2.1 GENERAL

In the recent years, the non destructive techniques such as radar, ultrasonic pulse echo and impact echo are gaining importance for the condition assessment of concrete structures similar to that of the traditional methods such as rebound hammer and ultrasonic pulse velocity methods. The Ground Penetrating Radar (GPR) shortly called as radar technique is a very effective method for investigating the integrity of concrete, thickness measurement and reinforcement identification in concrete structures. The Ultrasonic Pulse Echo is a one-sided technique which can be used for the thickness measurement, localization of reinforcement and ducts, and the characteristics of surface cracks. The Impact-Echo (IE) method is used to detect thickness, voids, honeycombing of concrete and masonry structures. The overall review of these techniques for the condition assessment of concrete structures is given in the following sections.

2.2 GROUND PENETRATING RADAR (GPR)

Bungey J.H. et al. (1993) used a technique called simulation tank which consisted of an emulsion of oil and water and the proportion of water and oil was formulated in a way that it was equivalent to the dielectric constant of concrete. It was reported that this method is not suitable for assessing concrete slab specimens or concrete structures in the field. Failure to allow for differences in relative permittivity could lead to an error in cover estimation of up to 30% in some cases.

Micheal et al. (2003) in their work used GPR for subsurface exploration and monitoring. They have used for inspection of various foundations floor systems such as structurally suspended slabs, retaining walls, decks, tunnels, balconies and garages.
Several case studies were carried out to locate rebar, tension cables, grade beams, conduits, voids and slab thickness. From the studies and experiments, they found that GPR provides an efficient and versatile means for concrete evaluation studies. The rebar, tension cables, grade beams were successfully located and the thickness of slab member was determined.

Maierhofer.C. (2003) presented the application of Ground Penetrating Radar for nondestructive evaluation of concrete infrastructure. The possibility of performing nondestructive measurements quickly and with convenient recording of the measurements results is particularly beneficial. The technique is well-suited for locating tendon ducts at depths down to 50 cm, detecting voids and detachments, and measuring thickness of structures that are only accessible from one side. This paper shows that GPR can be used for regular inspection, searching for the cause of damaging, and quickly assessment of civil engineering structures. This case study demonstrates the wide range of application of GPR for nondestructive investigation of concrete structures. Data interpretation can be simplified by the analysis of 3D data cubes and visualization of slices in different orientations. To detect the structure behind reinforcement, the relative polarization that suppresses reflections from rebars should be selected. When several reinforcement grids are laced inside the concrete structure, the GPR technique cannot supply definitive results as the electromagnetic pulses are almost completely reflected and do not penetrate in to the element. Another disadvantage is that when the moisture content is too high, the absorption of electromagnetic waves increases sharply and scattering effects are enhanced. They have concluded that the antenna frequencies from 500 MHz to 2.5 GHz have yielded very good results for inspection of concrete structures.
Vincent Utsi et al. (2004) discussed that Ground Penetrating Radar is one of the methods used for the determination of depth and position of reinforcement bars in concrete. Recent work suggests that GPR can also be used to estimate rebar diameters. This work presents the results of GPRmax3D simulations for two centre frequencies of GPRs applied to a range of rebar sizes at different depths. This is compared with real measurements of different rebar sizes in air using a 4GHz GPR system. A further comparison is made with measurements of rebar depths and sizes obtained from a practical GPR survey of ceilings in a series of prefabricated blocks of flats originally erected in the late 1960s.

Shaw et al. (2005) focused their work on the use of neural network approach to automate and facilitate the post processing of ground penetrating radar results. Signal reflections from reinforcing bars displaying hyperbolic image are detected using multilayer perceptron (MLP) network. The results show that the use of MLP network approach could be effective in the identification and location of embedded steel reinforcing bars. Casting of a large number of specimens was impractical and so an alternative approach known as simulation tank which was filled by oil/water emulsion was used. This emulsion was designed to have similar dielectric and conductive properties of real concrete and so large number of data were taken efficiently and cheaply. A radar SIR-2 model of Geophysical survey and system instruments (GSSI) was used for inspection and 1 GHz antenna was used. Encouraging successful results were obtained in bar identification, lateral positioning and depth estimation. Promising results were obtained but further development is essential.

