Structural Health Evaluation of Concrete Road Bridges – an NDT Approach

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Abstract. For a good construction, safe operation and timely maintenance of any bridge structure, a comprehensive structural evaluation becomes necessary. For this purpose, any kind of destructive testing is highly undesirable. Non-destructive testing and evaluation (NDT&E) methods provide an ideal means for a quick testing and a comprehensive evaluation of different parameters related to the strength, durability and overall structural integrity of concrete bridges. Some of these parameters are the elastic modulus/ in-situ compressive strength, uniformity and homogeneity of concrete, presence of cracks, voids and other imperfections, identification of reinforcement profile, cover and diameter, etc. This paper presents the NDT&E of Indian Railways Road bridges. The various NDT&E methods utilized are presented, and the findings are mutually compared to highlight the effectiveness of a particular method in a specific situation or for a specific purpose.

Introduction

Structural condition evaluation of reinforced cement concrete structures may be performed generally for the estimation of its remaining service life, and choice of the rehabilitation measure to be adopted, if required. Ideally, such testing should be done without damaging the concrete. The tests available for condition evaluation of concrete, range from the completely non-destructive (where there is no damage to the concrete), to those where the concrete surface is slightly damaged, to destructive tests (where the surface has to be repaired after the test).

Non-destructive testing and evaluation (NDT&E) technology provides ideal means to evaluate various structural condition parameters of a structure without affecting its functionality and serviceability. Different NDT&E methods employ different physical phenomenon such as, wave propagation (seismic, ultrasonic, electromagnetic, infra-red, acoustic), vibration, deflection, impulse rebound, electrical resistivity, electrical/thermal conductance, etc. to detect and identify any anomalies or deterioration in the test medium, which is otherwise not directly visible or identifiable. All these methods, in general, are based on measuring the response of the test medium to the applied stimulus, and using this information to characterize the medium's geometrical and/or engineering properties [1,2,3].

Reinforced concrete structures like road over/under bridges, undergo a loss in structural integrity over time. This may be caused by inferior quality of construction or deterioration arising mainly from physical (overloading, fatigue, shrinkage, creep, honeycombing, abrasion, cavitation, frost action, etc.) and chemical (alkali–silica reaction,

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corrosion, carbonation, crystallization, salt chloride attack, expansion, leaching, acid action, weathering, etc.) processes. A number of non-destructive testing (NDT) equipment are available for the in-situ testing and subsequent assessment of various structural integrity parameters of a reinforced concrete structure. The range of properties that can be assessed using these tests include density, elastic modulus, strength, quality, surface hardness, surface absorption, location of reinforcement, its size and distance from the surface, corrosion, voids, delamination, cracks, etc [4,5].

Thus, a comprehensive structural evaluation of a concrete structure requires the use of a number of different non-destructive testing and evaluation (NDT&E) methods. To overcome the limitations of individual methods, a complementary approach can be adopted whereby; different NDT&E methods are used at the same location to complement each other in structural condition evaluation of the concrete member. The integration of such an approach in structure management system should be able to provide information that helps in assessment of the present structural condition, effectiveness of the maintenance measures applied earlier, deterioration models, and the prognosis of further deterioration [2,3,4,6].

Further, a number of different NDT&E methods may be available for assessment of a single condition parameter. Hence, it is desirable to have the ability to take informed decisions regarding the choice of a particular method, which will be best suited for the given test conditions (related to location, geometry and state of the structural component being tested, etc.). This ability can be developed if the test data from each of the employed methods is analyzed, and a relative comparison of effectiveness of these methods in parameter estimation is made.

In this study, various non-destructive testing and evaluation methods are used to estimate each of the various strength parameters of structural components of four concrete road bridges, located at Railway Colony, Manak Nagar, Lucknow, India. To complement the NDT&E, ground truth information is obtained by extracting core samples from the test locations. The test data set from each of the employed methods is analyzed, and a relative comparison of effectiveness of these methods in parameter estimation is made. This comparison is based on various related aspects like accuracy and reliability, overall cost of equipment and operation, comprehensiveness of the method to give detailed and varied information, time and resources required, ease of operation of the equipment, and ease of data analysis. Based on this comparison, the study provides suggestions to enable one to take informed decisions regarding the choice of methods for estimation of relevant strength parameters of concrete structural members.

2. Methods and equipment

In this section, various methods employed for NDT&E of concrete components of road bridges have been described, along with their respective principles of working. The standard codes of practice for these methods are also mentioned. The field techniques of conducting in-situ tests, and the methodology employed have also been discussed.

The following equipment have been used in this study to determine the various parameters related to the strength, durability and overall structural integrity of the super structure of the concrete road bridge [1,6].

- For in-situ compressive strength estimation of concrete:
  -Analog Rebound Hammer, Digital Rebound Hammer, Cut And Pull Out Test, Core Cutter, Penetration Resistance Test (Windsor Probe), Ultrasonic Pulse Velocity meter.
- For quality estimation of concrete:
  -Permeability meter, Ultrasonic Pulse Velocity (UPV) meter
- For examining the condition of reinforcement:

-Corrosion Analyzer (Half Cell Potentiometer), Resistivity meter

- For identification of profile of reinforcement and measurement of cover:
  -Profometer
- For visual inspection and crack detection:
  -Video Boroscope, Crack Detection Microscope

2.1 Estimation of compressive strength

Compressive Strength of a material is its ability to sustain axial compressive stress. A variety of NDT&E methods are available to evaluate the compressive strength of a concrete structural component. This section presents the compressive strength related NDT&E methods and corresponding equipment that are used in this study. The underlying principle for each method, working of equipment, etc. are discussed in details.

