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Review of Non-Destructive Tests for Evaluation of Historic Masonry and Concrete Structures

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Abstract The paper discusses non-destructive tests (NDTs) useful for condition evaluation of old structures and historic monuments based on a review of available literature. The application of these tests for the evaluation of various structures constructed of stone or brick masonry or reinforced cement concrete has been discussed. The types of defects present in structures built of different material media vary greatly. Therefore, it has been recognized that not all NDT methods or all combinations of NDT methods can be used for all structures. Further, the type and degree of a structural defect is a function of the environment the structure is subjected to. Because of the great amount of research which has been recently conducted in this field, general parameters which could be identified by various NDT techniques for various building materials and the advantages and disadvantages of each technique need to be identified. The authors have been able to achieve this by means of a literature survey. The authors have also discussed a number of national and international standards (codes) established by technical societies as standard guidelines for application of NDT techniques. A few abnormalities in this regard have also been discussed.

Keywords Non-destructive tests · Condition evaluation · Stone masonry · Brick masonry · Reinforced cement concrete · Environment · National and international standards

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1 Introduction

Service life appraisal has become an important component of modern-day structural engineering. The service life of a structure is determined by its design, construction, aging and maintenance during use. The combined effect of structural performance should be considered. The techniques used today for condition evaluation are capable of evaluating structures or structural elements for varying levels of damage. The choice of a technique depends on a variety of factors from the structural parameters required to the feasibility of a test procedure to the procurement costs of test equipment. While such considerations can be of great but varying levels of importance in selecting a test procedure for damage assessment of any structure, the one which plays the most vital role in the monitoring of historic monuments is certainly the preservation of original material. This is not to say that the parameters for which a structure is being tested and the cost of testing do not play significant roles. In fact, the role of a non-destructive testing (NDT) engineer is precisely to identify advanced NDT techniques which will facilitate rapid, cost-effective and reliable condition monitoring for assessment of all required parameters of existing infrastructure. To achieve this target, good, deep knowledge of the available NDT techniques and result patterns of similar surveys which were conducted in the past is of paramount importance.

Although many non-destructive testing techniques and equipment for evaluation of civil engineering structures have evolved over the past decades, many of them have been developed to evaluate concrete structures, concrete being the prominent modern-day building material. The evaluation of historic structures, therefore, poses a different challenge altogether. The principal material used for the creation of such structures would vary greatly (the structure may be carved out of a single rock or made out of pure white marbles or it may be a brick masonry structure). The knowledge about the ancient raw materials and their technical process and chemical changes is, therefore, essential for the assessment of historic masonry. This is because the kinds of distresses which may occur in structures vary with variation in the material used in their construction. So for implementation of NDT method, it is important to describe what shall be found and what shall be rejected. An important aspect of evaluating historic structures, therefore, is the understanding of the type of distresses that may be observed and the cause for such distresses. The techniques which could monitor structures for the types, causes and degree of distresses also need to be identified.

Typically, common type of distresses include cracks, spalls, efflorescence, surface erosion, salt or moisture influences or irregularities which may derive from a variety of factors from difference in loading to difference in material or microstructure, etc. Such irregularities or damages can be easily detected by a variety of non-destructive techniques, but which NDT technique would cater to particular requirements is a thing to be studied. In several cases, a combination of different techniques is required. Generally, the combination of techniques, apart from supplying to the need of fully evaluating a structure for the required parameters, can be of great use in verification of results, i.e., to ensure the quality of estimates made. This is required because most non-destructive tests depend not on direct data, but the correlation of a particular property of material to its strength or other aspects. For example, in an ultrasonic pulse velocity test, the strength, quality and other parameters such as elastic modulus of material are assessed by measuring the velocity of an ultrasonic pulse passing through a structure or a structural element. Higher velocity is then attributed to higher strength or better quality and lower velocity is said to depict material of lesser strength or poorer quality. The results of this test are often used in conjunction with the results of other tests such as Rebound Hammer method and flat-jack method, etc. Combining techniques may have a third objective of zoning the area where a highly sophisticated non-destructive investigation will be performed, thereby decreasing the number of borings by identifying the areas where borings will be more useful. This particularly helps in bringing down the costs of undertaking an in situ test. Such combinations of techniques should, in any case, produce complementary results. If two tests produce mutually contradictory test results, both results would have to be discarded. Moreover, uncertainty appears in all conclusions made, whether made on the basis of results obtained from a single non-destructive test or a combination of tests. This, again, can only be overcome by having prior knowledge of the results obtained in similar inspections.

Each of the contexts discussed herein points to a common fact: The knowledge of various non-destructive testing techniques is of maximal importance before undertaking condition assessment of any structure, more so when the subject being studied is a historic building. Therefore, this paper aims to put forth an interesting and informative set of results that have been obtained in condition monitoring of historic monuments in the past. Several methods have been discussed, studies on several kinds of material media have been presented, and it has been endeavored to draw out what tests or what combination of test procedures would be helpful in different scenarios.

2 Overview of NDT Methods Used for Different Materials

The structures discussed herein have been classified as stone masonry structures, brick masonry structures and reinforced cement concrete (RCC) structures. The techniques discussed herein have been broadly classified into visual, physical, sound or acoustics, penetrating radiation, microwave/radar, thermal imaging, characterization and methods for recognizing metal corrosion (these methods are of use especially in the case of reinforced concrete structures).

