Nondestructive test methods for concrete bridges: A review

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HIGHLIGHTS

- NDT techniques applicable to concrete bridges are reviewed.
- Different damage levels, NDT methods along with remedial measures are proposed.
- NDT methods are suggested to address specific problems related to structures.
- Importance of structural health monitoring for concrete bridges is highlighted.

ABSTRACT

NDT methods applicable to concrete bridges are reviewed. The methodology, advantages and disadvantages along with up-to-date research on NDT methods are presented. Different damage levels, having less dependence on inspector judgment, are suggested. Moreover, a flow chart based on damage level along with NDT methods and potential remedial measures are proposed for periodic health monitoring of structures. NDT methods are also suggested to address specific problems related to structures. Finally, the relation between some of the well-known NDT methods and most common problems encountered by the field engineers is proposed. Hence, the importance of structural health monitoring is highlighted.

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ACI, American Concrete Institute; AE, acoustic emission; ASTM, American Standards for Testing Materials; EM, electromagnetic; ER, electrical resistivity; GPR, ground penetrating radar; IE, impact echo; IR, impulse response; NDE, Non-destructive evaluation; NDT, Non-destructive test; PCC, plain cement concrete; RC, reinforced concrete; RCP, Rapid Chloride Ion Penetration; SAFT, Synthetic Aperture Focusing Technique; SHM, structural health monitoring; UPV, ultrasonic pulse velocity; VBM, vibration-based monitoring; VBDD, Vibration Based Damage Detection.

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1. Introduction

Maintaining safe and reliable civil infrastructures for daily use is important for the well-being of mankind. Operation and maintenance have become more complex with the increased age of the structures. The process of determining and tracking structural integrity and assessing the nature of damage in a structure is often referred to as health monitoring [1]. In history a lot of work has been done regarding infrastructure monitoring, inspection, repair, and design code specifications. For example, in United States of America in every two years almost 600,000 bridges are inspected and depending upon their condition they are scaled [2]. Federal Highway Administration defined the scaling system (0–9) for the rating of the structures, in which 9 stands for newly constructed bridge while 0 for failed bridge. According to this rating, more than 40% of the national bridges are structurally deficient or not functioning [2]. Moreover, the average life of a bridge in USA is 42 years while bridges are designed and constructed for at least 50 years [3]. Therefore, there is a great need for the health monitoring and maintenance of the concrete bridges [2].

Concrete degradation, steel corrosion, change in boundary conditions, and weakening of connections in structures over time are major concerns in highway bridges. If a damaged bridge remains unattended, the structural integrity and service capability of the bridge would deteriorate over time [4]. Therefore, frequent condition assessment and health monitoring of the highway bridges is required. Health monitoring of structures specially bridges can be classified into two broad categories i.e. global health monitoring and local health monitoring. Global health monitoring is the technique in which only the occurrence of damage is detected, while in local health monitoring, the extend, location and severity of damage is identified [1]. Both global and local health monitoring techniques are necessary and important for safe and sound operation of structures.

Non-destructive test (NDT) and nondestructive evaluation (NDE) offer skills to engineers and owners to speedily and effectively examine and monitor aging structures. These methods are used to detect the damage and used for local health monitoring of structures [1]. Moreover, NDT can prevent the unpredictable and premature collapse of structures. Various researchers have provided the guidelines and application of these methods for the evaluation of structures [5–13]. In this paper, we have reviewed various NDT methods which are applicable especially to concrete bridges. The methodology, advantages and disadvantages along with the up to date research on NDT methods are presented in Section 2. For better understanding, capabilities and limitation of the well-known NDT methods is presented in tabular form. The planning and selection of NDT methods is discussed in Section 3. Here, we have proposed different damage levels based on crack lengths, spalling of concrete cover, support settlement, tilting of foundation (due to settlement of subsoil or erosion of soil) and corrosion of reinforcement along with inspection type are suggested. These measurement units will provide relatively better information and less dependence on the inspector judgement. As field engineers and specialist are dissatisfied by NDT methods, a flow chart based on damage level along with NDT methods and potential remedial measures are proposed for periodic health monitoring of structures.

In this section, NDT methods are also suggested to address specific problems related to structures. Moreover, the relation between some of the well-known NDT methods and most common problems encountered by the field engineers is proposed. Finally, in Section 4, the conclusions and recommendations are covered.

2. Nondestructive Test (NDT) methods

In civil engineering field, engineers and specialists mainly used NDT methods for providing the counter check information related to structures rather than as an integral part of testing procedures. The main reason for this is the lack of awareness about testing procedures, equipment handling and data collection using NDT [6]. McCann and Forde [6], presented variety of NDT methods which are appropriate for civil structures. According to ACI 228.2R-98 [7], NDT methods are used in construction industry mainly due to following reasons.

- Quality control in new construction.
- Troubleshooting of problems.
- Condition assessment of existing structures.
- Quality assurance of repair works.

Furthermore, NDT methods are selected (a) If direct physical measurement is not possible or too expensive like monitoring of soffit of bridge on the river or sea. (b) When it is required to spread a limited physical analysis [6].

Non-destructive tests are classified on the basis of test sources, nature or methodology of tests and purpose of test. However, in this review paper, NDT methods are classified on the basis of test sources. The techniques which are based on the Audio–Visual characteristics of the operator are grouped in Audio–Visual methods while those techniques which use the stress waves for detection of damages and material properties are placed in stress–wave methods. The techniques which use electrical or electro–magnetic signals for material analysis are placed in the category of...
electro-magnetic methods while the techniques which give definite results are placed under heading of deterministic methods. Finally, in order to make this review paper more comprehensive, some other test methods like vibration method, Infrared method and Radiographic methods are also discussed.

2.1. Audio–Visual methods

2.1.1. Visual inspection

Visual inspection is one of the versatile and powerful NDT methods for inspecting visible surfaces. However, its effectiveness depends on the experience and knowledge of the investigator especially with structural behavior, materials and construction methods [7]. Visual inspection is most extensively used for monitoring the damages in concrete structures [1,7,14–18]. According to Perenchio [19], visual inspection is one of the first steps in evaluating concrete structures. It is a quick method for identifying the apparent and superficial problems. This method is rapid & inexpensive but it never offers detailed and quantitative information about the interior defects. It is normally carried out to determine cracking, seepage, spalling, exposed reinforcement, staining, moisture ingress, beam delamination, concrete deterioration and reinforcement corrosion [17]. Hand held magnifier, stereo microscope, fiberscopes and borescopes are some of the tools that

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**Fig. 1.** Concrete deterioration between spans (a) seepage, (b) efflorescence, (c) concrete cover delamination, (d) widen cracks [18].

**Fig. 2.** Description of the bridge structure in the inventory module, by Gattulli and Chiaramonte [16].
can be used for visual inspection [7]. Some of the defects observed by Gokhan [18] using this technique during the inspection of concrete bridge are illustrated in Fig. 1.

The main disadvantage of visual inspection is that it detects the cracks, deterioration and damage only when it begins to affect the life of the structure or in some cases it has badly affected the internal layers of the structure while only minor cracks appear on the surface [20]. This is especially true in case of long span bridges where it is very difficult and almost impossible to visually inspect the complete bridge. It was reported by Dubin and Yanev [21] that the biennial visual inspection of Brooklyn Bridge in New York cost around 1 Million USD [2]. According to one study conducted by Federal Highway Administration (USA), at least 56% of the average condition ratings of concrete bridges were found incorrect and most probably 95% information was taken from the visual inspection [2]. It is due to the reason that inspection of all the bridge elements particularly soffit of the bridge on the stream or river is very difficult. Its effectiveness, however, to a large extent is governed by the investigator's experience and knowledge. We would like to mention here that visual inspection is typically one aspect of the total evaluation plan. Therefore, it is suggested that this method should be combined with other NDT methods so as to obtain real condition of the structure.

Gattulli and Chiaramonte [16], used visual inspection for condition assessment of a bridge management system for Italian railway. Their approach for condition assessment was applicable to concrete, steel and masonry bridges. Deficiency levels and associated maintenance and repair priority was also provided in the study. They proposed four different simulation models (bridge inventory, computer aided visual inspection, automated defect catalog and priority-ranking procedure) to predict the rating index. An automated bridge inventory was proposed (Fig. 2) which offered complete data necessary for the bridge characterization and assessment.

2.1.2. Chain drag

Chain drag test is performed according to the guidelines given in ASTM D 4580-86 [22]. This test is used to mark the delaminated areas on the surface of the deck [10,22–25]. Initially a grid system is laid on the bridge deck. Thereafter, chains are dragged on the surface of the deck and all those areas where a dull or hollow sound is heard by the operator are marked. Finally, with the help of grid lines, a map is prepared for locating these delaminated areas. Frequently, one operator is enough for chain dragging and defining the boundaries of delaminated areas. In Fig. 3, it can be seen that one person is performing the chain drag test on the deck where grid lines are also visible. However, efficiency and reliability of this method is increased by using two persons [10]. One person initially drags the chain and hear the dull sound over the deck while the second person further clarify the boundaries of the defected areas with the help of rock hammer and record the findings. A clear ringing sound represents a sound deck while a muted or hollow sound represents a delaminated deck. The hollow sound, which is a result of flexural oscillations in the delaminated section of the deck, creates a drum like effect. Its frequency is typically in between 1–3 kHz range and is within the audible range of a human ear. The presence of any delamination changes the frequency of oscillation and, therefore, the audible response of the deck [25].

From above discussion, it is clear that this method depends upon the human factor which makes it less reliable. However, investigators can use this technique for periodic inspection in conjunction with other methods. Moreover, this method can be used for comparison of data with other NDT methods.

Barnes et al. [23], used the chain drag method in combination with half-cell method and compared the results with GPR method. They investigated the defects by applying chain drag and half-cell method on bridge deck. The bridge deck consisted of two-lanes and was constructed by using reinforced concrete on steel girders.

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**Fig. 3.** Chain drag test [25].