2.1.1 Rebound Hammer (Schmidt Hammer)

Rebound Hammer method can be used for assessing the indicative compressive strength of concrete with the help of suitable co-relations between the rebound index (explained later) and compressive strength; comparing the uniformity and quality of concrete to the specification requirements, or with quality of another concrete member/structure. It can be rapidly and very conveniently used for differentiating the acceptable parts of a structure from unacceptable ones.

Principle and code: The method is based on the principle that the rebound of an elastic mass depends on the hardness of the surface against which the mass strikes. The rebound hammer testing may be carried out as per IS:13311(Part2) [7].

Device and Methodology: The device consists of a hammer mass controlled by a spring and a plunger. The plunger is pressed against the concrete surface and the rebound of the mass because of the action of the spring is noted (refer Picture 1(a)). This number is called the Rebound Number or Rebound Index. The extent of rebound depends on the hardness of the concrete surface. The corresponding compressive strength can then be read from a calibration graph provided on the body of the hammer [1,6].

To establish a correlation between compressive strength of concrete and its rebound number given by Schmidt hammer, both properties are measured on same concrete cubes. The cube specimens are held in a compression testing machine under a fixed load and the rebound number is determined. Then, the compressive strength is determined for the same cube. In this way, the correlation is established; using which, the indicative strength of the structure can be assessed [1,6].

In general, the rebound number increases with strength. It is affected by a number of parameters i.e. type of cement, type of aggregate, surface condition and moisture content of the concrete, curing and age of concrete, carbonation of concrete surface, etc. Moreover the rebound index is indicative of compressive strength of concrete upto a limited depth from the surface. The internal cracks, flaws etc. or heterogeneity across the cross section will not be indicated by rebound numbers. As such the estimation of strength of concrete by rebound hammer method cannot be held to be very accurate and probable accuracy of prediction of concrete strength in a structure is ± 25%. If the relationship between rebound index and compressive strength can be found by tests on core samples obtained from the structure or standard specimens made with the same concrete materials and mix proportion, then the accuracy of results and confidence thereon gets greatly increased [1,6].

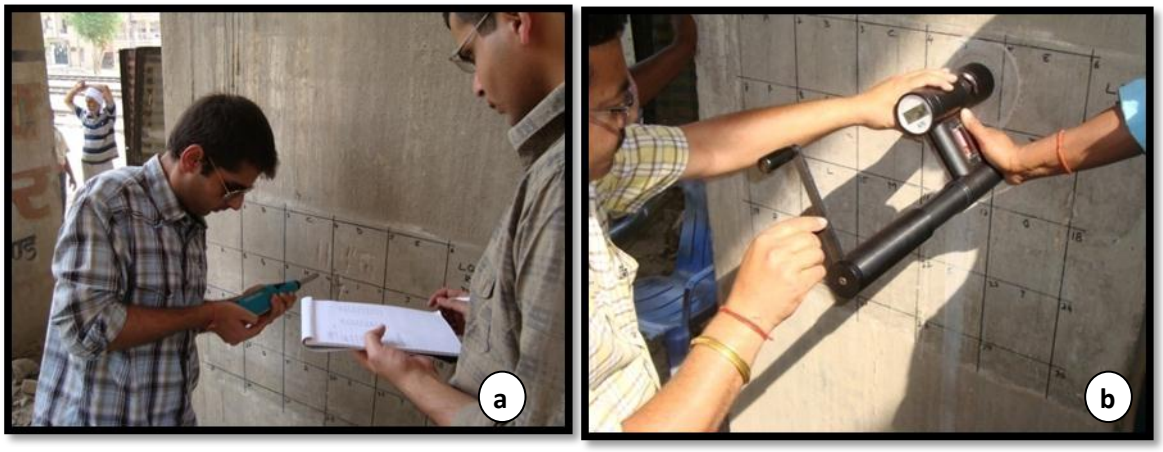
2.1.2 Digital Rebound Hammer

The digital rebound hammer is an improvement over the Schmidt Hammer. It has a microprocessor based transducer which converts the rebound of the hammer to electric signals and displays it on the screen in the selected stress units. The device is capable of storing multiple readings. It can directly displays the mean of the readings and can be connected to a computer for data transfer and analysis in the field itself [1,6].

2.1.3 Cut and Pull Out Test

Cut And Pull Out (CAPO) test is a pull out test used to determine the compressive strength of concrete. The test is considered superior to the rebound hammer and the penetration resistance test, because large volume and greater depth of concrete are involved in the test.

Principle and code: A pull out test measures the force or load required to pull out an embedded insert in the concrete mass. The test subjects concrete to slowly applied load and measures actual strength property of the concrete. The ultimate pull out load is then used to estimate the compressive strength based on previously established relationships. This test may be conducted as per ASTM C900-01 [8] and BS 1881-207 [9].
Device and Methodology: The CAPO test measures the force required to pull an embedded metal insert with an enlarged head from a concrete structure. The pull out strength is proportional to (and equal to10-30%) the compressive strength of concrete and is of the same order of magnitude as the direct shear strength of concrete [1,6].