Andreas Loizos et al. (2007) used GPR to capture continuous pavement layer thickness. The present paper focuses on the accuracy of pavement asphalt layer thicknesses estimation using GPR data analysis by employing different estimation
approaches based on material dielectric properties. The control unit of the GPR system was connected to a 1 GHz air-coupled horn antenna which operates as a transmitter and receiver together and has a penetration depth ranging between 0.5 m and 0.9 m. During the data collection the antenna was suspended approximately 0.5 m above the pavement surface. A comparative analysis of GPR data and asphalt-drilled cores data incorporating a variety of pavements was performed. Pavement thickness measurements are necessary for quality control purposes for new, reinforced or rehabilitated road pavements. Thus using GPR the thickness of old as well as rehabilitated pavements were determined accurately.

Frank Lehmann (2008) adopted radar for the inspection of tunnel lining thickness. Radar wave with frequency of 0.5 to 1.7 GHz is used. The in-situ groundwater had soaked the tunnel lining and thus heavily decreased the penetration depth. In parts, the usable depth range was well below the aim of 40cm and thus did not have the required reliability to test the whole tunnel lining. Additionally, concrete-grouting boundaries with little difference in electrical impedance can hardly be detected. It is clearly visible, that the concrete cover of the inlaid reinforcement decreases towards the crown. A following open cut confirmed a concrete cover of only 5mm. Ground Penetrating Radar for lining thickness determination was refrained from at a very early stage in the testing. The two decisive reasons were the following: It was not possible to distinguish the two cases ‘GPR penetration depth is too shallow’ and ‘lining thickness is adequate’. The difference in electrical impedance between adjacent layers was not big enough. A minimum required void thickness of 6mm was too big to draw conclusions about the bond quality.

Paulo J.S. Cruz et al. (2008) discussed the testing of prestressed concrete bridges using GPR. The main aim of their research is to show the strong need and usefulness of
radar technique, which can provide non-visible Information about structural geometry and integrity required for strengthening and rehabilitation purposes of bridges. GPR is used to locate tendon ducts and ordinary reinforcement which is fundamental in rehabilitation works. Inspection of bridge decks in case of prestressed concrete bridges is critical task but it is successfully carried by GPR which replaced radiography methods. Three large concrete bridges located in northern part of Portugal are inspected. In first two cases, the position of tendon ducts is located, which is a fundamental element of safety of bridges. In the last case study they detected different materials and construction defects. They concluded that the tendon ducts were in some cases shifted with respect to the original design location. They concluded that GPR is progressively replacing other techniques, such as radiographies, as it is usually considered faster and safer to apply.

**Che Way Chang et al. (2009)** used ground penetrating radar for the detection of cylindrical objects buried under concrete. Physical and theoretical modeling and experimental results of buried reinforcing steel bar were obtained and studied using measurements of radargram data. Reinforcing steel bars of radii 1.6 cm and 1 cm were detected and radius was estimated from radargram data. Several concrete specimens were cast and tests were carried on them to study the effects of varying reinforcing steel bars diameter in the GPR response. Depth of rebar and diameter of various bars were calculated. Digital image processing technique was used to enhance the quality of the reflected signal prior to its evaluation to get better results.

**Vega Perez-Gracia et al. (2009)** adopted ground penetrating radar technique to obtain an imaging the subsurface with maximum resolution. Horizontal and vertical resolution are related to the ability of the system to detect as different anomalies two close targets placed in the same plan or in a vertical plan, respectively. This work presents a resume
of several simple experiments made with two commercial 1.0 and 1.6 GHz centre frequency antennas. Raw data were obtained during the evaluation of modern or ancient structures. The images obtained in these evaluations are compared to the results obtained in the laboratory measurements. In laboratory, GPR measurements were carried out with a commercial 1.6 GHz nominal centre frequency antenna. GPR measurements allow determining the horizontal position of the bars when resolution was available to determine these targets as separated anomalies. Plain structures (experimental configurations, load bearing wall and slab) allow obtaining better resolution than more complex ones (historical building). Also, properties of the different materials affect the final resolution.