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**Fig. 4.** Coin tap test for checking the debonding and delamination in concrete and steel.

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**Fig. 5.** (a) Force–time histories of impacts on good and disbonded areas of CFRP skinned honeycomb structure; (b) spectra of time histories [27].
Delaminations were marked by using chain drag method in geometric shapes/figures which provided the estimate regarding the actual delaminated areas and were often used as the boundaries for repair and maintenance area. The authors suggested removing the cover material during repair and maintenance work, especially for the exposed corroded steel bars, which lie outside of the boundaries marked by chain drag survey. The difference between chain drag based delaminated area and GPR based delaminated area was 2.5 m² or 0.4% with a standard deviation of 1.3% of the deck surface area. Chain drag results and GPR results were much similar and very close to each other using thresholds developed by the authors.

2.1.3. Coin tap test

Coin tap test is the simplest form of Impulse echo method [6]. It is amongst the oldest methods of NDT and frequently used for crack and damage detection [6,26–29]. Specifically, it is used for laminated structures and bonded joints [27]. In the past, this method was widely used in UK for detecting defects/discontinuities during tunnel linings [6]. In this method, wall or lining or bridge portion is strike with coin or lightweight hammer and echo or ringing is heard. Whenever, the impulse hammer hits the cavity or defaulted portion of structure, a significant change in the frequency is noticed. It is a rapid method and can be used anywhere easily, because human ears are very sensitive to detect change in the frequency of sound. Moreover, different types of equipment can also be used to detect the difference in frequency and make this technique convenient to use anywhere. Fig. 4 shows the application of coin tap test in steel and concrete structures.

The physical basis of coin-tap test was investigated by Cawley and Adams [27]. It was observed that during the tap the presence of defect such as delamination beneath the surface of the structure changes the force characteristics. As defect becomes larger, the duration of impact increases and the peak force reduces. It was also observed from the force–time history spectra that as the defect become larger, the rate of reduction in force amplitude with frequency increases. Fig. 5(a) shows measured force–time histories from taps on good and disbonded regions of a honeycomb structure. The impact over the good area is more intense and of shorter duration than that on the damaged area. In Fig. 5(b), the amplitude of the force input to the damaged area falls off rapidly with increasing frequency, while the impact on the sound area has a much lower rate of decrease of force with frequency. The authors showed that the defects like delaminations and disbonds can be modeled as spring where the stiffness of spring would be same as of layer(s) above the defect. The authors concluded that this method is more reliable and provide satisfactory results on thin structures. In this method no coupling fluid is required which make this technique more rapid then ultrasonic testing techniques.

In Cawley [26] research, a high frequency version of coin tap test by tapping the structure (aluminum plates with flat-bottom holes) with a lighter coin (below 1 g) was investigated. The lighter coin was used to enhance the frequency range of excitation. Test results showed that high frequency coin tap is more capable to observe the cracks and voids in greater depth as compared to conventional coin. This method when tested on aluminum plates with flat-bottom holes showed that high frequency coin tap can detect 50 mm diameter defect located at 7 mm depth, while the same defect with 5 mm depth was not detectable by conventional coin tap test. However, the results of this low mass striker were not good on honeycomb specimen with fiber reinforced plastic skin. According to the authors, it may be due to reduction in excitation frequency range by the low out of plane stiffness of the fiber reinforce plastic. It was recommended that the method may be efficient on structures made with metals or unreinforced plastic.

Wu and Siegel [28], used hammer to apply force on structure and measured its value by accelerometer and the resulting sound with the help of microphone. From the experimental results, it was found that both accelerometer and microphones have valid role as instruments for automating defect and damage detection. However, according to the authors, “it is hard to say in any universal sense whether forces-only or sound-only methods are more useful coin-tap methods”.

The traditional coin tap test is low cost but it is operator dependent. Therefore, in Georgeson et al. [29] research work, an illustration of low cost tap hammer developed by Boeing was given. This low cost tap hammer provides quantitative measure about impulse time of hammer/composite which can further be linked with delaminations in structure. The instrumented tap hammer provides numeric value that can easily be linked with the quality of local parts and thus removes discrimination of workers. Moreover, the effect of operator differences and background noise on investigated data can be eliminated.

2.2. Stress-wave methods

2.2.1. Acoustic emission

Acoustic emission (AE) test is most extensively used for damage detection in several fields in general and transportation sector in particular [9,30–36]. In 1939, Hopwood [30] for the first time applied the concept of AE testing to a bridge for structural health monitoring [9]. Carter and Holford [31] and Holford and Lark [33] reviewed the application of AE in bridge monitoring. AE testing is used for three major areas of damage i.e. source location, source identification and severity assessment [32]. The automated source location capability of AE make this technique more distinguished in NDT [32,34]. This test is based on transient elastic waves. These elastic waves are produced from the structure under observation by rapid release of energy and the transducers are used to collect these waves. Thus, two integral components are necessary for AE test. The first is the material deformation which produces the elastic waves and becomes the source while the second is transducers that receive these elastic stress waves.

The schematic layout of the AE testing which represents the overall operational principle of an AE monitoring system is shown in Fig. 6. Whenever a crack, damage or flaw develop within the interior layers of structure, it release burst of energy [36]. This energy (primary and secondary emissions) is mostly in the form of high frequency sound waves [36]. The primary emissions are those which are generated from the under observation structure while the secondary emissions are those which are produced from some external material or source. These waves travel within the object and are received by transducers and sensors [36]. The travel time of these waves is very important. If both transmitter and transducer are placed on the opposite sides than the shortest travel time would indicate the sound concrete while the longer travel time is an indication of inferior quality of the concrete. The longer travel time may be due to the reason that the signal got diffracted.

![Fig. 6. Principle of acoustic emission [36].](image-url)
along the edge of the large void. Moreover, no arrival at transducer may indicate that signal got reflected through the air interference in void [7].

There are numerous qualitative as well as quantitative ways to interpret these signal parameters or waveforms. For example, parametric analysis of the AE signal resulted in evaluation criteria such as: (i) A concrete beam integrity (CBI) ratio, defined as the ratio of the load at the onset of new AE in a subsequent load cycle to the maximum prior load [37] and (ii) calm and load ratios of reinforced concrete beams; where the calm ratio is the cumulative AE activities ratio during the unloading process to the maximum of the last loading cycle and the load ratio is the ratio between the load at onset of AE to the prior load [38], etc.

AE testing provides the real time examination of the material characteristics when subjected to under load/stress [36]. The major advantage of AE is that it can be used for both global and localized monitoring of damage portion. This method can be used for continuously monitoring and can detect the activity from considerable distance [35]. The wireless sensing of large structures using radio frequency transmission scheme given by Grosse et al. [39] is shown in Fig. 7. Traffic flow remains undisturbed during performance of this test and it also provide a reliable analyzes [36]. The major disadvantage of AE is that no standard procedure is available which can be applicable to all types of the structures and specifically bridges [36]. This method requires experienced personnel and several trial sessions so as to eliminate the real-time noise from the gathered data. It is also problematic to apply the quantitative AE analyzes on actual structures [36]. Another disadvantage of local AE technique is that it is limited to 8 AE channels [35].

Acoustic emission monitoring plan is mainly categorized into two types i.e. global and local monitoring [31]. In global monitoring, the entire integrity of complete structure is assessed while in local monitoring, a particular zone of damage is examined. The global AE monitoring involves connection of sensors in such a way that the major portion of the structure or entire structure can easily be investigated. Fig. 8 shows different types of sensors used in AE. Load can be applied from regular traffic or by heavy truck to stimulate the flaws. The global AE monitoring can be used for periodically evaluation of the structures. The main benefit of global AE monitoring is that it examines the complete structure and if investigations are required for some specific area than it can be further done by using local AE monitoring [35]. The continuous monitoring will enable the investigators to constantly assess the health of any old or newly constructed structure. Moreover, there is a strong possibility that, in future, visual inspection can be replaced by global AE monitoring [35]. In local AE monitoring, small or local areas of the structure are concentrated. The dimension of local area may vary from few centimeters to meters [35]. Loading is normally applied by normal traffic for release of energy.

The application of AE for locating damages in steel–concrete composite bridges was investigated by Holford et al. [32]. The source location of damage was based on measurement of time difference between arrivals of individual AE events at different sensors in an array. The source location in global monitoring detected certain suspected regions in the complete structure. Thereafter, local monitoring was used to locate the defects and supply information about the emitted waveforms. The authors concluded that the method gives realistic information about the concerned region.

2.2.2. Impact echo testing

Impact echo (IE), is a stress-wave method that can be used for flaw detection and determining the thickness of structural member such as bridge decks and slabs. In early 1970s, impact methods were used for evaluation of concrete piles and drilled shaft foundations [40] while, in 1980s, it was developed for testing of concrete members such as assessing the quality of bond in overlays and
determining the depth of crack [41–52]. Schematic working principal of impact-echo method is shown in Fig. 9. Initially a two dimension grid system is drawn on structure and IE is carried over the specified location. Scott et al. [10], used a spacing of 2 ft between the grid lines. An impactor is used to produce the transient pulse in the structure by applying impact loading (Fig. 10). Depending on the materials characteristics, the stress pulse infiltrate into the structure at a specific speed and produces waves (P, S and surface waves) that are reflected by internal interfaces/defects or external boundaries. Transducers are used to receive these reflected waves from any discontinuity present in concrete. Fast Fourier Transform (FFT) analysis is then used to transform time domain signal into frequency domain signal. The location of the damage portion, crack or discontinuity and depth of member can be found by using simple formula [10].

\[ T = \frac{C_p}{2f} \]

where \( T \) is location of discontinuity or point from where waves reflect, \( f \) is the wave frequency and \( C_p \) is the velocity of the compressional propagating wave.