Picture 1: (a) Digital rebound hammer test in progress, (b) Cut And Pull Out test in progress

The pullout test can be of two types: Pre-planned, where the metal inserts are cast along with concrete and post-planned, whereby the Insert is fixed by under cutting and subsequent expanding procedure in the hardened concrete of existing structures. The CAPO test is of the latter type. While selecting the location for conducting a CAPO test, it should be ensured that reinforcing bars are not within the failure region. The surface at the test location should be flat. An 18 mm hole is cored perpendicular to the surface. A slot is routed in the hole to a diameter of 25 mm and at a depth of 25 mm. A split ring is expanded in the recess and pulled out using a loading ram reacting against a 55 mm diameter counter pressure ring (refer Picture 1(b)). The concrete in the strut between the expanded ring and the counter pressure ring is in compression. Hence ultimate pullout force is related directly to compressive strength. When the insert is pulled out a conical frustum of concrete comes along with it. The ultimate pullout load measured by the device is converted to an equivalent compressive strength by means of previously established relationships [1,6].

A good number of correlation studies have reported that compressive strength is linear function of pull out strength [1,6].

2.1.4 Core Drilling Method

Core drilling method is a direct way of measuring the actual strength of concrete in the structure as it provides the ground truth information. In this method, suitable sized cores are extracted from the test location and further tested in the laboratory, according to the requirement.

Principle and code: The core drilling method and compressive strength test are covered in the standard code IS:1199 [10]. The provision of IS 456:2000 [11] (vide clause 17.4.3) states that, "Concrete in the member represented by a core test shall be considered acceptable if the average equivalent cube strength of the cores is equal to at least 85% of the cube strength of the grade of concrete specified for the corresponding age and no individual core has strength less than 75%".
Device and Methodology: A suitable core-cutter device is used. Cylindrical specimen of 100 mm or 150 mm diameter are common; other sizes may also be permitted but the least lateral dimension should not be less than three times the maximum size of the aggregates used. The core specimen to be tested should preferably have a height of twice the diameter. If there are difficulties in obtaining samples of such size, the length to diameter ratio is permitted to be lower, but in no case lower than 0.95. The samples are to be stored in water for two days prior to testing and are to be tested in moist condition. The ends of specimens are trimmed, flattened and capped with molten sulphur or high alumina cement or some other permissible capping material to obtain a true flat surface. The specimen is then tested in a compression testing machine [1,10].

The test location and the number of cores to be taken are of utmost importance. The location should be such that no reinforcement is encountered. If secondary reinforcement or surface reinforcement is unavoidable, the strength of core can be taken as 10% less than the measured strength.

2.2 Estimation of concrete quality

Durability of concrete under aggressive environment, homogeneity of the concrete, presence of cracks, voids and other imperfections; these are some important factors on which bearing capacity of a component in a reinforced concrete structure is dependent upon. Hence, regular quality assessment of concrete is essential. The test procedures and influencing factors affect the measured values and hence the assessment of the quality of in-place concrete. For this project permeability tester and UPV meter were used for the quality assessment of concrete.

2.2.1 Permeability Tester

Among other factors, bearing capacity of a structural element in a concrete structure is also dependent on its durability under aggressive environmental influences which depends essentially on the quality of the surface layer. The permeability of the concrete at the surface (cover layer) is an excellent indicator of the potential durability and resistance of a particular concrete against the ingress of aggressive media in the gaseous or liquid state. The permeability tester allows a quick and efficient non-destructive evaluation of the

quality of the concrete, with respect to its durability, by measuring the air permeability of cover concrete.

Principle and code: The rate at which fluid flows through the concrete is a measure of its permeability. The relevant codes of practice for this test are: ASTM C1202 [12] and BS 1881 [9].
Device and Methodology: The components of the device are: display unit, control unit, vacuum cell, and vacuum pump. The method involves a two chamber vacuum cell and a pressure regulator, which ensure that an air flow at right angles to the surface is directed towards the inner chamber. This permits the calculation of the permeability coefficient (k) on the basis of a simple theoretical model. The test requires a dry surface without any cracks and it should be ensured that the inner chamber is not located above any reinforcement bar. Pressure loss is calibrated on a timely basis. After a large change in temperature and/or pressure, 3 to 6 measurements of electrical resistance of the concrete and its mean value is taken for the measurement of coefficient of permeability. The unit measures the pressure increase as a function of time according to a specific sequence. The associated data is automatically collected by the display unit and the permeability coefficient and the depth of penetration of the vacuum are calculated. The measurement takes 2-12 minutes, depending on the permeability of the concrete. In the case of dry concrete, the quality class of the concrete cover can be read from a table using the k value. In the case of moist concrete, k is combined with the electrical concrete resistance (ρ) and the quality class is determined from a monogram [1,6].

However, there are some limitations to this test. The determination of k and ρ cannot be carried out on wet surfaces as the moisture entering the unit could damage the membrane in the pressure regulator. In order to obtain an exact idea of the quality of the cover concrete of a structure or of a finished component, several readings are necessary. The quality classification of the cover concrete provided are generally for young concrete and may not be applicable for old concrete. The corrections applied for the effect of moisture content on the permeability, by the measurement of the electrical resistance, generally leads to satisfactory results in the case of young concrete. For old concrete, further investigations are required. Care should be taken to generate sufficient vacuum. If the concrete cover is too permeable, the unit may not be able to reach the desired vacuum [1,6].