Bala.D.C. et al. (2010) used GPR for condition assessment and quality control of concrete pavements. 1000 MHz antenna was used and the presence of reinforcement along the road with its depth, concrete thickness was determined successfully. Data were collected in a grid format of dimension 2m x 2m with inter line spacing 10 cm between two adjacent lines in both X and Y. The presence of rebar which were covered with the RCC layer could be detected clearly. The rebar plan map with its array dimension (27 cm x 27 cm) was detected. The position of rebar from the top surface was detected. It was concluded that the radar technique was useful for the determination of second layer of reinforcements and also the underlying objects and that the presence of first layer affects the radar signals in penetrating further. The masking effect of rebars on the relatively deeper objects was observed in which some utility objects lying below the second layer of rebar and in the middle of the depth profile was not identified clearly.

Lai.W. L, Kind.T. and Wiggenhauser.H (2010) reported a new approach to evaluate corrosion of reinforcement in concrete by ground penetrating radar. Pulse GPRs were
used to monitor the continuous corrosion process in concrete, in which the changes of amplitudes, travel times and Short Time Fourier Transform (STFT) spectrograms associated with the bar reflections were continuously measured. The yearly long corrosion process of reinforcement bar was rapidly accelerated within 10 days by impressing 2A direct current across two embedded reinforcement bars serving as anode and cathode. When corrosion started, it was found that the travel times, amplitudes and the frequency spectra from the bar reflection reached a maximum or minimum, but the trends of these parameters were then reversed when the crack became wide open. The results presented in this paper will pave the way for future corrosion characterization using GPR, both in laboratory and in field.

Raktipong Sahamitmongkol (2010) discussed that the relationship between the amplitude of the reflected response of Ground Penetrating Radar pulse and the scanning angle is experimentally investigated. It is found that amplitude of a reflected radar wave increases when the size of rebar increases and changes with scanning direction. The amplitude of reflected radar wave from a rebar with specific size is maximized if scanning direction is perpendicular with the axis of reinforcing bar. Empirical formulation for the relationship between size of rebar and amplitude of reflected wave is proposed based on the experimental result. The method can be modified and applied for the detection of reinforcement arrangement as well as to measure the size of reinforcement in the actual reinforced concrete structure.

Piervincenzo Rizzo (2010) discussed that civil infrastructures such as bridges, buildings, and pipelines ensure society's economic and industrial prosperity. Quantitative and early detection of defects in pipes is critical in order to avoid severe consequences. This paper describes about the usage of ground penetrating radar for pipeline inspection. In pipe applications, pipes can be measured from the ground
surface or from the inside by moving the probing system along the pipe length. GPR
provides an accurate estimation of broken wires in some pipe segments. However,
some results showed that the number of broken wires in pre-stressed concrete pipes can
be either underestimated or overestimated. A second level of inspection for ferrous
mains would be the use of electromagnetic methods to ascertain the amount of pitting,
corrosion, or graphitization that has taken place.

2.3 ULTRASONIC PULSE ECHO TECHNIQUE

Thomas Voigt et al. (2003) studied the in situ testing of early age concrete strength
using ultrasonic technique and compared the wave reflection measurements on mortar
and concrete to strength. It is shown that the reflection loss is linearly related to the
strength gain of mortar and concrete at early ages. The experiments have revealed a
relationship between the homogeneity of the tested materials and the consistency of the
reflection measurements. The repetition of simultaneous measurements of wave
reflections and compressive strength on mortar results in similar strength-reflection loss
relationships. Multiple measurements on the same concrete gave multiple strength-
reflection loss relationships. The accuracy of the strength predictions made with the
proposed method is discussed and compared to that of other nondestructive test
methods.