Different authors used various ways for interpreting the severity of delamination in bridge deck with IE method [25]. For example, a delaminated point in the deck will theoretically demonstrate a shift in the return frequency toward higher values because the
wave reflections occur at shallower depths. Moreover, depending on the extent and continuity of the delamination, the partitioning of the wave energy reflected from the bottom of the deck and the delamination may vary. Hence, the initial or incipient delamination, described as occasional separation within the depth of the slab, can be identified through the presence of return frequencies associated with the reflections from both the bottom of the deck and the delamination. It is worthy to mention here that progressed delamination is characterized by a single peak at a frequency corresponding to the depth of the delamination. Finally, in cases of wide or shallow delaminations, the dominant response of the deck to an impact is characterized by a low frequency response of flexural-mode oscillation. This response is almost always in the audible frequency range, unlike responses from the deck with incipient delamination that may exist only in the higher frequency ranges [25,51]. Impact echo method can be applied to plate like structure. Plate like structures are those in which transverse direction of structure is at least five times the thickness of structure. Bridge decks, slabs and walls are the examples of plate-like structures [10].

A new concept for impact echo testing was presented by Grosse et al. [53]. They showed that IE has great ability to detect more accurately large voids, inhomogeneity and the thickness of concrete structures (Figs. 11 and 12). According to the authors, this method effectively detects cracks and reliability of this method is increasing with the passage of time.

Azari et al. [54], investigated the sensitivity of Impact Echo method to different parameters like slab thickness and defects in slab and found that it is very sensitive to slab dimensions (Fig. 13). The size of slab panel was found to greatly affect the energy reflected from lateral boundaries. They suggested that these reflected waves may interfere with outgoing signal and can impact IE frequency response and measurement of thickness. For a fixed size of slab, as slab thickness increases less energy was reflected back from bottom boundary as compared to lateral boundary. The authors concluded that the combination of IE with ultrasonic wave method is more effective in detecting and locating the defects within concrete slab.
2.2.3. Sonics

Non-destructive sonic test was abundantly used in past for assessing and determining the civil structures and materials [6,7,55–58]. This method is based on the stress waves. Mechanically, stress waves are transmitted into the structure and when intervene by any discontinuity; these waves reflect and collected by the receivers. Transmission modes for sonic wave tests include (a) direct, (b) semi-direct, (c) indirect [6]. The different modes of transmission are illustrated in Fig. 14.

In direct transmission method compressional waves of frequencies ranging from 500 Hz to 10 kHz penetrate through the structure [6]. Waves are transmitted from one side of structure and received at opposite site. Upgraded form of direct transmission is semi-indirect transmission mode [6]. Semi-indirect transmission method, also known as sonic tomography [6], is used on the paths which are not transverse to wall surfaces of structure. The efficiency of results is increased by adopting a dense grid system for data recording (Fig. 15) [57]. Colla et al. [57], used the recorded travel time data of sonic signal waves to draw 3-D velocity distribution across the entire structure. McCann and Forde [6] plotted velocity magnitude into the format of contour map [6]. Grid points were drawn on x–y axes and velocity coordinates on z-axis. This format provided information about the relative conditions of internal fabrics of structure [6]. Moreover, 3-D velocity distribution map helped in diagnosing the local alterations in velocity which can be further linked with the different areas of weakness and flaws [6]. In indirect method, also known as sonic reflection method or sonic-echo method, the signal generator and receiver are placed on the same face of structure. Recorded stress waves (direct stress waves) are echoed from the inner discontinuities or from rear face. This method is not recommended due to poor resolutions attained from the low frequency energy [6]. Moreover, it is difficult to discriminate between reflected waves and surface waves [6]. Sonic methods can be utilized for evaluation of material uniformity, void detection, depth of surface crack, internal properties of fill material or structure, average compressive strength, internal dimensions and shape of the structure [6]. As an example, if the length of the pile shaft is known and the transmission time for the stress wave to return to the transducer is measured, then its velocity can be calculated. Conversely, if the velocity is known, then the length can be calculated. Since the velocity of the stress wave is primarily a function of the dynamic elastic modulus and density of the concrete. Therefore, the calculated velocity can provide information regarding the concrete quality [7].

When the stress wave has traveled the full length of the shaft, these calculations are based on the following formula

\[ C_b = \frac{2L}{\Delta t} \]

where \( C_b \) = bar wave speed in concrete; \( L \) = shaft length; \( \Delta t \) = transit time of stress wave.

Empirical data show that a typical range of values for \( C_b \) can be assumed, where 3800–4000 m/s would indicate good-quality concrete, having a compressive strength on the order of 30–35 MPa [59]. For the case where the length of the shaft is known, an early arrival of the reflected wave would mean that it has encountered a reflector (change in stiffness or density) other than the toe of the shaft.

Colla et al. [57], evaluated and compared the performance of sonic and ultrasonic tests on rubble masonry walls. The authors found that ultrasonic frequencies have high depletion rate due to presence of voids, joints and homogeneities. Therefore, they suggested that sonic test should be preferred for rubble masonry walls. Berra et al. [58], also concluded that for masonry walls and in comparison to ultrasonic test, sonic test is more suitable and appropriate in detecting the cracks, delaminated joints and large voids.

The effect of sonic test on existing partially damaged and repaired structures was investigated by Binda et al. [55]. Sonic velocities were used to analyze the structural health of masonry walls of Cathedral of Noto. According to the authors, this test can be used to identify different levels of damage in structural elements and can also examine the efficiency of grout injection.

In 2003, Binda et al. [56], investigated the effect of sonic and radar tests on masonry structures. Both tests gave reliable information about the damage portions. However, the results of sonic tests were found to be better than radar test. The authors suggested that these test can be used to recognize different materials on the surface of large areas and can identify variation in material characteristics. Furthermore, this test might be used for evaluating the effectiveness and distribution of grout in the structure. Results of sonic tests were found better then radar test.
Fig. 16. Bridge deck survey using ultrasonic equipment (top) test results, (bottom) equipment and data collection [25].

Fig. 17. Validation test specimen: (a) validation test site; (b) sketch depicting locations of built-in defects as well as marked test lines and test points [65].

Fig. 18. Point-by-point condition rating of validation test specimen based on: (a) longitudinal measurements; (b) transverse measurements [65].
2.2.4. Ultrasonic NDT

Ultrasonic pulse velocity (UPV) method is one of the oldest NDT methods for determining the relative condition of concrete by measuring the time of pulse of ultrasonic waves over a known path length [7]. It can be used to locate abnormal regions in the member [7,54,60–67]. The ultrasonic device consists of a transmitting and a receiving transducer. The transmitting transducer produces stress pulse that propagates in the member. The signal is then received by the receiving transducer and the results are displayed in the form of travel time. As the wave reach out to a defect, a small part of the emitted energy is reflected back to the surface. Defects, in this case, are identified as any anomaly of acoustical impedance different from the concrete element tested. However, in regions where there is significant deterioration or micro cracking, concrete will have a noticeably lower velocity when compared with concrete in intact regions. ASTM C597-09 [67], covers the requirements of suitable ultrasonic pulse velocity device. The main difficulty which needs to be addressed is good coupling of the transducer with the surface. This issue can be addressed by using viscous material such as petroleum jelly or grease. However, on uneven surfaces it is very difficult to achieve adequate coupling. It needs to be pointed out here that for most applications, 50 kHz frequency transducers are suitable [7]. Fig. 16 illustrate the working of ultrasonic NDT equipment on a bridge deck.

The development work for the ultrasonic imaging of concrete was described by Schickert [63]. Ultrasonic method has a strong potential for detail and in-depth assessment of concrete structures by using short wavelengths as compared to other nondestructive method. SAFT (Synthetic Aperture Focusing Technique) and tomographic reconstruction, which are imaging methods were used to provide quality and high resolution images. These algorithms utilized the data and measurement taken from pulse-echo method. Amongst all measurement system, transducers were found most vital for transmitted signals since ultrasonic waves passed twice from transducers to the concrete. Due to highly different acoustic impedances, air gap between transducer and concrete surface greatly deteriorated the quality of pulse waves. Therefore, the coupling of transducers directly affected the image quality (signal to noise ratio, resolution and uniform amplitude distribution) of concrete. Schickert mentioned that conventional coupling techniques were not adequate and difficult to apply. Therefore, air coupled transducer may be useful. Moreover, water or dry coupling was recommended for future work.

The accuracy and precision of ultrasonic testing with low frequency of approximately 55 kHz for characterization of delamination in deck of concrete bridge was evaluated by Shokouhi et al. [65]. A reinforced concrete slab (20 ft × 8 ft × 8.5 in.) was used to simulate a concrete bridge deck (Fig. 17). It was found that defects as small as 30 cm² could be reliably detected using multiprobe ultrasonic array. Delaminations deeper than 6 in. were directly detected and characterized while delaminations shallower than 2.5 in. were detected indirectly. Point-by-point condition rating of validation test specimen was also given (Fig. 18). The authors concluded that multi-sensor low frequency ultrasonic testing is useful for delaminations detection and characterization and has great potential for in-depth testing of selected areas of bridge decks [65]. However, high initial cost and the need for lane closure during testing are the main drawbacks of this technique.

The micro and macro scale defects in concrete were investigated by Shah et al. [64] by measuring linear and non-linear ultrasonic parameters. It was found that wave depletion was much susceptible to different levels of power and damage. With the increase in damage level, high voltage pulses diminished more as compared to low voltage pulses. Both linear and nonlinear methods were found to be sensitive to the w/c ratio. Moreover, for all levels of damage, a high power resulted in higher wave velocities.

The authors suggested that more research should be conducted to determine the influence of power levels on pulse velocity with different damage levels [64].

In [61], Bogas et al. experimentally investigated the influence of several parameters (cement type and content, amount of water, type of admixture, initial wetting conditions, type and volume of aggregate and partial replacement of normal weight coarse and fine aggregates by lightweight aggregates) on the relationship between ultrasonic pulse velocity and compressive strength of concrete. Eighty-four different compositions having compressive strength ranging from 30 to 80 MPa were prepared. Test results showed that the relationship between UPV and compressive strength of concrete was less affected by the aggregate volume in light weight concrete than in normal weight concrete. Moreover, it was found that different types of cement and different initial wetting conditions of aggregate have little effect on the relationship between UPV and compressive strength.