2.2.2 Ultrasonic Pulse Velocity Meter (UPV)

The UPV method is used to establish the quality of the concrete used, value of dynamic elastic constant of the concrete, homogeneity of the concrete, and presence of cracks, voids and other imperfections. This test is useful for quality control during new constructions, and also for periodic evaluation of a concrete member, to measure the changes occurring with time on the properties of the concrete, and taking any remedial measure, against deterioration, if necessary.

Principle and code: The UPV test is conducted as per IS: 1331-1992-Part1 [13]. The inherent principle of assessing the quality of concrete is that relatively higher velocities are obtained when the quality of concrete is good, in terms of density, homogeneity and uniformity, rather than when quality of concrete is poor. Presence of a crack, void or flaw inside the concrete, which comes in the way of transmission of the pulses, attenuates the pulse strength and it passes around the discontinuity, thereby making the path length longer, consequently, lower velocities are obtained [1,13,14].

Device and Methodology: UPV uses an ultrasonic pulse which is induced into the concrete from an electroacoustic transducer, and undergoes multiple reflections at the boundaries of different material phases within the concrete, developing a complex system of stress waves which includes longitudinal (compressional), shear (transverse) and surface (Rayleigh) waves. The receiving transducer detects the onset of the longitudinal waves, which are the fastest. The velocity of the pulse depends on the elastic properties of the concrete. Generally, a frequency of around 50 kHz is used for evaluation of concrete. The equipment components used are: electrical pulse generator, display unit, transducers, amplifiers, measuring range, and electronic timing device. The transducers can be mounted on the surface of the concrete member under test, in the following ways: (a) direct (on opposite faces), (b) semi-direct (two adjacent faces), and (c) indirect (both transducers on one face only). The accuracy of velocity determination is governed by the accuracy of the path length measurement. In direct transmission arrangement, the transfer of energy between transducers is maximized. A minimum path length of 150 mm is recommended for the direct transmission method involving one unmolded surface. The direct transmission arrangement was used for this study [1,6,13,14]. Adequate acoustical coupling (e.g. petroleum jelly, grease, liquid soap and kaolin glycerol paste) between the concrete and the face of each transducer is used.

The ultrasonic pulse velocity of concrete is mainly related to the density and modulus of elasticity of concrete, which in turn depends upon the material and mix proportions used. They also depend on the method of placing, compaction and curing of concrete, and the quality of concrete, in terms of uniformity, incidence or absence of internal flaws, cracks and segregation, etc.

2.3 Assessment of reinforcement

For effective inspection and monitoring of concrete bridges, the condition assessment of reinforcement is an important step. Even for deciding appropriate repair strategy for a distressed concrete bridge, the determination of corrosion status of reinforcing bars is a must. Most of the NDT&E methods used for corrosion assessment are based on electrochemical process. For this project half cell potentiometer and resistivity meter were employed for condition assessment of reinforcement.

2.3.1 Half Cell Potentiometer Test/Corrosion Analyzer

Electrochemical Half-cell Potentiometer test provides a quantitative assessment of reinforcement corrosion over a wide area without the need of major removal of the concrete cover. The method detects the likelihood of corrosion of steel but cannot indicate the rate of corrosion. Distinction can be made between corroded and non-corroded locations by making measurements over the whole surface.

Principle and code: It is covered by ASTM C876–91 [15].Corrosion analyzer is based on electro-chemical process to detect corrosion in the reinforcement bars of structure. During active corrosion, the steel-concrete system in the reinforced concrete element represents short-circuited galvanic cell, with the corroding area of the reinforcement bar acting as the anode, the passive surface as the cathode and concrete as electrolyte. The excess electrons generated during corrosion flow through the concrete between anodic and cathodic sites, generating current which is accompanied by an electric potential field surrounding the corroding bar. The equipotential lines intersect the surface of the concrete and the potential at any point can be measured using the half potential method.

Device and Methodology: Before starting the test, the test surface is made wet (this should be done at least 45 minutes prior to conducting the test). To measure half-cell potentials, an

electrical connection is made, through a small drilled hole) to the steel reinforcement in the concrete member to be tested. This is connected to a high impedance digital millivolt meter, often backed up with a data logging device. The other connection to the millivolt meter is taken to a copper/copper sulfate or silver/silver chloride half-cell, which has a porous connection at one end which can be touched to the concrete surface. This will then register the corrosion potential of the steel reinforcement nearest to the point of contact. By measuring results on a regular grid and plotting results as an equipotential contour map, areas of corroding steel may readily be seen [1,6].

2.3.2 Resistivity Test

This test is used to measure the electrical resistance of the cover concrete. This test is used to assess the probability or likelihood of corrosion of the reinforcement bar.