Schickert et al. (2003) demonstrated the ultrasonic reconstruction by the Synthetic
Aperture Focusing Technique (SAFT) has a great potential to image concrete elements
and detect embedded objects. Its algorithm focuses ultrasonic signals received at many
aperture points by coherent superposition, yielding a high-resolution image of the
region of interest. Using this approach, several problems caused by the strongly
inhomogeneous structure of concrete are diminished, where scattering of transmitted
pulses leads to disturbing phenomena such as attenuation and structural noise. This
contribution is intended to review the work of the writers on the application of SAFT reconstruction to concrete testing. First, consequences of scattering of ultrasonic waves in concrete are qualitatively explained. Then the use of SAFT is discussed in comparison to traditional A-scan and B-scan techniques. Different reconstruction algorithms and implementations are presented for one-, two-, and three-dimensional SAFT. Pulse-echo measurement systems are described, which are able to acquire large sets of data on linear and planar apertures employing single transducer, transducer array, and scanning laser Doppler vibrometer arrangements. To illustrate the application of the SAFT techniques, examples from laboratory and field experiments are described comprising imaging of back walls, tendon ducts containing faults, layers, and reinforcement in concrete elements.

Hui Xiang et al. (2008) developed an algorithm to determine the dynamic properties of the concrete prism specimen through the progression of damage. The proposed algorithm used ABAQUS to simulate the dynamic response of the specimens. A MATLAB program was used to update the material properties by minimizing the sum of squared differences between the measured and simulated harmonic frequencies. Excellent agreement was obtained between the reconstructed elastic modulus values and values obtained by testing the prisms according to ASTM C 215.

Pristov Ed et al. (2011) studied the efficiency of the Ultrasound-Echo technique on a test slab with built in delaminations and air voids at known locations. They concluded that ultrasound-Echo method proved to be effective in the measurement of concrete slab thicknesses and in the detection of delamination and void areas. Using the measured P-wave speed gave accurate thicknesses in cases of known actual thicknesses. At the location of a delamination or air void the peak resonant frequency shifted from the thickness resonance to a low frequency resonance. In general, the low
frequency shift increased as the delamination size increased and as the depth decreased. A surface area plot of the collected data clearly showed the accuracy in identifying the delaminated and air void locations.

2.4 IMPACT ECHO METHOD

The Impact-Echo (IE) method was introduced by Sansalone and Carino (1986) and is used to detect thickness, voids, honeycombing etc. of concrete and masonry structures. The strength of the method is its ability to measure the thickness of concrete parts with good accuracy with one side accessibility such as foundation slabs, tunnel lining etc. Use of long wavelength low-frequency stress waves of impact-echo distinguishes with other traditional ultrasonic methods (Schubert, F and Wiggenhauser, H., 2004). The dominant frequencies that appear as peaks in the spectrum are associated with multiple reflections of stress waves within the structure, and they provide information about the thickness of the structure, its integrity, and the location of flaws (Ertugrul, 2005).

Sansalone M and Carino N.J (1989) demonstrated the feasibility of detecting delaminations in reinforced concrete slabs using the impact-echo method a non-destructive technique based on transient wave propagation. The results of two laboratory studies were discussed. One study involved detecting artificial delaminations embedded at unknown locations in a reinforced concrete slab. All the artificial delaminations in the slab were located. The second study was aimed at showing the feasibility of detecting delaminations in reinforced concrete slabs with asphalt concrete overlays. Two reinforced concrete slab specimens with corrosion induced delaminations were tested. Prior to overlaying the slabs with asphalt concrete, the depths of delaminations as determined by impact-echo testing were verified by drilling at selected points. After the asphalt concrete layers were applied, the slabs were
retested. It was found that the impact echo method could successfully locate the
delaminations in the slabs through the asphalt concrete layer.