2.2.5. Impulse response (IR)

Impulse response (sonic mobility) is a stress wave method [7,68–70] that is especially used for deep foundations [68]. This method uses low-strain impact to produce the stress waves. When the hammer strikes the concrete, compressive stress waves are generated whose frequency can vary from 0 to 3000 Hz depending on the material used in the hammer (soft rubber, metal) [7]. The force (measured by load cell) and the velocity (measured by the receiver) time based signals are recorded by the data acquisition system, which is then transformed by computer into frequency domain using fast Fourier transform algorithm [7]. The ratio of the velocity response spectra and impact spectra is termed as mobility spectrum [25]. However, if measured response is displacement, the ratio of the displacement and impact spectra represents a flexibility spectrum while the inverse ratio is termed mechanical impedance (dynamic stiffness spectrum). In some analyses, the flexibility spectrum is matched by a flexibility spectrum (response spectrum) for an assumed single-degree-of-freedom (SDOF) system. Once the two spectra are matched, the modal properties of the SDOF system provide information about the stiffness and damping properties of the system. The underlying assumption of this process is that a structure’s response can be approximated by the response of SDOF system. The modern IR test equipment is shown in Fig. 19 while the schematic working principle and field application is illustrated in Fig. 20. This method can be
used to determine the length of piles and piers, cross-sectional area of pier, provide information about dynamic stiffness of the shaft-/soil composite [7]. Theoretical interpretation of impulse response application regarding pile length and dynamic stiffness are given by Turner [70]. Even though the concept behind impulse response and impact echo is similar, there are significant differences when it comes to bridge deck testing. Impact echo is based on the excitation of particular wave propagation modes above the probable anomalies within the deck or between the top and bottom of the deck. The frequency range is typically in between 3 and 40 kHz. On the other hand, impulse response relies more on the structural response in the vicinity of the impact and, therefore, the frequency range of interest is much lower i.e. 0–1 kHz for plate structures [25].

Davis [68] applied this test method on different concrete structures which include cooling towers, arch bridge, bridge deck, prestress box beam bridge, freeways and terra coda clad steel column. Fig. 21 shows the exposed wall of cooling tower after the IR test and stiffness contour map of pre-stressed box beam bridge. According to Davis [68], this method play an important role in evaluation of floor slabs, pavements, concrete bridges, decks, piers fluid retaining structures and silos. Moreover, this test can be used for rapid evaluation of large structures and identification of problematic zones for detailed investigations. The author concluded that IR test plays an important role in rapid assessment of large concrete structures during on site testing and immediately allows identifying the problematic areas within structure for detailed investigation. This results in financial benefit and increased confidence on this technique.

The Impulse Response s’Mash test method was used by Gorzelanczyk et al. [69] to measure the length of piles. The authors used this method to determine the length and continuity of concrete prefabricated piles in a quick manner. The pile length measured by IR method was found similar to the designed length. However, professional person is required for analyzing stress waves signals which is a major drawback of this method.

2.3. Electro-magnetic methods

2.3.1. Ground penetrating radar (GPR)

GPR is the most successful and well-known Non-destructive test for investigation of bridge decks and pavements [7,23,71–79]. It is used for structural health monitoring of concrete structures like buildings, bridges and tunnels [73,78,80,81] and provides an electromagnetic (EM) wave-reflection survey. GPR is rapid and quick method for assessing in-depth characteristics of subsurface

![Fig. 20. Impulse response test method: (a) the concept, (b) example of using in practice [69].](image1)

![Fig. 21. (Left) Exposed cooling tower wall after IR testing, (Right) stiffness contour plot of pre-stressed box beam bridge [68].](image2)
layers and can be used for detecting damages, delaminations, voids (more than 1 in. deep and 1 in. diameter) [82], cracks and their lengths, cavities, recognizing steel reinforcement and its diameter [72], thickness of member, identifying regions of high moisture content, settlement of layers and monitoring of deformation induced by strain [71,76,77,83–86]. Initially grid lines are marked on structure at different intervals (usually 2.5 ft) [17]. Then on these grid points GPR equipment moves for data recording of complete structure. Typical GPR include an antenna, a control unit, a display unit and a data recording device [7]. The antenna transmits short pulses of electromagnetic energy that penetrate through the material and a portion of this energy is received by the antenna when it is encountered by an interface between materials of dissimilar dielectric properties [7]. For continuous acquisition of data along the bridge deck, the antenna is either mounted (150–500 mm above the pavement surface) on the vehicle or it can be dragged across the pavement surface [7]. The control unit controls the pulse, amplify the received signal and provide output to the display unit (oscillo-graphs, graphic facsimile recorders) [7]. The data obtained (arrival time and energy level of reflected electromagnetic pulse) can be analyzed by various techniques such as cluster analysis, quantitative peak analysis, and topographic plotting [7]. The velocity and travel time of the electromagnetic pulse signals provide information about the location and depth of the discontinuity [87]. Moreover, since the travel time of signals and depth of the discontinuity are directly proportional to each other, therefore, it is also possible to detect interface surfaces between air and concrete, steel and concrete, steel and water [87]. Reflections of electromagnetic radiation pulse at interfaces between materials with different relative dielectric constants is shown in Fig. 22. We would like to mention here that large amount of data is obtained from this test; therefore, an experienced interpreter/analyst is required.

Hugenschmidt and Mastrangelo [75], quantified the accuracy and reliability of GPR on bridge structure under real circumstances. They applied the GPR method on a bridge which was marked for demolition. For concrete cover over the top layer of re-bar, the difference in results between radar and reality was 10 mm. The main reason for this difference in results was related to the resolution problem in small cover areas and uncertainties in interpretation. Moreover, the pavement thickness was also measured and the difference in the results between GPR and reality was found to be 9 mm. The main reason for the gap in the results was small concrete cover which resulted in overlapping reflections from re-bar and bottom of pavement. According to the authors, the quality of results depends on two parameters (1) the object under testing and (2) qualification and experience of persons conducting test. Fig. 23 shows the working of GPR test equipment.

Hugenschmidt [74], used mobile GPR system for concrete bridge inspection (Fig. 24). The results of mobile and manual data
GPR were compared for accuracy. The accuracy of the mobile radar for layer thickness was in between 5 and 15 mm if signal velocity is assumed to be horizontally invariant. However, the accuracy can be improved if velocity variations are taken into account. The authors concluded that mobile GPR data acquisition system is cost effective method as compared to manual data GPR. Moreover, interruption in traffic flow can be reduced to minimum by using this method.

An experimental investigation was carried out by Yehia et al. [79] to evaluate the effect of different parameters such as mix variations, changes in temperature and concrete maturity on defect detection ability using GPR method in bridge decks. Overall they prepared sixteen concrete samples and eight were simulated with defects. Fig. 25 shows the specimen made for experimental testing. The authors found that GPR can detect defects in bridge deck with radius to depth ratio \( r/d \) as small as 0.15. The existence of defects under steel reinforced was found to limit the defect detection ability of GPR. Porous lightweight aggregate can absorb and retain water which limit GPR to identify the damage at early stage. Furthermore, defects were not detectable in lightweight concrete mixes within 3 months of casting concrete.

2.3.2. Conductivity

Electromagnetic conductivity is a technique which provides geometrical, electrical information and degree of saturation about the materials [6]. Alteration in the conductivity characteristics of concrete indicates the damage in concrete [6,57,89–91]. This method uses the response of the ground against the propagation of electromagnetic fields. The electromagnetic fields, which are generated through the transmitting coils, passes through the object and their response is monitored. Since the receiving and the transmitted fields are different both in amplitude and phase, hence, this difference provides certain information on materials geometry and electrical properties [57]. In this method, normally a grid system is laid on the surface of the material and the measurements are taken on specific grid points. For better results and maximum accuracy level, it is suggested to have overlapped reading for every half meter [57]. Data is then recorded by the digital data recorder and later on, it is transferred to the computer for plotting contour maps of the conductivity distribution in both horizontal and vertical plane.

The relationship between concrete mix proportions and electrical characteristics of concrete was investigated by Whittington et al. [91]. The determination of electrical conductivity of concrete mix was based on the hydration of cement paste, rate of hydration of cement paste within concrete, degree of hydration of concrete and water cement ratio of mix. Indirectly, this method was used to determine the quality of concrete and its strength at particular time. A simplified model proposed for conduction of current through concrete is shown in Fig. 26. Whittington concluded that it can be used for real time structural health monitoring of structures. For example, the growth of a crack can be identified as an alteration in the conductivity characteristics of concrete.

Colla et al. [57], used this rapid, low cost and not-contacting technique for the assessment (inhomogeneity identification, moisture movement detection over time) of masonry arch bridge (Fig. 27). The main parameters which controlled the conductivity procedures were clay content, moisture level (humidity) and salinity [57]. However, the conductivity method was unable to collect data at deeper locations.

It was shown by Smith-Rose [92] that conductivity increased approximately by the square of the moisture content in soil sample. In a typical case, the conductivity for dry soil at a frequency

![Fig. 24. EMPA’s mobile GPR system [74].](image)

![Fig. 25. Specimens used in the investigation (a) singly reinforced specimen cross-section and (b) doubly reinforced specimen cross-section [79].](image)
of 1200 kilocycles per sec was of the order of $10^5$ electrostatic units (corresponding to a resistivity of 9 mega ohms per cm cube), while at a moisture content in between 12 and 26 percent a limiting value in between $10^8$ and $2 \times 10^8$ electrostatic units (resistivity 9000–4500 ohms per cm cube) was obtained [92]. Burial-type four-electrode units used for monitoring applications are shown in Fig. 28.