Principle and code: It is covered by ASTM C1202–12 [12]. Once the reinforcement bar loses its passivity, the corrosion rate depends on the availability of oxygen for the cathodic reaction. It also depends on the concrete, which controls the ease with which ion migrates through the concrete between anodic and cathodic site. Electrical resistance, in turn, depends on the microstructure of the paste and the moisture content of the concrete. The combination of resistance measurement by resistivity meter and potential measurement by corrosion analyzing instrument give very reliable information about the corrosion condition of the rebar. The resistivity increases as the capillary pore space in the paste is reduced, so higher resistivity also indicates the good quality of concrete.
Device and Methodology: The test configuration includes four equally spaced electrodes are electrically connected to the concrete surface (refer Figure 2). The outer electrodes are connected to a source of alternating current, and the two inner electrodes are connected to voltmeter. Before starting the test, the test surface is made wet (this should be done at least 45 minutes prior to conducting the test). One of the equipment available for measurement of resistivity is Resistivity Meter. It consists of a set of four probes fitted with super conductive foam tips to ensure full contact on irregular surfaces. Once the probes are kept in contact with the concrete surface, the electronic display will indicate the resistivity directly on the screen [1,6]. The equipment used for this test is a portable, battery operated, four probe device which measures concrete resistivity. The corrosion of steel in concrete is an electrochemical process, which generates a flow of current and can dissolve metals. The lower the electrical resistance, the more readily the corrosion current flows through the concrete and greater is the probability of corrosion. The resistivity is numerically equal to the electrical resistance of a unit cube of a material and has units of resistance (in ohms) times length. The limits of possible corrosion are related with resistivity as under:

Table 1: Relationship of Resistivity with Limits of possible corrosion (Source: Guidelines on Non Destructive Testing, RDSO[1])

S.No.	Resistivity (ρ)	Limits of Possible Corrosion
1	12 kWcm	Corrosion is improbable
2	8 to 12 kWcm	Corrosion is Possible
3	8 kWcm	Corrosion is fairly certain

The method is slow as it covers small area at a time. The system gives better indication of corrosion in reinforced concrete, if used in combination with half-cell potentiometer.

2.4 Identification of reinforcement profile and measurement of cover

In any reinforced concrete structure, an adequate cover is essential to prevent corrosion of the reinforcement. For old structures, the reinforcement details may not be available due to which the strength determination and hence the finalization of the strengthening scheme becomes difficult. Sometimes, the bridges are to be checked from strength point of view to permit higher axle load, and in absence of reinforcement details, it becomes very difficult to take an informed decision. Also, during extraction of cores, layout of the reinforcement grid is required. For these reasons, identification of reinforcement profile and measurement of cover becomes indispensable.

2.4.1Profometer

It is used for detecting location and size of the reinforcement, and the concrete cover. This instrument is also known as rebar locator.

Principle and code: The method is based on measurement of the change in electromagnetic field caused by the steel embedded in the concrete. It is covered by BS 4408:1969-Part1 [16].

Device and Methodology: The device is a portable and handy instrument, normally used to locate the reinforcement, with an electronic display. To ensure satisfactory working of profometer and to get accurate results, it should be calibrated before starting the operations and at the end of the test. To check the calibration accuracy, the size and cover of the reinforcement of the test block is measured at different locations on test block and the recorded data should match with the standard values prescribed on the test block. Path measuring device and spot probes are together used for path measurements and scanning of reinforcement bars. These are connected with profometer and are moved on the concrete surface for scanning the reinforcement bars and measuring the spacing. Diameter and depth probes are used in conjunction with the profometer to measure the diameter of rebar and its concrete cover respectively [1,6].

For carrying out this test, proper access to the test section is essential. Before actual scanning, marking is done with chalk on the concrete surface by dividing it into panels of equal areas. The method is very fast and gives quite accurate results if the reinforcement is not heavily congested. The equipment is light and a single person can perform the test.

2.5 Crack detection

Crack detection microscope and video boroscope are used for visual inspection and determining the location and/or width of cracks and other anomalies visible from the surface.

2.5.1 Crack Detection Microscope

It is a device designed for measuring the crack width in concrete or other materials. The microscope is connected to an adjustable light source. The image is focused by turning the knob at the side of the microscope and the eye piece graticule can be rotated through 360^0 to align with the direction of the crack under examination. The 4 mm range of measurement

has least count of 0.02 mm. Current codes of practice state that the measured maximum crack widths should not exceed certain values; e.g., 0.3 mm as per BS 8110: Part 2 [17], for most types of environment. One has to place the scale of the microscope on the crack and read the number of divisions and multiply it by the least count of the microscope to get the crack width in millimeters [1,6].

The crack detection microscope is very easy to use. It can measure the width of fine cracks (<1 mm). However, it can measure visible cracks only. Also, it cannot adequately measure the depth of cracks.

2.5.2 Video Boroscope

A boroscope is used to look inside inaccessible or small voids. For example, if cable ducts are not injected, it is possible to inspect the strands by means of an endoscope through a contact drilling (here a drilled hole from the surface to the cable duct). The boroscope equipment includes a lighting source and a fiber optic cable to transfer the light to the boroscope. A system of lenses enables the boroscope to be used as a monocular. A camera can also be mounted on the boroscope for photo documentation [1,6]. Generally, the method is appropriate and may also be used for visual inspections of structural components such as expansion joints, honeycombs and cracks/slots.

