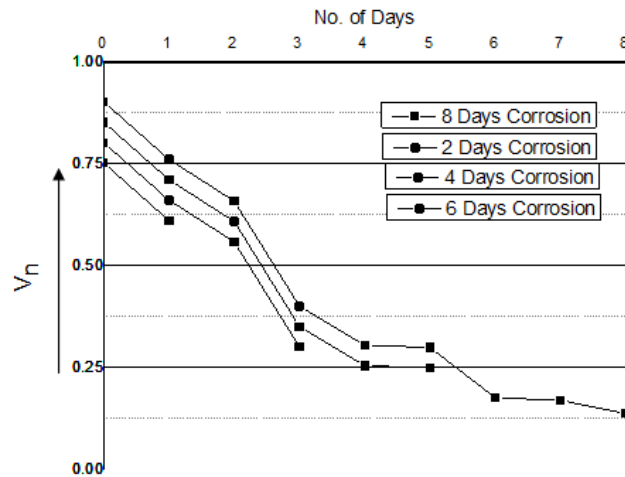


Fig. 6.5: V_n for specimen undergoing corrosion to different ages using S_o mode at 0.5 MHz

6.4.2.4 Corrosion method by means of guided wave

From above investigation of ultrasonic signature with S_0 mode, following observation can be made

- After 6 hrs, brine solution turns its colors to reddish-brown because of sediments occur in solution due to corrosion. After 24 hr PT signature was recorded this shows very small change in its signal strength.
- After 2 day of corrosion exposure, the signals drop is more due to extent of corrosion. Signal drop more increases as no. of days to corrosion increase due to mass loss increases.
- After first 5 days PT signature using S_0 mode falls rapidly indicates major surface changes occurring because of start of corrosion but insignificant core changes.
- After 6-8 days, S_0 mode shows very small changes with increasing disclosure to accelerated chloride corrosion environment. This demonstrates corrosion extends to further in specimen and not confined to surface, this zone referred as 'core corrosion zone'.

6.5 DESTRUCTIVE TESTING

6.5.1 Testing details

A destructive experiment was conducted for accelerated chloride corrosion of distinct stages to facilitate a possible calibration of ultrasonic guided waves with different ages and distinct stages of corrosion. In this test, flexural strength of specimen was measured. Four specimens (600 mm x 72 mm x 72 mm) are subjected to ultrasonic PT signature to record basic standard signature comparing to healthy state. The mass of these specimens were also recorded before exposure to accelerated chloride corrosion. Afterward, these specimens were introducing to accelerated corrosion of 2, 4, 6 and 8 days respectively. All parameters like concentration of brine solution, current setting etc were kept up constant for all specimens experiencing to accelerated chloride corrosion. All specimens were examined through S_0 mode after every 24 hours of corrosion.

Figure 6.4 establish graph of variations in ultrasonic voltages at different days of corrosion via core sensitive mode at a specific area. All outcomes demonstrate consistency in

results hence; ensure the repeatability in the experiment. The S_0 mode at 0.5 MHz is more responsive to profile change in examine the specimen and also demonstrates repeatable patterns for specimen test which is exposed to 2,4,6 and 8 days of corrosion. All specimens display a drop in ultrasonic voltages with expanding chlorides environment.



(a) Healthy



(b) 8 Days corrosion



(c) 6 Days corrosion



(d) 4 Days corrosion



(d) 2 Days Corrosion

Fig. 6.6: Flexural Testing of (a) Healthy (b) 8 days corroded (c) 6 days Corroded (c) 4 days corroded (d) 2 days corroded CFST specimens.

6.5.2 Destructive Experimentation and relationship with Ultrasonic Peak to Peak voltages

Loss in mass of specimen due to exposure to corrosion at different period was calculated along with the load-deflection curve behavior after the time of exposure was done. After a specified period of time the acrylic tank was removed and the specimen is cleaned with acetone to dislodge all corrosive products. Specimens are weighed to evaluate remaining mass. This action is done for all four specimens with every 24 hours of accelerated exposure of corrosion. The load deflection curve of all specimens is plotted in **Figure 6.7**. Stresses can be calculated by using original cross-sectional area of the specimen and strain can be calculated using extensometer. Healthy specimen shows a well defined ductile behavior with elastic and plastic region but corroded specimen shows the load deflection curves decreases representing lower strength in the samples. As no. of days to corrosion exposure increases, flexural strength of CFST decreases. We can observe from graph that after eight days of corrosion the flexural strength is very low because corrosion exposure was maximum. After second day, initial phase of corrosion starts so flexural strength of specimen was high. Flexural strength of specimen after sixth day rapidly falls due to corrosion was at its maximum extent. Hence, a huge loss in strength of corroded specimen, initially the properties of specimen were unaffected but as further load are gradually increase the elastic modulus and stiffness of specimen goes affected. This shows the catastrophic effect of pitting corrosion.