2.3.3. Half-cell potential

Half-cell potential is an electrical technique used for evaluation of corrosion activity of steel reinforcement [7,93–98]. The standard equipment (Fig. 29) consists of a copper–copper sulfate half-cell, connecting wires and a high voltmeter so that very little current flows through the circuit [7]. When a metal is submerged into an electrolyte, positive metal ions will resolve (oxidation) and will accumulate at the metal–liquid interface. As a consequence, the metal–liquid interface becomes positively charged, and a double layer is formed. Anions, from the electrolytic solution (in concrete –$\text{Cl}^-$ and –$\text{SO}_4^{2-}$), are attracted to the positively charged side of this double layer and accumulate there, forming the so-called half-cell. A potential difference between the metal and the net charge of the anions in the electrolyte builds up, which depends on the solubility of the metal and the anions present in the solution. This potential difference will give us information about the corroded reinforcement [25]. As per ASTM C876-91 [93], if the reinforcement is corroding, the electrons would tend to flow from the reinforcement to the half-cell, where copper ions would be transformed into copper atoms deposited on the reinforcement. A display of more negative reading on the voltmeter would be an indication of high probability that the reinforcement is corroding. During experiments, it was observed that the negative potential will be more when some defects like cavities are present in the surface [98]. For bridge decks, initially a grid system is laid on the deck. ASTM C876-91 [93] suggests a spacing of 1.2 m, however, a closer spacing is recommended if the voltage difference between the adjacent points exceeds 150 mV. For reliable assessment of corrosion activity, some researchers suggested a spacing of about 0.6 m [94].

The results of the survey can be prepared in the form of equipotential contour maps to assess corrosion activity on concrete bridge and can then be used for the maintenance and repair work [6]. The results of survey can also be formulated in the form of cumulative frequency diagram [93]. It has been pointed out by Gu and Beaudoin [97], that when the portable half-cell is moved on the marked grid points, the longitudinal distribution of corrosion potential is mapped. Finally, the results can be evaluated by either numeric or potential difference technique [93]. Half-cell potential method can be applied at concrete structures irrespective of thickness of concrete cover and size and detailing of reinforcement [96]. It can indicate the corroding reinforcement not only near the external surface but also in greater depth [96]. It needs to be pointed out here that the testing and interpretation of results must be done by experienced personnel. Some limitations of this method include (1) the wire has to be connected to the reinforcement, (2) it is difficult to take correct reading if any coating is present on the surface like epoxy, paint or asphalt, (3) it does not provide information about the rate of corrosion, (4) correction factor has to be applied if the test is performed outside 17–28 $^\circ$C range [7,93].

In [95], Elsener observed that half-cell potential method can be easily used for assessing the corrosion of rebars after repair and thus scrutinize the effectiveness and durability of repair work. It was found that for accurate results and effectiveness of repair work, two parameters are crucial, one mechanism of repair principle and second measurement time after repair work. The
interpretation of measurements was found to depend on the resulting pH and on the conductivity of pore solution in concrete. Elsener concluded that more negative potentials do not indicate corroded bars but alkaline environment of bars. The schematic illustration of half-cell measurements is given in Fig. 30.

According to Gu and Beaudoin [97], several factors must be considered for accurate interpretation of half-cell measurements such as oxygen, electrical resistivity of concrete, concentration of chlorides and chemical admixtures. It is generally believed that more negative reading in potential is an indicative of high probability of corrosion; however, this is not always true. The authors found that many factors can shift the measurements toward positive and negative values. They suggested that half-cell data provide the probability of corrosion only at a given location on specific time of test. However, long-term monitoring of this data is more valuable.

2.3.4. Electrical resistivity measurement

Electrical Resistivity (ER) (the inverse of the conductivity) of concrete is the ratio between applied voltage and resulting current in a unit cell [99]. It is mainly influence by the moisture content and varies from $10^1$ to $10^6 \Omega \text{m}$ [100,101]. By comparing different reading points, valuable information regarding the concrete inner surface characteristics can be extracted [6,99–104]. In this method, minimum two electrodes are used out of which one is the reinforcing steel bar. A voltage/current is applied between the electrodes and resulting current/voltage is measured. The ratio of voltage and current gives the resistance while the resistivity is calculated by multiplying resistance with a factor known as cell constant. The distribution of concrete resistivity in reinforced concrete is depended upon several factors like location of steel and depth to surface value [99]. The top surface layer is another important parameter. If the top surface is too much dried out, the resistivity will be higher than the normal concrete while if it is wet then the resistivity will be less as compared with normal concrete. This problem can be minimized by using the four point method. For example, the Wenner setup uses four probes that are equally spaced [25]. A current is applied between the outer electrodes while the potential of the generated electrical field is measured between the two inner ones. The resistivity is calculated according to the following formula:

$$\rho = \frac{2\pi a}{l}$$

where $\rho = \text{resistivity (in } \Omega \text{m}); a = \text{electrode separation (in m)}; V = \text{voltage (in V); and } I = \text{current (in A)}$.

Polder et al. [99], concluded that concrete resistivity method is very important and matter of concern due to its linkage with corrosion of steel. High corrosion rate was observed in areas of low resistivity as compared with high resistivity. This test can be used to determine moisture content, homogeneity and corrosion rate of reinforcing steel bars [99]. Different reading points can be correlated with the ability of corrosion currents to flow through the concrete, which is a based upon three parameter i.e. moisture content, salt content and water/cement ratio [6]. Temperature related corrections must be done to the data because resistivity value will got twice if temperature decrease about 20 °C or a change of 3–5% per degree occurs [99].
Surface resistivity method can be used to evaluate the risk of chloride ion penetration in the concrete. Hence, this method is an alternative method of Rapid Chloride Ion Penetration (RCP) test. Ryan et al. [104], used surface resistivity method to determine resistance of concrete to chloride ion penetration and concluded that this method is sound, easier, faster and more reliable method as compared with RCP.

Saleem et al. [103], evaluated the effect of chloride and sulfate ions on ER of concrete. Test results showed that the moisture content, chloride and sulfate contamination control the ER of concrete. The ER of concrete decreased due to sulfate contamination. In this situation corrosion of steel bars will increase due to carbonation. It was observed that impact of moisture content on the electrical resistivity of concrete is very small when the salt concentration is high. Moreover, in nearly dry concrete, high salt concentration could greatly increase the steel corrosion. The schematic of electrical resistivity measurement set up is shown in Fig. 31.

Lataste et al. [102], used ER measurements to categorize the damage in concrete specifically crack. Four-probe square array is presented in Fig. 32. The measurements were taken on upper part of a slab (1 x 0.5 m² area) which was 40 years old. This area was selected due to presence of delaminated region and large crack as shown in Fig. 33. This area was also inspected by visual and hammer test. ER was found to assess the crack width (crack opening).
and depth, which are important for determining serviceability of structures. The authors suggested that the coupling of ER with acoustic method will produce the accurate diagnosis.

2.4. Deterministic methods

2.4.1. Proof load test

Proof load test provides the actual load carrying capacity of structures [105–110]. It is also used as diagnostic test to verify analytical or predictive structural models. This test is appropriate only when either unsatisfactory load rating is indicated by the analytical procedures or it is not possible to perform analytical test on structure due to lack of structural documentation or deterioration. Therefore, it is suggested to perform proof load test on all those structures on which assessment is not possible due to insufficient structural drawings or it does not meet with requirements of the most advanced assessment theories.

Earlier proof load test was used as check to design assumptions and quality of construction work. But, later on it was used for assessing the load capacity of existing structures (especially bridges) with the ultimate goal to determine directly the maximum allowable load for a structure with essential safety level. Acoustic emission is the useful method to follow up the loading process to control the load increment before propagation of any damage to the structure [108]. According to Casas and Gomez [105], proof load test is very efficient in assessing the capacity of existing bridges. The targeted proof load can be calculated on the basis of reliability theory as many variables involved are of random nature. The value of the targeted proof load can also be obtained as nominal traffic load multiplied by the target-proof load factor.

For bridges, if the proof load test is successful then it shows that the bridge is capable of resisting more load than the applied proof load. This reduces uncertainty and increase reliability of the structure. However, the main risk involved in performing this test is that if unsuccessful, the structure may damage or collapse [106]. Moreover, the testing procedures for proof load test are not well documented [107]. The proof load test is very expensive and
roughly costs around 6% of bridge replacement [106,110]. Application of proof load test on a bridge in early 60s is represented in Fig. 34. Saraf and Nowak [109], carried out proof load test on three simply supported steel girder bridges. These selected bridges varied in span length from 11.0 to 15.5 m and aged more than 60 years. Two military tanks were used to load the bridges as shown in Fig. 35. Weighed of each tank was 530 kN and these tanks were used to increase the mid-span bending moment in different steps. Values of Stress and deflection were measured on the steel girder at selected points. The authors found that these measured stresses and deflections were less as compared to the analytical calculations. The composite action between steel girders and concrete slab was observed even at maximum load level. It was noted that nonstructural members contributed to the flexural stiffness and for all bridges bearings provided partial restraint to rotation at supports.

2.4.2. Coring

Cores are considered as semi-destructive method and are used to determine the internal defects in structures. ASTM C 42/C 42M-04 [112], provide the standard test method for obtaining and testing the drilled cores. Cores are extracted to measure the compressive, splitting tensile and flexural strength of in-situ concrete. These are used to check the quality of construction and measure the strength of old structures [10,25,112,113]. Strength of concrete is affected by the location of the cores, amount and distribution of moisture and orientation of cores [112]. Core drill and saw is used for the drilling of cores from specimen. Usually, cores are extracted from concrete structures particularly from highways and bridges after performing preliminary NDT survey. Scott et al. [10], used 10 cores samples from different locations marked by preliminary survey for detail investigations. The cores extracted from different locations were thoroughly inspected for the cracks, delamination, deterioration, seepage and corrosion (Fig. 36). After the experiment, the core places are filled up by grouting or any other method. It is worth mentioning here that the data obtained from cores is reliable and can be used for further investigation and selection of repair and maintenance work. This method is applied extensively in highways, bridge-deck and concrete structures. Core is a destructive and expensive method. However, its results are used with NDT to achieve the high level of confidence.

