Selection of suitable NDT methods for building inspection

Mohamad Pauzi Ismail

1Industrial Technology Division, Agensi Nuklear Malaysia, Bangi.
Corresponding author: pauzi@nm.gov.my

Abstract. Construction of modern structures requires good quality concrete with adequate strength and durability. Several accidents occurred in the civil constructions and were reported in the media. Such accidents were due to poor workmanship and lack of systematic monitoring during the constructions. In addition, water leaking and cracking in residential houses was commonly reported too. Based on these facts, monitoring the quality of concrete in structures is becoming more and more important subject. This paper describes major Non-destructive Testing (NDT) methods for evaluating structural integrity of concrete building. Some interesting findings during actual NDT inspections on site are presented. The NDT methods used are explained, compared and discussed. The suitable methods are suggested as minimum NDT methods to cover parameters required in the inspection.

1. Introduction
British Standard defined non-destructive testing (NDT) as a test that does not impair the intended performance of the element or member under investigation [1]. NDT has been used widely in industrial sectors such as petroleum, petrochemical, ship construction, aircraft, railway, power station, gas pipeline etc. Materials used in these industries are mostly made from steel and aluminum, which involved processes such as welding, casting, forging or machining during construction. The quality of the product was checked and evaluated by NDT methods. Similarly, in-service inspections are also performed by this method to detect so-called in-service defects such as corrosion or fatigue cracks.

The use of NDT in inspecting concrete is not as common as in the metallic construction. This may be due to lack of demand or no specific requirement by code or standard from the related sectors as compared to metallic construction. No criteria for acceptance except for visual inspection and no personnel certification scheme available for NDT inspectors. However, research and development activities in various NDT methods indicate that NDT has a great potential to be applied on concrete structures. Most materials in buildings, bridges, dam, tunnels, etc. are made of concrete. This construction requires concrete of high quality in terms of strength and durability. NDT has the ability to estimate the strength and durability of critical construction without damaging them and the test can be carried out on-site.

Following the collapse of the New World Hotel in Singapore, the Singaporean government has imposed an act to ensure that all buildings of more than 2 floors must be inspected for their quality at an interval of every 5 years. Similarly in Malaysia, The Street, Drainage and Building Act (Amendment 1994, Act A903) was amended as a follow up of the Highland Tower tragedy. The Act stipulates the requirements for the periodical inspection of buildings. These requirements apply to buildings exceeding five storeys and all buildings must be checked for their safety and quality in every 10 years before certificate of fitness (COF) can be issued.
In mechanical construction, there are existing codes or standards available to be used as a guideline. For example ASME code is commonly used for construction of boiler and pressure vessel, API code for constructions in petroleum industry and AWS code for constructions of steel structures. In such cases the application of NDT is well specified. However in the case of civil construction, there is no specific code or standard currently available that can be used as a guideline for the selection and application of suitable NDT methods. British Standard only specifies visual inspection for criteria of acceptance, e.g. based on crack width.

Since there are so many NDT methods available including new and conventional which make us confuse which method to be chosen, the author would like to recommend and discuss the most effective, reliable and cheaper method based on practical experience on site.

2. Non-destructive testing methods

There are several NDT methods applicable to concrete structures. Table 1 lists the suitable NDT methods for checking specific properties of concrete quality [2]. The importance of checking certain properties according to the type of structures is listed in Table 2 [2]. Table 1 indicates that there are 11 NDT methods applicable for concrete inspection. They are rebound hammer, penetration resistance, pull out, ultrasonic, radar, thermography, radiography, acoustic emission, magnetic or eddy current, half-cell potential and visual (photography) methods.

The Schmidt rebound hammer is basically a surface hardness test with little apparent theoretical relationship between the strength of concrete and the rebound number of the hammer. However, within certain constraints, empirical correlation has been established between strength properties and the rebound number. The correlation between rebound index \( N \) and compressive strength \( K \) varies from one researcher to another. The author [3] proposed a polynomial correlation which agrees with the manufacturer’s calibration curve.

\[
K = 10.8 + 0.95N+0.017N^2
\] (1)

The estimated error is \( \pm 30\% \).