3. Results and Discussion

This section presents the results of the tests conducted for various components of the concrete road bridges, located at four different test sites at Lucknow, India; namely, Site 1, Site 2, Site 3 and Site 4, respectively. The tests were conducted at two different times, firstly, in October 2011 (average ambient temperature range 19-32 °C), and secondly, in April 2012 (average ambient temperature range 20-38 °C). Inferences are drawn from the test results, which is helped by the experience of the authors as well as that of the NDT&E engineers of the Research Design & Standards Organization (RDSO), Lucknow, Indian Railways, in conducting these tests, and using the results in making informed decisions regarding structural condition evaluation of concrete members of road bridges (over/under of railway).

3.1 Estimation of Compressive Strength of concrete bridge components

Generally concrete cubes are cast and crushed in a compression testing machine to determine their average compressive strength. Thus, performing tests on a concrete cube by a chosen NDT&E method, and subsequently crushing it in a compression testing machine (CTM), is a nearly accurate way of comparing the various NDT&E methods/equipment available for compressive strength determination. As most of the non-destructive tests cannot be performed on a 150 mm x 150 mm surface of the cube, so only rebound hammer is used for direct comparison with compressive strength determined using CTM on the same cubes. Figure 1 gives the comparison of CTM values with those got from digital and analog rebound hammers (R-hammers). Thus, for comparing compressive strength values estimated from other NDT&E methods to those got from the CTM, they can first be compared to R-hammer values (since they are convenient and feasible to use almost everywhere), and then Figure 1 can be used.

The indicative compressive strengths of concrete, obtained by using different NDT equipment, at different site locations, are given in Tables 2 to 5. In Table 2, the average

compressive strength of concrete cube by analog rebound hammer is the average of two test values. Proper calibration is necessary and has been performed for all the equipment used in this study.

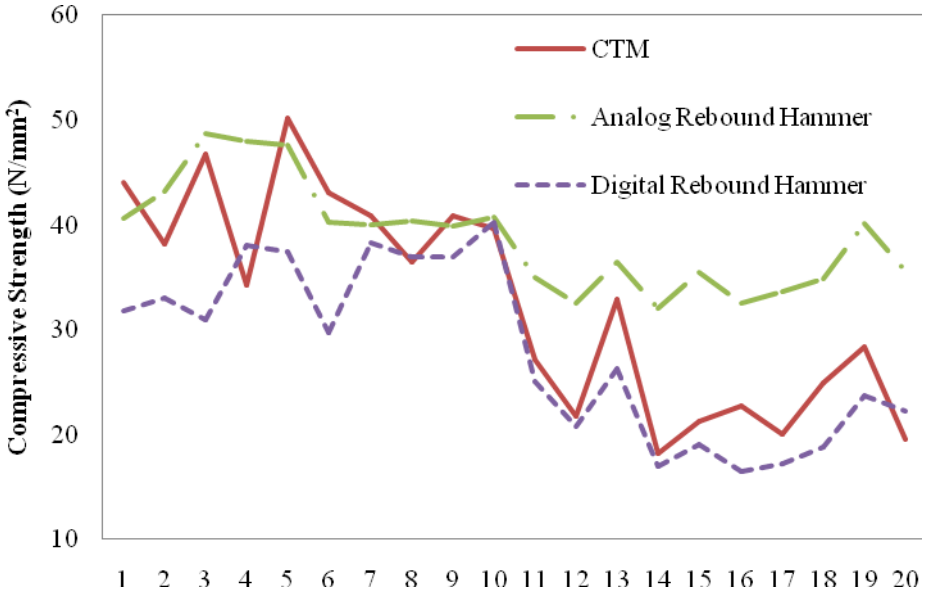


Figure 1: Comparison of compressive strength values as obtained using CTM, and analog and digital rebound hammers

Table 2: Indicative Compressive Strength of Concrete using different equipment (Site 4: ROB, Rectangular bridge Pier)

Instrument	Compressive Strength (N/mm^2)	
	Location 1	Location 2
Digital R-Hammer	53.83	40.50
Analog R-Hammer	50.89	49.60
CAPO	23.20	-
Core Cutter	12.73	-

-Test could not be conducted due to difficulty in accessibility or geometrical restraints

Table 3*:* Indicative Compressive Strength of Concrete using different equipment (Site 1: RUB, Retaining wall)

Instrument	Location 1	Location 2
Digital R-Hammer	33.25	20.25
Analog R-Hammer	46.87	34.80
CAPO	33.30	23.07
Core Cutter	28.00	20.36

Table 4: Indicative Compressive Strength of Concrete using different equipment (Site 2: ROB, Bridge pier)

Location	Digital R-Hammer	Analog R-hammer
1	46.25	57.07
2	48.75	64.75

Table 5: Indicative Compressive Strength of Concrete using different equipment (Site 3: ROB, Bridge deck)

Location	**Rebound Hammer (Digital)**	**Rebound Hammer (Analog/Simple)**	**CAPO**	**Windsor probe**	**Core Cutter**
1	18.00	23.43	25.4	28.18	25
2	50.00	53.16	46.2	43.47	-
3	47.75	46.78	62.1	48.34	-
4	42.50	47.42	46.2	41.81	-
5	45.50	46.10	39.5	41.29	36
6	29.00	37.00	32.6	29.52	28

-Test could not be conducted due to difficulty in accessibility or geometrical restraints