Suzuki et al. [114] obtained the cylindrical core samples from the walls of canals (more than 40 years old), in Hokkaido prefecture, Japan so as to determine the mechanical properties of the concrete. In cores freeze–thaw damage was heavily observed. Compression test showed that samples effected by freeze–thaw have 3.87 times lower strength as compared with non-cracked samples. The cracked in cores were also inspected by X-ray computed tomography method and AE. Moreover, the damage of concrete structures was evaluated quantitatively by AE and X-ray method.

McIntyre and Scanlon [113], proposed the relationship between core-cylinder specimens. Cross-section of core and cylindrical specimens are given in Fig. 37. Due to the destructive nature of collecting samples, core strength was found to be less than the cylinder strength. Some of the energy used to cut and remove the sample invariably cause micro-cracks, bond failure or weakening between cement matrix to aggregate surface and major cracks in core. Authors proposed that overall average core-cylinder strength
ratio was 0.923. The major problem with the core test is that it provides information about small region of total volume of concrete from where it is obtained.

2.5. Miscellaneous tests

2.5.1. Dynamic/vibration testing

Vibration testing is most commonly used for measuring the structural health of structures. In late 19th century, vibration/dynamic field tests were applied to different concrete structures [115]. Various researches used this method on bridges to assess their condition and structural health [115–124]. In dynamic test, the structure is subjected to excitation forces and its response is measured by means of transducers [125]. Natural frequency, mode shapes and modal damping values are measured during testing and are known as modal parameters [125]. The values of these modal parameters change whenever a structure deteriorates. After inspecting these parameters it is easier to find out the structural health and condition of the structure [125]. It is worth mentioning here that the changes in these parameter mainly depend upon the location, type and severity of defects and flaws [125]. Two types of methods (ambient and forced vibration) are used for vibration testing. In ambient vibration testing method, there is no control on the input or applied force [122] while in forced vibration testing method, the input/applied forces is controlled.

Vibration-based monitoring (VBM) of civil infrastructure is explored by Brownjohn et al. [126]. VBM is a subcategory of structural health monitoring plan and emphasis on the dynamic part of performance [126]. It provides enough data for the structural investigation and leads to the another study area which is a subgroup of VBM and known as Vibration Based Damage Detection (VBDD) [126]. VBDD methods are not only limited to determining the natural frequencies of the structures, but can also be used for diagnosing the change in support conditions/bearing, degradation of the material properties and contribute in probabilistic post-earthquake assessment using modal parameters [126]. This method is relatively cheap and easy and the measurement points can be selected in accordance to test situation.

A model calibration method was proposed by Robert-Nicoud et al. [127]. This method is based on the structural behavior such as material characteristics and support conditions. A methodology for dynamic based assessment, using ambient vibration testing, was applied to reinforced concrete arch bridge by Gentile [123]. Output-only modal identification and updating different uncertain parameters of the computer models [123].

In [128], Brenchich and Sabia used dynamic tests on a masonry bridge to detect the natural frequencies and mode shapes. The compressive tests were also conducted for the comparative characterization of the brickwork. Dynamic characteristics were determined by using natural and forced vibration loading. These loadings were used to find out stiffness and to some extent estimate the structural damage and some types of global deterioration.

The effects of harmonically forced vibration tests on two-span post-tensioned reinforced concrete bridge was investigated by Bedon and Morassi [119]. This bridge was located in northern Italy which is prone to high seismicity. The Frequency response function (FRF) was determined by using low levels of excitation with series of harmonic forced-vibration applied in the form of stepped-sine technique. Thereafter, the acceleration response of the bridge was measured and the acceleration-time histories were used to determine the FRF of the bridge.

In recent past, Cunha, et al. reviewed the latest features of vibration/dynamic testing [120]. According to the authors, forced vibration has a disadvantage especially when it is applied to long span bridges. The problem was related to exciting the important and significant vibration modes in a controlled way specifically in a low range of frequencies with adequate energy. However, the latest advancement in technology make it possible to measure precisely low levels of dynamic response produced by the ambient excitations like traffic or wind. The ambient or free vibration tests are the most real and effective method used for determining the modal parameters [120]. Moreover, this method can be applied during the construction and rehabilitation stage [120]. Fig. 38 shows the application of free vibration test on the bridge. The non-contact measurement techniques such as radar or laser provided ease and efficiency in application of dynamic testing [120].

2.5.2. Infrared thermography

Infrared thermography, a global inspection method, allows large surface area to be inspected in a short span of time. Concrete surfaces absorb the solar energy in day and release it in night [129,130]. Therefore, Infrared thermography is used for detecting the delaminations and anomalies in concrete surface [6,7,25,131–134]. The three main properties that influence the heat flow and distribution within a material include the thermal conductivity, specific heat capacity \( (C_p) \), and the density \( (\rho) \). The electromagnetic spectrum range used to measure the Infrared thermography is shown in Fig. 39. Infrared thermography for testing concrete is based on two heat transfer mechanism, radiation and conduction [7]. In the first mechanism, a surface emits energy (electromagnetic radiation) and the rate of energy emitted by the surface per unit area can easily be calculated by Stefan–Boltzmann law. Since infrared radiations are not visible to human eye, therefore, special sensors are required to detect these radiations. After calibration,

![Fig. 38. Free vibration test at bridge [120].](image-url)
the output can be converted to temperature [7]. In the second mechanism, the surface temperature is measured under condition of heat flow. Since heat flow through concrete is affected by subsurface anomalies, therefore, it can be used to detect subsurface anomalies [7]. It should be noted that delaminated areas heat up faster and cool down more quickly when compared with concrete. Moreover, they can develop surface temperatures from 1 °C to 3 °C higher than the surrounding areas when ambient conditions are favorable [25].

Typical Infrared thermography equipment consists of a scanner, data acquisition system and a visual recorder. The scanner transmits infrared radiation, the data acquisition system records and analyzes the data while a visual recorder such as digital video camera is used to record the scanned data.

This method has been used to locate delamination in reinforced concrete pavements and bridges decks. The advantage of applying Infrared thermography is that it is safe, efficient, cost effective in terms of time, non-invasive and non-contact. The inspected materials can have distances ranging from a few millimeters to several kilometers, if provided with suitable lens [130]. Some of the limitations of this method include [7] (1) the equipment is very expensive, (2) it cannot give the depth of the defects because it takes the image of a surface, (3) the testing is influenced by environmental conditions such wind speed, solar radiation, moisture content and surface emissivity, hence corrections are required for these parameters [133], (4) trained operator and analyst is required to capture data and interpret it correctly. Therefore, it is suggested to use this method with ground penetrating radar [133]. Moreover, combination of the two methods (Infrared thermography and impulse radar) is widely used in civil engineering industry and applied to highway bridges, asphalt pavement, sewer system, canals, aqueducts and airport pavement for various findings [132,133]. Infrared image of a span of a bridge is shown in Fig. 40.

Infrared thermography in general can be divided into two major categories: active and passive. It is based on excitation methods for observing the temperature difference. Usually, external stimulations are not required for passive thermography while different types of stimulus are employed in active thermography. The fundamental concept of Infrared thermography for Non-destructive testing is that abnormal temperature profiles indicate potential defect. Difference between temperature at a suspected area and a reference area indicates abnormal behavior. In general, passive thermography is rather qualitative because it is simply used to pinpoint anomalies. On the other hand, active thermography requires some energy to be brought to the target in order to obtain significant temperature differences for indication of subsurface anomalies [135].

According to Stanley and Balendran [134], thermography is the best method used by many researchers for detecting the seepage sources and heat loss calculation from the buildings. The scanning system was much sensitive and can identify the temperature differences of up to 0.1 °C. For normal scanning of buildings, the maximum recommended distance is 50–100 m. Authors enlightened that infrared thermographic method not only identify the existing defects and problems in the structure but also provide the advance
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<td>Ultrasonic (acoustic) stress wave based method</td>
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<tr>
<td></td>
<td>impedance method, extension of vibration test</td>
<td>(5) Detect delamination</td>
<td>(5) Shallow defects may remain undetected</td>
</tr>
<tr>
<td>Acoustic emission</td>
<td>Transient elastic waves</td>
<td>(6) Detect material interface, specifically interfaces between concrete and air (e.g.</td>
<td>(6) Some defects might remain undetected due to use of lower frequencies</td>
</tr>
<tr>
<td></td>
<td></td>
<td>grouting defects and concrete and steel (reinforcement) [60,62,66,140]</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(7) Detect grouting defects</td>
<td></td>
</tr>
<tr>
<td>Ground penetrating</td>
<td>Use electromagnetic waves</td>
<td>(1) Real-time damage detection</td>
<td>(1) Reliable data interpretation is highly dependent on the selection of test points</td>
</tr>
<tr>
<td>radar</td>
<td></td>
<td>(2) Remote monitoring</td>
<td>(2) Smaller defects may remain undetected</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(3) Applicable for both local and global monitoring</td>
<td>(3) Automated apparatus is not available</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(4) Continuous monitoring without interrupting the traffic flow</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(5) Reliable analysis</td>
<td></td>
</tr>
<tr>
<td>Half-cell potential</td>
<td>Electrochemical method</td>
<td>(1) Able to determine the buried objects</td>
<td>(1) Inability to direct image</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(2) Produce contour maps of subsurface features</td>
<td>(2) Unable to detect delamination in bridge decks, unless they are epoxy-impregnated or filled with water</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(3) Used for condition assessment of civil structures specially related to soil</td>
<td>(3) Extreme cold conditions effects the GPR data</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(4) Detect voids and anomalies</td>
<td>(4) Completely frozen moisture will remain undetected</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(5) Evaluate thickness of members</td>
<td>(5) Frozen moisture influence the acquired signal</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(6) Measure thickness of concrete cover</td>
<td>(6) Deicing salts affect the dielectric constant</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(7) Determine rebar configuration</td>
<td>(7) Unable to estimate mechanical properties of concrete like strength, modulus</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(8) Detect delamination and its potential</td>
<td>(8) Unable to provide absolute information about the presence of corrosion, corrosion rate or rebar section loss</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(9) Detect concrete deterioration</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(10) Sensitive to corrosive environment</td>
<td>(9) Expensive method as compared to other ones</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(11) Estimate concrete properties</td>
<td></td>
</tr>
</tbody>
</table>

(continued on next page)
## Capabilities and limitations

The capabilities and limitations of some of the well-known and most important NDT methods are summarized in Table 1.