. **Figure 6.7: Destructive Testing**

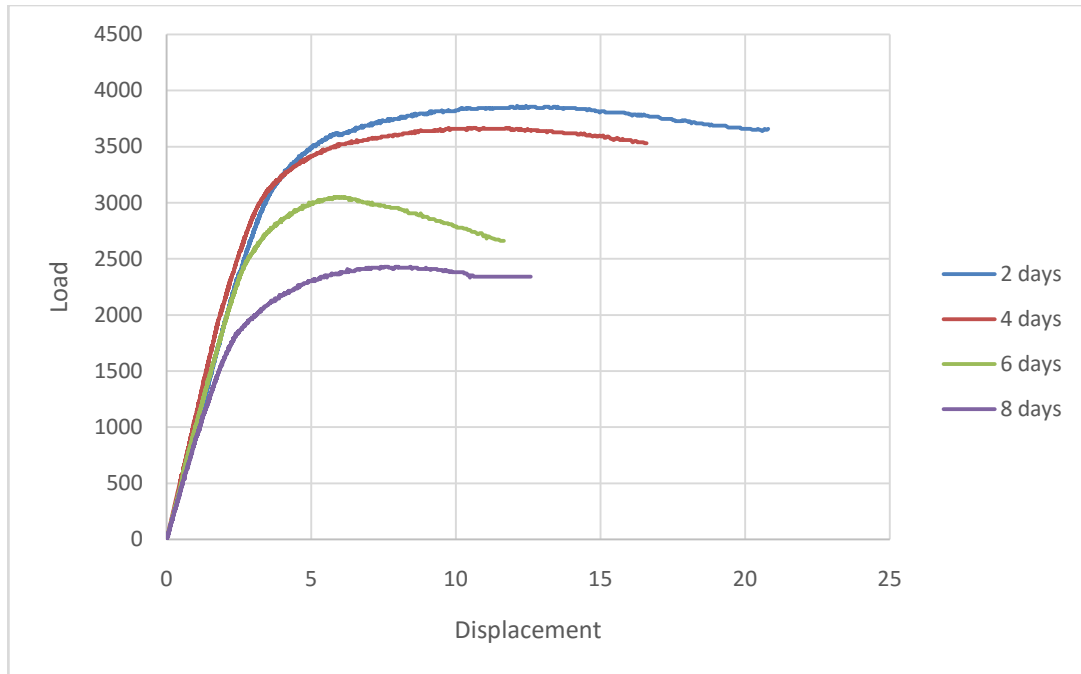


Figure 6.8: Load Deflection curves for CFST specimen at different ages of corrosion

6.8 SUMMARY

In this chapter, In-situ methodology for observing corrosion is developed. Core sensitive modes are used in monitoring CFST specimen experiencing accelerated immersed current corrosion in presence of chlorides. In this investigation a methodology has been developed for observing continuous corrosion and evaluating mass loss, strength and stiffness of the specimen. The flexural strength of specimen decreases with increasing rate of corrosion. So this methodology correlates the flexural strength with rate of corrosion.

CHAPTER 7

CONCLUSION AND FUTURE SCOPE

7.1 INTRODUCTION

Present work is engaged on generating a cost effective, in-situ health monitoring to quickly identify, locate the map of material loss in form corrosion on CFST specimen. CFST specimens are very difficult to monitor by conventional techniques due to inaccessibility constraints. In this work ultrasonic Lamb wave is used to identify and used as an impending and effective health monitoring tool. A pair of transducer arrange in Pitch-Catch orientation is used to scan the CFST specimen in PT pulse transmission modes. Sensitivities of particular Lamb wave modes to the variation of damage have been used to detect the degree of damage. This methodology was first develop for mass loss identification and also successfully applied to CFST specimen undergoing actual accelerated corrosion in chloride environments. Particular mode of ultrasonic guided wave is used to study the effectiveness as well as progression of corrosion in the simulation technique. Particular mode of ultrasonic guided wave could identify the onset as well as progression of corrosion in the specimen. The conclusion of present work is further summarized in the following sections

7.2 LAMB WAVE PROPAGATION IN CFST SPECIMEN

The propagation characteristics of different Lamb wave modes in CFST specimen geometries were inspected to establish a damage monitoring method. The CFST assemblies as in High-rise building and in-situ structure this method is very promising. Capabilities of guided wave at a particular mode have been excited and identified. Finally, the selected modes through CFST specimen would facilitate utilized for damage identification in specimens. Major conclusion drawn from the study of Lamb wave propagation in CFST structures can be summarized as:

- Distinct Lamb wave modes can be effectively produced in CFST structures specimen by orienting the transducers at a particular incident angles (θ) in pitch-catch orientation.
- Transducers must be placed on an o distance from the CFST specimen on the Perspex semi cylindrical block making equal inclination angle (θ) with vertical. If the distance