The Windsor probe, like the rebound hammer, is a hardness tester, and its inventors claim that the penetration of the probe reflects the precise compressive strength in a localized area is not strictly true. However, the probe penetration does relate to some property of the concrete below the surface, and, within limits, it has been possible to develop empirical correlations between strength properties and the penetration of the probe. It can be used for estimating compressive strength, uniformity and quality of concrete. Expertise required is low, however license from Police Department is required for operation of explosive materials. The equipment is easy to use and does not require surface preparation prior to testing. It is good for determining in-situ quality of concrete. The results are not subject to surface conditions, moisture content or ambient temperature. It requires minimum edge distance and member thickness. It slightly damages small area. Calibration by manufacturers does not give precise prediction of strength for concrete older than 5 years and where surface is affected by carbonation or cracking [4].
Table 1. List of items can be evaluated by non-destructive testing (NDT).

| NDT methods | Items          |
|-------------|---------------|
|             | Strength      | Bond, depth | Cracks, depth | Cracks, width | Steel development | Honeycomb, voids | Backwall voids |
| 1 - Rebound hammer | ●             |             |               |               |                  |                |
| 2 - Penetration resistance | ●                 |             |               |               |                  |                |
| 3 - Pull-out | ●             |             |               |               |                  |                |
| 4 - Ultrasonic | ● ● ●          | ● ● ● ● ● ● | ● ● ● ● ● ● |               |                  |                |
| 5 - Radar | ●             | ● ● ● ● ● ● | ● ● ● ● ● ● |               |                  |                |
| 6 - Thermography | ●             | ● ● ● ● ● ● | ● ● ● ● ● ● |               |                  |                |
| 7 - Radiography | ●             | ● ● ● ● ● ● | ● ● ● ● ● ● |               |                  |                |
| 8 - Acoustic emission | ●             | ● ● ● ● ● ● | ● ● ● ● ● ● |               |                  |                |
| 9 - Magnetic or eddy current | ●             | ● ● ● ● ● ● | ● ● ● ● ● ● |               |                  |                |
| 10 - Half-cell Potential | ●             | ● ● ● ● ● ● | ● ● ● ● ● ● |               |                  |                |
| 11 - Photography | ●             | ● ● ● ● ● ● | ● ● ● ● ● ● |               |                  |                |

Table 2. Inspection of structure.

| Items    | Strength           | Elastic Modulus | Deflection | Crack | Distribution | Width | Depth |
|----------|--------------------|-----------------|------------|-------|--------------|-------|-------|
|          | ● ● ● ● ● ● ● ● ● | ● ● ● ● ● ● ● | ● ● ● ● ● | ● ● ● | ● ○ ○ ○ ○ | ○ ○ ○ | ○ ○ ○ |
|          | ● ● ● ● ● ● ● ● ● | ● ● ● ● ● ● ● | ● ● ● ● ● |       | ● ○ ○ ○ ○ | ○ ○ ○ | ○ ○ ○ |

Pullout Testing is the test involves drilling a hole in which a standard threaded or wedge anchor is placed. This is then pulled until the concrete raptures. With a calibration charts the maximum force gives an indication of the strength of concrete. Pullout devices can be inserted during casting of concrete. It provides an estimation of the compressive and tensile strengths of hardened concrete. User expertise is low and can be used in the field. In-place strength of concrete can be measured quickly and appears to give good prediction of concrete strength. Pullout devices must be preplanned and inserted during the
construction stage, or inserted in hole drilled in hardened concrete. A cone of concrete may be pulled out, necessitating minor repairs. It can only test a limited depth of material. As it is a surface method, and in reinforced concrete could only be used to assess the concrete cover quality [4]. As indicated in Table I, the ultrasonic method can be used to estimate strength, elastic modulus, slab thickness, crack depth, and to detect voids, lamination and bar location. It is recognized as the only NDT method available at this time, which is capable of determining the crack depth to a certain degree of reliability. The technique was also used to monitor the mixing materials during construction, determine the concrete uniformity, thickness measurement and to estimate the depth of damage caused by fire [5]. The ultrasonic pulse velocity method can only estimate strength with an accuracy of 20% [6] at best. Better and reliable strength estimation is by combination with rebound hammer. Although there are many other combination, combination between rebound hammer and pulse velocity is the most popular. Figure 1 show typical strength estimation curve by combination between rebound number and pulse velocity for Malaysian concrete design based on DoE method.

![Figure 1. Strength estimation by combined rebound no. and pulse velocity [7].](image)

Reinforcement bar in concrete can be located using radar technique or magnetic method (cover meter). Radar method is an easy, fast and accurate technique for measuring cover thickness and arrangement of the bar. On the other hand, cover meter can also perform the same as the radar method but the method is rather slow and needs some experiences to understand/interpret the signal. It is worth to mention that both methods are not so accurate for measuring the diameter of the bar. Figure 2 and 3 show radar profile for rebar detection.