### Table 1. Continued

<table>
<thead>
<tr>
<th>Test name</th>
<th>Description</th>
<th>Applications/capabilities</th>
<th>Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical resistivity</td>
<td>Based on voltage and current measurement</td>
<td>Detects cracks, delamination and concrete disintegration</td>
<td>(1) Chain drag is not applicable to vertical surfaces (2) Depends upon hearing skills of the operator (3) Unable to detect initial delamination (4) Ineffective on bridge decks with overlays</td>
</tr>
<tr>
<td>Infrared thermography</td>
<td>Based on electromagnetic characteristics of the deck related to temperature variation</td>
<td>Detect delamination in concrete</td>
<td>(1) Chain drag is not applicable to vertical surfaces (2) Depend upon bearing skills of the operator (3) Unable to detect initial delamination (4) Ineffective on bridge decks with overlays</td>
</tr>
<tr>
<td>Chain drag and hammer sounding</td>
<td>Based on sound characteristics of the deck</td>
<td>Detect delamination in concrete</td>
<td>(1) Chain drag is not applicable to vertical surfaces (2) Depend upon bearing skills of the operator (3) Unable to detect initial delamination (4) Ineffective on bridge decks with overlays</td>
</tr>
</tbody>
</table>

2.5.3. Radiography

Radiography is a nuclear NDT method in which high energy electromagnetic radiation passing through the test object/member is recorded on a photographic film placed on the other side of the member. This method can be effectively used to detect reinforcement location, voids in concrete, material heterogeneity and layers of different materials, honeycombing and voids in grouting of post-tensioning ducts. However, the test personnel require specialized safety training and licensing. The radiation can be produced by X-ray tube (X-radiography) or radioactive isotope (gamma radiography). Schematic illustration is given in Figs. 41 and 42. Radioactive isotope generate radiations which pass through the concrete and sensed by the detector. The detector converts these radiations into the electrical pulses, which are further analyzed or counted by other techniques. The selection of radiation source and amount of energy absorbed by the material depends on the thickness and the density of the member as well as the exposure time that can be tolerated. On the radiation based photograph, high density materials (reinforcement) appear as a light area while low density regions (voids) appear as a dark area.

According to Song and Saraswathy, radiography is a reliable method for locating internal cracks, variations in density of material and voids in material. Moreover, Ibrahim, evaluated the application of different NDT methods on the composite structures. It was demonstrated that the number of voids having diameter in between 20 and 50 mm can be detectable by X-ray imaging while Neutron methods is suitable for inspection of moisture in thick structures.

Suzuki et al. [114], used X-ray computed tomography method for damage evaluation in a concrete canal. Concrete cores were taken from the existing canal and the distributions of cracks in these cores were inspected with helical computerized tomography (CT) scans. The Output images were visualized in gray scale where dark portion represents the air while white segment shows the dense part. The samples were scanned constantly at 0.5 mm pitch overlapping and depending on the length of each specimen a total of 200–400 two dimensional images were obtained. The values of the absorption coefficients obtained from the CT scanning system were transformed into CT numbers using the international Hounsfield scale. The authors found that the CT numbers varied according to the material properties. Variance of the CT number increases with the increase in damage. Finally, crack properties were quantified using X-ray CT data.

2.6. Capabilities and limitations

The capabilities and limitations of some of the well-known and most important NDT methods are summarized in Table 1.
time, reliability and simplicity, some methods are preferred over others. Ideally, it is required to adopt a method which can detect all important defects and anomalies present in the structure. Therefore, the selection of NDT method must be based on the yielding of the information.

In construction industry, most of the field engineers and specialists are dissatisfied by use of NDT methods due to using inappropriate method for a specific problem. Therefore, it is recommended to do preliminary study before selecting any NDT method. In literature, this study is normally referred as desk study [6]. Different steps of desk study are given in Fig. 43.

According to the requirements of the Standards for Technical Condition Evaluation of Highway Bridges [141], every bridge needs to be inspected at least once every 24 months. The inspection is done to monitor the evolution or possible deterioration of the bridge's working condition and to allow timely decision for repair, rehabilitation, and/or emergency treatment such as strengthening or closure [142]. Periodic inspection of the structure is the first step for continuous health monitoring. Uemoto [11], identified the damage levels based on periodic inspection (Table 2). The author provided the scale of deterioration (0–5) and explained the evaluation procedure by using visual aids. All the parameters were elaborated in general terms and for simplicity the parameters were limited to cracks, stains and spalling. Hence, the judgment was based purely on the inspector understanding, which may lead to wrong selection of method. Therefore, in this research, the description of damages levels is provided in terms of numbering system based on severity of defects to the bridge members. The measurement units are used which will provide comparatively better information and less dependence on the inspector judgment. Elaboration of each damage level based on crack lengths, spalling of concrete cover, support settlement, tilting of foundation (due to settlement of subsoil or erosion of soil) and reinforcement of corrosion is given in Table 3. This will provide an ease to the field engineers for better understanding of the damage levels. For example, crack lengths, support settlements and tilting of supports are measured and based on quantitative reading; they are classified under certain damage level. However, further research is required so as to correlate the source of error with the damage level. For example, the source of crack propagation is important. The behavior of cracks due to temperature and shrinkage would be different when compared to shear and flexural cracks. Some other important features such as the inspection type and potential remedial action against each proposed damage level are included. The measurement units are used which will provide comparatively better information and less dependence on the inspector judgment. Elaboration of each damage level based on crack lengths, spalling of concrete cover, support settlement, tilting of foundation (due to settlement of subsoil or erosion of soil) and reinforcement of corrosion is given in Table 3. This will provide an ease to the field engineers for better understanding of the damage levels. For example, crack lengths, support settlements and tilting of supports are measured and based on quantitative reading; they are classified under certain damage level. However, further research is required so as to correlate the source of error with the damage level. For example, the source of crack propagation is important. The behavior of cracks due to temperature and shrinkage would be different when compared to shear and flexural cracks. Some other important features such as the inspection type and potential remedial action against each proposed damage level are included. The measurement units are used which will provide comparatively better information and less dependence on the inspector judgment. Elaboration of each damage level based on crack lengths, spalling of concrete cover, support settlement, tilting of foundation (due to settlement of subsoil or erosion of soil) and reinforcement of corrosion is given in Table 3. This will provide an ease to the field engineers for better understanding of the damage levels. For example, crack lengths, support settlements and tilting of supports are measured and based on quantitative reading; they are classified under certain damage level. However, further research is required so as to correlate the source of error with the damage level. For example, the source of crack propagation is important. The behavior of cracks due to temperature and shrinkage would be different when compared to shear and flexural cracks. Some other important features such as the inspection type and potential remedial action against each proposed damage level are included. The measurement units are used which will provide comparatively better information and less dependence on the inspector judgment.

3. Planning and selection of NDT method

In the previous section, we highlighted the basic working principle, advantages & disadvantages of various NDT methods used for the evaluation of civil infrastructures. Depending on cost, available

<table>
<thead>
<tr>
<th>Damage level</th>
<th>Deficiency level</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>None</td>
<td>Minor deterioration to any elements</td>
</tr>
<tr>
<td>1</td>
<td>Marginal</td>
<td>Minor deterioration to primary supports elements</td>
</tr>
<tr>
<td>2</td>
<td>Moderate</td>
<td>Moderate deterioration to some of bridge element</td>
</tr>
<tr>
<td>3</td>
<td>Severe</td>
<td>Serious deterioration to some of structural element</td>
</tr>
<tr>
<td>4</td>
<td>Severe</td>
<td>Serious deterioration to primary structural elements</td>
</tr>
<tr>
<td>5</td>
<td>Failed</td>
<td>Some portion collapse/demolished</td>
</tr>
</tbody>
</table>

Table 3

<table>
<thead>
<tr>
<th>Level</th>
<th>Inspection</th>
<th>Crack lengths</th>
<th>Spalling</th>
<th>Support settlement</th>
<th>Tilting of foundation</th>
<th>Reinforcement corrosion</th>
<th>Potential remedial action</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Periodic</td>
<td>None/1 μm</td>
<td>None</td>
<td>100 μm</td>
<td>0°</td>
<td>None</td>
<td>Routine preservation activities</td>
</tr>
<tr>
<td>1</td>
<td>Periodic</td>
<td>Partial/100 μm</td>
<td>None</td>
<td>1 mm</td>
<td>0.05°</td>
<td>Some stains on surface Major maintenance activities</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Detailed</td>
<td>Some/&lt;1 mm (NDT limit) [143]</td>
<td>Partial bulge outward</td>
<td>50 mm</td>
<td>0.1° (Realized) [121] Fair amount of stains Partially stains Priority to remediate and repair</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Special</td>
<td>Fair amount/&lt;10 mm</td>
<td>Partial spalling</td>
<td>95 mm (Realized)</td>
<td>0.3°</td>
<td>Fair amount of rusts Fully slabs</td>
<td>Rehabilitation and replacement options</td>
</tr>
<tr>
<td>4</td>
<td>Special</td>
<td>Large amount/&lt;100 mm</td>
<td>Fair amount of bulge and spalling</td>
<td>200 mm (maximum allowable) [121] ≥ 200 mm</td>
<td>0.5° (max allowable) Large amount of rusts</td>
<td>Strengthen &amp; upgrading</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Special</td>
<td>Large/&lt;1 m</td>
<td>Large amount of bulge and spalling</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Fig. 44. Schematic layout of SHM procedure, NDT method selection and potential remedial measure.