Lin.J.M. and Sansalone.M.J (1996) summarized the results of a feasibility study in
which the impact-echo method was used to determine the interfacial bond quality in
layered concrete structures, such as in bridge decks with overlays or at the interface
between repair concrete and the concrete in the structure being repaired. In this context,

bond quality involves both the tensile strength and the amount of unbonded fraction of
area at an interface. This paper focuses on how bond tensile strength affects impact-
echo results. Results obtained from numerical (finite element), experimental, and field
studies were presented. The numerical studies were used to quantify the stresses in the
waves generated by elastic impact to determine whether these waves could be used as a
measure of bond tensile strength. Experimental and field studies were performed to
study impact-echo results obtained from a layered concrete plate with a variety of
interface conditions varying from strongly-bonded to delaminated as well as conditions
produced by removal of concrete by jack hammering and hydrodemolition. The pull off
test method was used to determine bond strengths in both the experimental and field
studies. The results showed that the stresses generated by short-duration (20 – 100μs),
elastic impacts are much too small to serve as a measure of bond tensile strength.

John S Popovics (1997) studied the effects of Poisson’s ratio on impact echo analysis.

An exact analysis model for impact echo data, Guided Wave Analysis (GWA), based
on elastic guided wave propagation theory was introduced and experimentally
demonstrated to be a powerful alternative to the existing Impact Echo analysis Model
(IEM). It was shown that the IEM model cannot account for changing values of the
material Poisson’s ratio, whereas the new GWA model can. Relationships among the
Poisson’s ratio, shear-wave velocity, and longitudinal wave-velocity of a material and
the associated impact-echo test results were developed through the use of the GWA model. This development involved a parametric investigation of predicted impact-echo test results for solid- and hollow-rod structures. The significant effect of Poisson’s ratio as well as longitudinal- and shear- wave velocity on such impact echo results was demonstrated, and directions of future work were suggested. Conclusions concerning the validity of the GWA and IEM models and the significance of IEM analysis errors, owing to the disregard of Poisson’s ratio as a significant factor, were also given.

Mary Sansalone (1997) discussed about the contributions of the people and the organizations that carried out the theoretical, numerical, laboratory and field studies that established the method and who developed the software and instrumentation that gave rise to a patented impact-echo field system. It also provides a unified explanation of impact-echo theory as it applies to the testing of structural elements, including plates (slabs, walls, bridge decks, pavements, etc.), bars (beams and columns), and hollow cylinders (pipes and tunnel and mine shaft liners) and to the detection of flaws within these elements.

Carino.N.J. (2001) described impact-echo method as a technique for flaw detection in concrete. The purpose of the paper was to provide an overview of the technique and to discuss the important parameters involved in this type of testing. One of the key features of the method was the transformation of the recorded time domain waveform of the surface motion into the frequency domain. The impact gave rise to modes of vibration and the frequency of these modes was related to the geometry of the test object and the presence of flaws. The principles involved in frequency analysis were discussed. The importance of the impact duration in relation to flaw detection and other factors affecting the smallest flaw that can be detected were also reviewed. The paper concludes with a summary of the ASTM standard governing the use of the impact-echo
method for measuring the thickness of plate-like structures. The author concluded that even though the use of frequency analysis has aided in interpreting test results, experience is needed in setting up optimal testing parameters, recognising valid recorded waveforms, and analysing test results.

Yiching Lin et al. (2002) developed a simple device for detecting the time of an impact demonstrated its efficiency in measuring the depth of surface-opening cracks in concrete. Surface-opening cracks in concrete were relatively deep so that a mechanical impact instead of an ultrasonic transmitter is used to generate stress waves with enough energy for successful evaluation. A technique called the time-of-flight diffraction technique with impact-generated stress waves was adopted for detection of surface-opening cracks in concrete. Because the initial time of the impact was unavailable in a mechanical impact device, two receivers were employed in the test. One of the receivers was used to determine the time of the impact indirectly. Laboratory studies were carried out on concrete specimens containing cracks with depths of 0.158 and 0.90 m. Field studies were performed on a dam damaged by an earthquake. Experimental results show that the new device can be used to accurately determine the crack depth in concrete. Using the device, the cost and effort for evaluation and signal analysis can be reduced, which largely enhances the evaluation efficiency.