An infrared camera is used to detect variations in infrared radiation output of a surface. Thermal gradients arise because of different in surface temperature between sound and unsound concrete. The temperature gradients are displayed on a monitor screen in the form of colour thermal contours. It can be used for detecting delamination, heat loss and moisture movement through concrete elements especially for flat surfaces. User expertise is not high but interpretation of results requires understanding of thermal behaviour and patterns. It is portable and permanent records can be made. Testing can be done without direct access to surface and large areas can be rapidly inspected using infrared cameras. It is very sensitive to thermal interference from other heat sources [4]. Figure 4 shows typical photographs and thermographs of wet area. The thermographs were taken a few minutes after sunset [5].
Radiography is the best method to check the condition of the bar (including sizing) and to detect void in concrete. Typical sources are Iridium-192 and Cobalt-60. Although Cobalt-60 has better radiation penetration in concrete, the equipment is bulky and difficult to handle in order to meet on-site safety requirement. It requires a very large safe operational area which is not practical in most of the construction site. Modern equipment such as Linac or betatron produce high energy X-ray, although the energy is high but dose rate is considerably low since X-rays are produced not continuously like gamma equipment but in the form of pulses and they use imaging plate as recording media instead of...
film. Figure 5 shows typical radiographic image on concrete sample using Iridium 192 gamma source [5].

![Radiographic Image](image)

**Figure 5.** Example of radiographic image of void and bar in concrete. SFD: 500mm, concrete thickness: 150mm, source: Ir-192, exposure: 4 Ci-hr, film: Agfa D7.

Acoustic emission is produced when a material is loaded beyond their elastic limit. Kinetic energy is released. They are inaudible but can be detected by sensors attached to the surface of a test object. This method has also been used in recent years to study the initiation and growth of cracks in concrete under stress. Extensive knowledge is required to plan the test and to interpret results. It monitors response of existing structure to applied load it is capable of detecting onset of failure and locating source of possible failure. Since acoustical signals come from defects throughout the structures a few transducers are enough to detect and locate defects over large areas [4]. The method is suitable for structures with dynamic loading such as bridges. The equipment is expensive on the market; however Nuclear Malaysia has developed a low cost acoustic emission system. A laboratory study has been carried out to evaluate the feasibility of detecting corrosion damage in rebars by the eddy current and magnetic flux leakage techniques. Many practical low frequency systems are capable of locating and estimating the size of the cross-section of the rebars via calibration charts [4].

Electrical potential of steel reinforcement is measured relatively to a reference electrode (half-cell). This enables potential contour maps to be plotted. The electrode potential of steel in concrete indicates the probability of corrosion. The half-cell provides a relatively quick method of assessing reinforcement corrosion over a wide area without the need for wholesale removal of the concrete cover. Quantitative measurements are made so that a structure can be monitored over a period of time and any deterioration can be noted. It is portable equipment. Field measurements can be readily made and results can be plotted in the form of equipotential contour diagram, which can indicate likely areas of corrosion [4].

Visual inspection is the method applied during the first survey of the structures. The purpose is to observe for any surface discontinuities. Visual features may be related to workmanship, structural serviceability and material deterioration. Figure 6 to 11 show a few of these in their typical form. Typical equipment used during the visual inspection includes special tapping hammer, crack gauge, magnifying glass, binocular and camera. For buildings, survey may be started from the outside of the building and followed by the inside survey with particular attention given to areas at the corner or any tension area of the building.
3. Selection of test method

Rebound hammer, penetration resistance, pull out and ultrasonic methods can be used to estimate concrete strength. So far no NDT methods can give the best estimation. However the popular combination for strength estimation is rebound hammer and ultrasonic testing. Ultrasonic is among the widest applications. It can be used for estimation of strength, elastic modulus, thickness and crack depth using conventional ultrasonic pulse velocity (UPV) method. Using advanced ultrasonic method such as multi array transducer, it can detect void, honeycomb, lamination and bar location. Ultrasonic is the only NDT method for crack depth measurement.
Radar is very good for bar location, plastic or PVC conduit and to some extent can be used for detection of lamination and void detection. Thermography is applicable for imaging crack distribution, wet area (water leakage), near surface void, honeycomb and lamination. Radiography is the most effective and easier method for detection of void, honeycomb, bar location, size and corrosion. Acoustic emission for concrete inspection is still under development it was used in steel or metallic construction for monitoring crack growth. It has potential application in structure with dynamic loading such as bridges. Magnetic and eddy current method can also be used to detect reinforcement bar and to some extent can be used to estimate the bar size.

However advanced ultrasonic with multi array probes probably can do the same function for radar, radiography and magnetic and eddy current method methods. Half-cell potential was the old method for bar corrosion but the reliability of the method is questionable. Visual inspection is the basic inspection method. It is used during first survey to decide whether or not there is a need for further investigation.

4. Conclusion

The cheapest NDT method is by visual inspection. However the valuable information can only be gathered by the well-trained eye. Like in mechanical construction, four or five NDT methods may be adequate for evaluating concrete structural integrity. It is recommended that Visual, rebound hammer, advanced ultrasonic and thermography methods are the minimum NDT methods to cover the required parameter for assessing the structural integrity of concrete building.

5. References

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