Table 4

<table>
<thead>
<tr>
<th>Measurement parameter</th>
<th>Non-destructive test method</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Delamination</td>
<td>Impact echo, ultrasonic pulse echo, chain drag and hammer sounding, ultra sonic surface waves, GPR, Infrared thermography, coin tap test, impulse response</td>
<td>In PCC, RCC and pre-stress concrete</td>
</tr>
<tr>
<td>Dimension measurement</td>
<td>Laser transit measure</td>
<td>Exposed dimension</td>
</tr>
<tr>
<td>Thickness/depth</td>
<td>GPR, impact echo, ultra-sonic, radar</td>
<td>Embedded dimension</td>
</tr>
<tr>
<td>Concrete cover</td>
<td>GPR, electro-magnetic, radar, X-ray</td>
<td>Top bars only/surface reinforcement</td>
</tr>
<tr>
<td>Spacing between</td>
<td>Electromagnetic, GPR, radar, impact-echo, X-ray</td>
<td>Top bars only</td>
</tr>
<tr>
<td>Diameter of bars</td>
<td>Electro-magnetic method, GPR</td>
<td>Top bars only</td>
</tr>
<tr>
<td>Stiffness</td>
<td>Dynamic testing, oscillation test</td>
<td>Frequency and amplitude</td>
</tr>
<tr>
<td>Deterioration</td>
<td>Acoustic emission, photograph, GPR, Infrared thermography, visual inspection</td>
<td>Stain, cracks</td>
</tr>
<tr>
<td>Surface defects</td>
<td>Thermography, digital still camera, impulse response, Infrared thermography, visual inspection, Coin tap test</td>
<td>Cold joints Including honeycomb in and at back of the structure</td>
</tr>
<tr>
<td>Inside defects</td>
<td>X-ray, sonic, ultra-sonic, impact echo, thermograph, impulse response, GPR, radar</td>
<td>Voids inside and at back of the structure</td>
</tr>
<tr>
<td>Micro deformation</td>
<td>Digital gauge, strain gauge</td>
<td></td>
</tr>
<tr>
<td>Large deformation</td>
<td>Laser transit measure</td>
<td></td>
</tr>
<tr>
<td>Vibration</td>
<td>Laser deformation measurement, LVDT, Acceleration sensor</td>
<td></td>
</tr>
<tr>
<td>Concrete compressive</td>
<td>Rebound hammer test, Pull-out test, core sample test, impact echo</td>
<td>General method, accuracy issues</td>
</tr>
<tr>
<td>strength</td>
<td>ainiency issues</td>
<td></td>
</tr>
<tr>
<td>Elastic modulus</td>
<td>Impact echo, ultra sonic surface waves, core sample test, ultra-sonic velocity</td>
<td>Continuous measurement required</td>
</tr>
<tr>
<td>Cracking</td>
<td>Acoustic emission, impact echo, ultrasonic pulse echo, impulse response, electrical resistivity, Infrared thermography, Coin test</td>
<td></td>
</tr>
<tr>
<td>Crack depth</td>
<td>Ultra-sonic pulse echo, ultrasonic surface waves</td>
<td>Effects of bars</td>
</tr>
<tr>
<td>Crack width</td>
<td>Thermography, Coin tap test, digital still camera</td>
<td>Direct measurement</td>
</tr>
<tr>
<td>Crack distribution</td>
<td>Thermography, digital still camera</td>
<td></td>
</tr>
<tr>
<td>Permeability</td>
<td>Electrical resistivity, on-site permeability test</td>
<td></td>
</tr>
<tr>
<td>Corrosion location</td>
<td>GPR, half-cell potential, Galvanostic Pulse measurement, electrical resistivity, natural potential</td>
<td>In situ and real time location</td>
</tr>
<tr>
<td>Corrosion degree</td>
<td>Electrical resistivity, electric current analysis, Galvanostic Pulse measurement, natural potential</td>
<td>Periodic measurement required</td>
</tr>
<tr>
<td>Debonding detection</td>
<td>Impact echo, ultrasonic pulse echo, impulse response, Infrared thermography, coin tap test</td>
<td></td>
</tr>
<tr>
<td>Grouting characteristics</td>
<td>Impact echo, ultrasonic pulse echo</td>
<td></td>
</tr>
<tr>
<td>Material layers/interface</td>
<td>Ultrasonic pulse echo, Infrared thermography</td>
<td></td>
</tr>
<tr>
<td>Chloride, carbonation, acids</td>
<td>Core sample test, electrical resistivity</td>
<td>Analysis by core sample</td>
</tr>
</tbody>
</table>
In this research, we have proposed a flow chart for periodic inspection of concrete bridges (Fig. 44). The health of structures is monitored and classified in terms of damage level. After classifying the damage level, several suitable NDT methods are suggested for detailed investigation of bridge. Since maintenance activities are the routine interventions which are applied to the structure to preserve the structural performance and health. Therefore, subsequently corrective measures are also proposed to recover the lost strength. Repair activities involve restoration of the existing damaged members to improve the condition, while rehabilitation and replacement activities involve the replacement of damaged members and focus on the root cause of the problem. Strengthening and upgrading activities involve the modification in existing structural members to improve and enhance the structural performance.

Most of the time field engineers are familiar with the problem related to concrete structures specifically bridges. However, they require precise NDT method which addresses their problem. In Table 4, NDT methods are suggested according to different issues related to structures. It will provide a guideline for field engineers to select NDT method.

The selection of NDT method based on the defect type is also proposed in this paper. The relation between some of the well-known NDT methods and most common problems encountered by the field engineers is illustrated in Fig. 45. Normally, periodical inspection is done by using visual aids or by simple NDT method(s). Currently, the most prominent on-site methods for detecting disbonds, defects, impact damages, cracks, fiber breakage and misalignment are visual inspection and tap testing [144]. Visual inspection is the first step for deciding the health of a structure and selecting NDT method for further examination. AE method is also used for periodic inspection. In comparison to visual inspection, it is obviously advantageous as it can provide the global as well as local monitoring of the structures. Moreover, it provides the real time monitoring of the structure. After the periodic inspection, detailed investigation is performed based on the defect type. Each defect type mention here can be further categorized and elaborated into different groups. We would like to mention here that these are the most common type of damages which are required to be investigated in almost all types of civil structures. This will provide an ease to the field engineers in selection of an NDT method. Coring, which is considered as semi-destructive method, can be used only for validating the results of other methods. Once the detail study is completed, the maintenance work can be started.

The selected method must be able to include all those problematic areas which cannot be examined by using traditional methods. The data recovered from the method must be reproducible and should serve as reference for carrying out investigation in future. In should also be kept in mind that the selected methods are constrained by allocated time and budget of the project. It is worth mentioning here that the experience of the investigator is most...
critical for executing any testing scheme in a successful manner. The testing scheme should be designed such that it provides the optimum level of knowledge about the health of structure. The investigator must also be familiar with the construction technique, damage mechanism and structural behavior besides knowing the capabilities and limitation of selected NDT method. The knowledge about the construction technique will help in anticipating about the exact location of possible anomaly in concrete. Moreover, information about damage mechanism will guide the investigator to choose the parameters that are required to be measured. Finally, the structural behavior will provide valuable information about selecting most vulnerable member for the existence of defects.

4. Conclusions and recommendations

In this paper, various NDT methods which are applicable especially to concrete bridges are reviewed. The methodology, advantages and disadvantages along with the up to date research on NDT methods are presented. Following are some of the important conclusions.

- For those structures which are inaccessible, dynamic testing, infrared and radar technology are the better choice. Moreover, global and local monitoring of structures in real time make AE a preferred method with compared to other NDT methods.
- For long span bridges, it is very difficult to inspect visually all the portions or elements of bridge, especially soffit of bridge. Proof load test is especially good for stone and masonry structures, whose drawings and design parameters are unknown. However, in reinforced concrete structures their structural details can be found by using electromagnetic method and coring. The Coin tap, chain drag and hammer tests are inexpensive in nature but these tests are depended on human factor, which make these tests less reliable. The investigators can use these methods for periodic inspection as they will give some better understanding about structure.
- The sonic and ultra-sonic tests are more reliable and have more capabilities to address maximum problems if coupling issue is properly resolved. GPR, Impact echo and Infrared thermography also provide reliable analysis of structure. If the shortcomings of these methods (GPR, Impact echo and IR) are addressed than these methods can provide the deterministic results. Electric based tests can be performed rapidly at any time and in any circumstance, but these tests provide information related to reinforcement only. Moreover, electric based tests are not helpful for brick masonry and stone structures. Radiation based tests provide good information about voids and cracks but X-ray, gamma rays and neutron rays are hazardous for the operator and community. Therefore, great care is required during these tests. Dynamic and vibration tests are reliable and extensively used in civil industry. However, these tests are unable to pick the problem related to elastomeric bearing pads. If NDT tests are used in combinations then it provides detailed and reliable information e.g. using chain drag in combination with GPR test or with sonic/ultrasonic tests.
- Different damage levels based on crack lengths, spalling of concrete cover, support settlement, titling of foundation (due to settlement of subsoil or erosion of soil) and corrosion of reinforcement are suggested, which will limit dependence on the inspector judgement. A flow chart based on damage level along with NDT methods and potential remedial measures are proposed for periodic health monitoring of structures. Most of the time field engineers are familiar with the problem related to concrete structures specifically bridges. However, they require precise NDT method which addresses their problem. Therefore, NDT methods are also suggested according to different issues related to structures. Finally, the relation between some of the well-known NDT methods and most common problems encountered by the field engineers is proposed. This will provide an ease to the field engineers to select the NDT method. Hence, this research tries to overcome the misperception about the NDT methods and encourage the field engineers an ease to use NDT as integral part of testing.
- Some of the NDT methods are developed for some specific industries, like radiography for the medical industry, GPR for the geologist and geo-physics, Electrical based methods for solving the electrical problems. Hence, there is a strong need to introduce a new discipline which bridges the gap between civil engineering and these technologies.

Acknowledgements

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