Schubert F and Wiggenhauser H (2004) found that in the impact-echo testing of finite concrete structures, reflections of Rayleigh and body waves from lateral boundaries significantly affect time-domain signals and spectra. They demonstrated by numerical simulations and experimental measurements on a concrete specimen that these reflections can lead to systematic errors in thickness determination. These effects depend not only on the dimensions of the specimen, but also on the location of the actual measuring point and on the duration of the detected time-domain signal.
Sarah L. Gassman, and Waleed F. Tawhed (2004) performed impact-echo tests on a precast, reinforced concrete bridge slab that was removed from a maintenance bridge built in 1953 in South Carolina. Impact-echo tests were first performed to non-destructively assess the initial condition and the distribution of damage throughout the slab by analyzing the variation in propagation wave velocity. It was found that the velocity varied by as much as 900 m/s throughout the slab. After the in-service condition was assessed, the slab was subjected to a full-scale static load test in the laboratory and impact-echo tests were again performed, this time to evaluate the initiation and progression of damage (stiffness loss and crack development) within the slab. After structural failure of the slab, a reduction in propagation wave velocity up to 6% was observed correlating to a reduction in slab stiffness. Cracks were detected within the concrete slab that was not visible from the surface. It was found that areas with preexisting damage experienced more crack growth when subjected to the load test than those that were initially intact. Also locations exhibiting stiffness loss, crack propagation, and localized damage could be differentiated such that the method can be used to make decisions between rehabilitating and replacing concrete bridge decks depending upon the severity of damage.

Ufuk Dilek and Michael L. Leming (2007) assessed the fire damage of a concrete slab using the pulse velocity and impact-echo testing. Both the NDE techniques and the laboratory testing of thin disks identified the presence of damage as a result of the fire. Analysis of the relatively thin concrete specimens permitted assessment of the presence and of damage in thin layers, and provided important and degree useful data on concrete properties for engineering assessment which was not available from NDE alone. Compressive strength results were consistent with the results of other tests but largely inconclusive by themselves. Impact-echo testing was able to identify the
presence of a severely deteriorated concrete layer but could not identify the extent or depth of damage or clearly identify less damaged areas. A distressed layer of concrete was found by subsequent laboratory testing to be limited to a near-surface zone in some areas as suggested by the pulse velocity evaluation, but pulse velocity based analysis resulted in an overestimate of the depth of the damage. The findings highlighted a shortcoming of using conventional strength testing alone on investigations involving relatively thin layers of damage and pointed out several key limitations in the use and interpretation of nondestructive evaluation and associated analysis in a field assessment project.

Chiamen Hsiao et al. (2008) investigated the impact response of concrete blocks and studied the feasibility of using the impact-echo method for detection of flaws in concrete blocks. Numerical studies were carried out to acquire the transient responses of intact concrete blocks subjected to impact. In addition, the impact responses of concrete blocks containing flaws were explored. Numerical results were verified by experimental studies on concrete blocks with/without flaws. It was shown that the impact response of a concrete block was composed of frequencies corresponding to the modes of vibration of the block. Among these frequencies, there was a predominant frequency and its value depended on the geometry and dimensions of the block for a given P-wave speed in concrete. It was also shown that the presence of a flaw disrupted the modes of vibration. A shift of the predominant frequency to a lower value is a key indication of the presence of the flaw. In addition, multiple wave reflections between the impact surface and the surface of the flaw produce a large amplitude peak in the spectrum at the frequency corresponding to the depth of the flaw.

Algernon D., et al. (2008) used the scanning laser vibrometer and obtained the 2D visualization of the elastic waves propagating along the surfaces of concrete specimens.
Time slices were prepared so that the wave field becomes apparent. The results obtained provide an appropriate basis for the comparison with numerical results from 3-D Elastodynamic finite integration technique (EFIT) calculations. Examples were presented for the application with phased array ultrasonic echo, air-coupled ultrasonic echo and impact-echo.

2.5 SUMMARY

Based on the review of literature, it can be seen that a holistic approach is required for the non destructive evaluation of various elements and features in a reinforced concrete structure. The scope for determining the minimum spacing of reinforcement using radar, influence of the first layer on the determination of second layer, influence of the main/secondary reinforcements in the determination of ducts and the minimum size of void that can be determined using radar and ultrasonic pulse echo are promising.