3.2 Evaluation of quality of concrete and reinforcement

Quality of concrete and reinforcement need to be assessed for a variety of purposes. For example, the homogeneity of concrete and standard of construction may be predicted by assessing the quality of concrete. Similarly, by judging the quality of reinforcement the corrosion in steel bars may be predicted. For conducting quality evaluation of concrete at different sites, UPV (with 54 kHz transducers) and permeability tester were employed (refer Table 6 for the assessment). Table 7 illustrates quality evaluation of reinforcement bars at different sites, conducted using corrosion analyzer and resistivity meter. Due to difficulty in accessibility or geometrical restraints and/or limitations of the instruments, some tests could not be performed at all the locations. Thus, more data is required for a comprehensive comparison to be made among these instruments. Also, during the quality assessment of the concrete, the tests generate contradictory sets of final result values, and so, the comparison has less reliability in such cases [3,13,18]. However, the results of the tests conducted have been included in this study for indicative purposes. It also shows the difficulty and indecisiveness that might originates in certain situations, when utilizing the NDT&E methods.

4. Cost Analysis

NDT&E offers a relatively fast and inexpensive means for structural evaluation in comparison to destructive testing. However NDT equipment is expensive (one time cost) and since it requires a certain degree of skill to conduct NDT and interpret its results, the operational costs for NDT may also be on a higher side. Due to the high operational costs and the expensive NDT equipment (refer Table 8), a proper cost analysis is one of the factors which should be considered while deciding upon the choice of NDT equipment suitable for a particular application.

Table 6: Quality evaluation of concrete at different locations using UPV and permeability tester

Site/ Location	Quality assessment of concrete	
	UPV*	**Permeability Tester**
Site 1: (RUB, Retaining Wall)	Good	Bad
Site 2 (ROB, Bridge pier)	Excellent	-
Site 3: Location 1	-	Bad
Site 3: Location 2	-	Bad
Site 3: Location 3	Excellent	-
Site 3: Location 4	Excellent	-
Site 3: Location 5	-	Bad
Site 3: Location 6	-	Bad
Site 4: (ROB 2, Rect. Bridge Pier)	Good	Very Bad

-Test could not be conducted due to difficulty in accessibility or geometrical restraints

* Excellent for P-wave velocity > 4500m/sec, Good for P-wave velocity 3500- 4500m/sec

Table 7: Quality evaluation of reinforcement at different locations using Corrosion Analyzer and Resistivity Meter

Site/ Location	Quality assessment of reinforcement	
	Corrosion Analyzer	**Resistivity Meter**
Site 1	Corrosion is unlikely	Corrosion is improbable
Site 2	-	-
Site 3	Corrosion is unlikely	-
Site 4	-	-

-Test could not be conducted due to difficulty in accessibility or geometrical restraints

Table 8: Approximate initial and operational costs of various test equipment

Equipment	Cost of equipment*(Indian Rupees)	Approximate Operational Cost*(Indian Rupees)	Relative Overall Cost
For Compressive Strength:			
Rebound Hammer	1,27,000	91,000(for 10 locations)	Low
Cut And Pull Out	9,71,538	1,09,000(for 6 locations)	High
Core Cutter	4,37,620	41,000(for 3 cores)	Medium
Compression Testing Machine	1,10,000	13,000(for 3 cubes)	Low
For Quality Estimation:			
Ultrasonic Pulse Velocity Meter	4,07,632	1,01,000 (for 10 locations)	Low
Permeability Meter	8,14,694	85,000 (for 5 locations)	High
For Reinforcement Profile and Concrete Cover:			
Profometer	2,77,131	72,000 (for 10 locations)	Not applicable
For Visual Inspection:			
Video Boroscope	14,23,858	1,06,000 (for 10 locations)	High

*The costs of equipment have been obtained for year 2011; Operational costs are for year 2011,in accordance with the information provided by RDSO.

4.1 Comparison of various methods

For the purpose of comparison amongst different NDT&E methods, various subjective characteristics of these methods need to be considered. Since the purpose of conducting any test is to obtain as accurate and reliable results as possible, this can be taken as the basic and most important parameter. Cost and versatility are other parameters that need to be accounted for in the comparison, from economic considerations. Also, time and the resources required for a particular method, the ease with which the test equipment can be operated, and the ease of data analysis are other important characteristics to be considered [3,18,19,20]. The subjective comparative assessment of each of these characteristics for the different methods utilized in this study is given in Table 9.

In order to quantify the aforementioned characteristics of different NDT&E methods, suitable weightage (in the range of a value of 1 to 10 to represent unfavorable to favourable condition, respectively) is assigned to each of these, according to its comparative assessment (refer Table 10). Further, depending on the perceived engineering importance of the characteristic, an importance factor is also allotted to it (refer Table 10). The weightage and importance factors allotted are based on experience gained by the authors while handling the NDT instruments on the field, as well as the engineering judgement of the NDT&E engineers of the RDSO. Making use of these assigned weightage and importance factors, the relative importance of each of the NDT&E method can be determined quantitatively using Eq. 1, and further used for the quantitative comparison of NDT&E methods (refer Table 11).