- of transducers is too large then signal will loss in surroundings. On the other hand if transducers are too close the signals will overlap with the initial pulse of transducers.
- After setting the transducers, ultrasonic testing of CFST specimen is carried out in pulse transmission configuration. The propagation distance (D_p) is the optimum distance that wave travel through specimen is set such that the signal fidelity is maintained for damage detection.
 - By using dispersion curve, theoretical considerations were confirmed with experimental generation of different modes.
 - Distinct Lamb wave modes exhibits distinct characteristics.
 - Specific mode is produced by changing the angle transmitting and receiving transducer both, but selection of mode is only depends on minimum attenuation for maximum scanning distance, good signal fidelity and the energy distribution profile across the specimen thickness.

7.3 CFST WITH NOTCHES

Guided Lamb wave mode with unique scanning capabilities is identified by monitoring their interaction with the seeded defects like machined notches. These modes were used to simulate the defects in the form of material loss in the specimen. By PT signal fidelity we can identify the extent of damage due to notch. Following conclusion can be made from the monitoring of a specimen with seeding notches:

- S_o Modes are sensitive to core of the specimen. So the damage is identified using Core Sensitive Modes.
- S_o Mode is further employ for in-situ scanning of CFST specimen to detect the presence, location and extent of damage.
- Scanning of CFST specimen through PT pulse transmission helps in detecting the issue of areas in the specimen due to damage. Degradation in PT signal could used to correlate the extent of notches. Effective combination of parameters like frequency, incidence angle expedite to comprehensive monitoring of the specimen.
- S_o Mode is more responsive to damages throughout the thickness of the specimen. This mode is also used for defect localization.
- This methodology can also be utilized for multiple notches of varying depths.

7.4 CFST WITH DEBONDS/DELAMINATION

The expansion in the received signal quality with expanded zone of delamination focuses towards expanded debond of steel tube from concrete causing less leakage of and rise in signal strength. This experiment concludes that if inside corrosion occurs then, there will be debond/delamination will occur inside the steel tube. From this PT signal strength will increase. By comparing PT signature from healthy and delaminated specimen will can analysis and evaluate the rate of corrosion.

7.5 ACCELRTATED CORROSION STUDIES

The damage identification technique developed for machined notches was extended to CFST specimen undergoing accelerated corrosion in chloride environments. A combination of the selected guided wave mode could effectively find out different corrosion mechanism occurring in the specimen. In addition to ultrasonic signals, destructive testing parameter of mass loss, flexural strength etc. of the specimen at various stages of corrosion has been monitored. Important conclusions derived from this study can be compressed as:

- The synergy of particular core sensitive Lamb wave mode with specimen experiencing accelerated progressive corrosion show similar pattern as with notches.
- These particular ultrasonic Lamb waves of core sensitive mode are used to identify the progression of corrosion deep in the specimen. Pitting corrosion could be discerned by the selected core sensitive mode.
- Specimens at various level of corrosion were ultrasonically monitored to investigate the capacity to predict the level of degradation of the specimen. It was done by pondering interaction between ultrasonic PT signatures and destructive parameters of mass loss and flexural strength.
- This ought to encourage assessment of wellness of the specimen for their intended purpose in corrosive conditions.
- By a skillful selection of ultrasonic guided wave mode complete corrosion occurring in CFST assemblies can be monitored using a pair of transducer.

7.6 FUTURE SCOPE OF RESEARCH

For real time monitoring of damages in CFST specimen, ultrasonic guided waves utilizing specific core sensitive modes can be successfully used. By judicious selection of

particular Lamb wave modes, it is possible to identify deep notches as well as the effect of chloride induced corrosion in CFST specimen. The capacity of ultrasonic to anticipate the level of weakening in the CFST specimen because of corrosion and to connect with the physical state of the specimen at various phases of consumption is effectively investigated. ULTRASONIC GUIDED WAVES can be actualized for health Checking of CFST structures and there is a great deal of potential future research in this area.

- To develop effective numerical method to model propagation of Lamb waves through CFST specimen.
- To investigate about the impact of turbulence, temperature variations in the coupling medium.
- To increase the execution speed, the signal handling device can be used for speedier and effective extraction of components from the signal.
- To build up a robotic setup including mechanical autonomy helps to do defect observing of a CFST structures.

7.7 SUMMARY

This investigation is a stage forward and ought to be helpful in building up a non-invasive, in-situ, and in-service damage observing method for CFST structures and their assemblies in pattern of notch, cracks, indentation and progressive corrosion due to environmental effects. In addition to this method their decay in quality, firmness, and mass loss are also important for the aspect of evaluation effectively endeavors to evaluate because of Consumption due to corrosion and it associates with ultrasonic voltages that would help in the non-destructive estimation of flexural strength of the structure.

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