Table 9: Comparative assessment of NDT equipment used

Equipment	**Comparative Assessment**					
	Accuracy & Reliability	**Cost**	**Versatility**	**Ease of Operation**	**Ease of Analysis**	**Time & Resources required**
For Compressive Strength:						
Rebound - Hammer	Medium	Low	Low	Easy	Easy	Low
CAPO	High	High	Low	Difficult	Moderate	High
Core-cutter	High	Medium	Medium	Difficult	Moderate	High
Windsor-Probe	High	High	Low	Difficult	Moderate	High
For Quality Assessment Of Concrete:						
UPV	High	Low	High	Difficult	Difficult	Low
Permeability-tester	Medium	High	Low	Difficult	Difficult	Moderate
For Visual Inspection:						
Video-Boroscope	High	High	Medium	Difficult	Difficult	High
Crack-Detection-microscope	Medium	Low	Low	Easy	Easy	Low

For calculating relative importance **Eq. 1** given below is used:

Relative importance=$W_A F_A + W_C F_C + W_V F_V + W_O F_O + W_O F_O + W_E F_E + W_T F_T$ **….(Eq. 1)**

where: $W_A, W_C, W_V, W_O, W_E, W_T$ =Weightage for Accuracy & Reliability, Cost, Versatility, Ease of Operation, Ease of Analysis, Time & Resources required, respectively; and F_A, F_C, F_V, F_O, F_E, F_T =*Importance* factor for Accuracy & Reliability, Cost, Versatility, Ease of Operation, Ease of Analysis, Time & Resources required, respectively.

Table 10: Weightage and importance factors for quantifying the characteristics of NDT&E methods

Parameters	Comparative Assessment	Weightage Assigned (W)	Importance Factor(F)
Accuracy & Reliability (A)	High Medium Low	10 5 1	4.0
Cost(C)	High Medium Low	1 5 10	1.5
Versatility(V)	High Medium Low	10 5 1	2.5
Ease of Operation(O)	Difficult Moderate Easy	1 5 10	0.5
Ease of Analysis(E)	Difficult Moderate Easy	1 5 10	0.5
Time & Resources Required(T)	High Moderate Low	1 5 10	1.0

Table 11: Relative performance of equipment based on comparative assessment

Equipment	Relative performance
For Compressive Strength:	
Rebound Hammer	54.5
CAPO	48.0
Core-Cutter	64.0
Windsor Probe	48.0
For Quality Assessment of Concrete:	
UPV	81.0
Permeability Tester	30.0
For Visual Inspection:	
Video Boroscope	56.0
Crack Detection Microscope	57.5

From Table 11, it can be seen that the best relative performance for compressive strength evaluation is achieved by core-cutter method, which is however destructive method, followed by the rebound hammer method, which is non-destructive. Similarly for quality assessment of concrete, UPV may be said to be the better suited method than permeability tester. For visual inspection, crack detection microscope scored higher than video boroscope. However, based on the field experience of NDT&E engineers of RDSO, who

regularly perform NDT&E for concrete bridge members, the video boroscope may be a better option for visual inspection, considering the ease of use and time taken, etc.

Based on experience of the authors in conducting field tests using various NDT&E methods, some guidelines are suggested for effective testing that minimizes the test constraints. These are: (a) Equipment like permeability tester and core cutter need constant supply of electricity, which is one of the principal requirements. If such tests are to be performed, then electric supply (like a portable generator) should be arranged prior to the commencement of the testing; (b) For condition assessment of the reinforcement, authors used corrosion analyzer and resistivity meter during the field tests. For both the tests, it is essential that the surface, on which the tests are being conducted, should be moist, to complete the circuit necessary for a valid measurement. This was done by using wet gunny sacks. Due to high test temperature, at some of the sites, the surface was not moist enough. So at those sites, tests could not be performed. Hence, the tests may be performed during early morning or late evening hours, so that the change in temperature during the period of testing, and overall rise in the temperature value is low. This suggestion is also valid for the tests where the test data can be affected by temperature, for example UPV testing.

Further, a life cycle cost analysis can be performed for various non-destructive testing and evaluation methods so that more informed decision can be made while selecting a particular method. More test data is required for a comprehensive comparison of various NDT&E methods. Effect of temperature should also be included in the test results and comparisons, for which test data is required at a range of test temperatures.

4. Conclusion

In this study, various non-destructive condition evaluation methods have been studied and they have been used in the field testing of reinforced cement concrete bridge members. Based on the data collected by the authors by performing numerous tests on four different sites, comparison have been made among various NDT equipments available for determining a particular parameter. Some of the NDT&E methods provided assessment of concrete deterioration at relatively high speeds of data collection. Whereas, some methods worked at lower testing speeds but gave high accuracy in results. Also based on these comparisons, suggestions have been made to help future NDT&E users in selecting the most appropriate equipment for the given test site and purpose of testing.

For in-situ compressive strength evaluation under field conditions, for an indicative assessment, the appropriate method to be used may be the rebound hammer method, due to its simplicity in operation and data interpretation. Also, the time and resources required for performing rebound hammer tests are less in comparison to other equipment. However, for core cutter method, the results are based on crushing of concrete cores, which are extracted from the site, in the laboratory environment, using the compression testing machine. For quality assessment of concrete, ultrasonic pulse velocity may be the best suited method due its relative simplicity in operation, low resources required and higher versatility and accuracy. For visual inspection, based on the field experience (of authors and NDT&E engineers of RDSO), the better suited method is video boroscope.

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