2.1 Visual Analysis

The first step in every non-destructive testing is generally recognized to be visual inspection, irrespective of the type of building being assessed, the parameters being sought and the material being tested. To inspect existing structures, visual inspection is the easiest and the most fundamental method [1]. A visual investigation can be particularly effective in macroscopic flaw detection. Visual inspection can help the surveyors to recognize the various kinds of defects present in an element and the specific areas where the deterioration has taken place. Without any information from visual investigation, the choice of areas to implement a reliable assessment by means of destructive or partially destructive or non-destructive techniques is very difficult [2]. However, the expertise of the surveyor is the parameter which decides the results of this preliminary testing procedure. It is also very likely that damage may have occurred in a particular area of the structure, but the damage could not be recognized visually [3]. Visual inspection alone cannot give concrete results when analyzing a concrete structure. Visual inspection can only detect crack or spall when structural deterioration has matured [4]. Therefore, this is a superficial testing technique.

2.2 NDT for Stone Masonry

Up to the beginning of the twentieth century, local stone was the cheapest and the most accessible building material. Historic structures made of stones when compared to modern-day RC structures are generally very long-withstanding.

Many of these longstanding structures have withstood the tests of nature for centuries. But, this does not exempt them from deterioration. The heritage value of these structures makes it imperative to preserve them and therefore, rebuilding such structures is not considered an appropriate response to their deterioration. Therefore, there has been a strong demand for condition assessment of such structures from time to time. In this regard, the report by Bodare is of great importance as it presents common geophysical and civil engineering NDT methods to describe their application to stone and to assess their potential of application [5]. The report reviews various commonly used NDT techniques in the context of stone material and presents their utility in recognizing local and global defects. Local defects were defined as defects concentrated in space with a volume of a few cubic centimeters and global defects as defects distributed through stones occupying much larger volumes.

2.2.1 Acoustic Methods

The survey conducted by Bodare [5] recognized, among other things, that ultrasonic pulse velocity (UPV) test is a test which is economically, culturally and technically feasible and can detect both global and local defects in stones. Svahn [6] took up a similar study, but to specifically identify the methods used in the conservation of Gotland sandstone [6]. This study also resulted in a similar conclusion about ultrasonic pulse velocity. The author further noted that the ultrasonic pulse velocity method gives a quantitative value which can be directly and correctly correlated with properties of stones. It was cautioned, in this study, that before undertaking UPV test, the material's moisture content, the direction of bedding planes and also the presence of salts in its chemical structure are to be investigated. Whether the measurement is direct or indirect may also affect the final results. The author further notes that all NDT techniques are generally influenced by the presence of moisture in the material. In sonic and ultrasonic tests, it is known that the input frequency changes with the characteristics of material. Due to the wall structure or the presence of a thick plaster or a partially detached plaster, the high-frequency components can be filtered. The output signals can have a low frequency. In this case, the test is unable to detect in detail the wall morphology, but it gives an overall description of the position of low-velocity points. In such situations, radar tests show some advantages [7]. The sonic test does not have the resolution required to detect the wall morphology. On the other hand, the pulses/echoes in case of radar test are highly distinguishable.

A more recent technology in the category of sonic–ultrasonic testing is impact-echo method. The method is performed on a point-by-point basis by using a small instrumented impulse hammer to hit the surface of a structure at a given location and recording the reflected energy with an accelerometer mounted adjacent to the impact location [8]. The P-wave produced by the impact undergoes multiple reflections at an interface where a transition between a high-impedance material and a low-impedance material exists (the interface between the material medium and air) [9]. Each time the P-wave arrives at the test surface, it causes a characteristic displacement. This waveform has a periodic pattern that depends on the round-trip travel distance of the P-wave. Therefore, a key feature of the method is the use of frequency analysis for flaw detection. A frequency response function is calculated for the impulse hammer/accelerometer system, and reflections of the compressional wave energy are indicated by pronounced resonant frequency peaks in a frequency spectrum record. These peaks correspond to the depth of flaw in the construction material [9,10].

The impulse echo method was used by Lombillo et al. [11] to identify different zones/layers and their thickness in a rubble masonry wall. The different frequencies at which the peaks appear in the frequency response record corresponded to the thickness or flaw depth resonant frequencies.

The method was also employed to identify the internal structure of metamorphic rocks by Jording [12]. However, the research raised questions regarding the method's applicability on metamorphic rocks and the impact of environment on the results obtained from the test. The author suggested that for better results, ground-penetrating radar (GPR) could be used along with impact-echo test.

In most sonic tests, to get useful levels of sound energy into the material, the air between the transducer and the material must be removed. This procedure, known as coupling, involves the application of a gel or a couplant between the transducer and the specimen. The application of couplants is crucial as even tiny gaps between the transducer and the test specimen cause acoustic impedance, thereby inhibiting the test procedure and the results. A number of common substances such as water, motor oil and grease have been employed as couplants. commercially available couplants include propylene glycol, glycerin and silicon oil [13–15].

2.2.2 Radar Methods

In case of ground-penetrating radar (GPR), an antenna transmits a short electromagnetic pulse with frequencies in the FM-radio band, normally 80 MHz–1 GHz. When the pulse reaches an electric interface in the medium, some of the energy is reflected back and the rest is transmitted. Depending on the material and the time elapsed between the excitation of the wave and its reflection; the structure's properties are defined. Thus, it is the electromagnetic analogue of sonic tests. But, the two tests, viz. sonic test and radar test, have different origins: stress waves for sonic test and electromagnetic waves for radar tests [7]. Because of this difference, the amplitude of the reflection, which is produced as a response to the propagation of wave through the material media, is different for the two methods. For stress waves, the reflection produced is almost 100%. On the other hand, only about 50% of the energy is reflected at an interface between the material media and air. Because of this difference, radar methods are not as sensitive as stress-wave methods. However, the radar method is able to penetrate beyond the interface between the material media and air and identify features below it. Again, the parameters affecting the two tests are also different. For sonic tests, the velocity of stress waves passing through a solid, homogeneous and isotropic material depends on the density, dynamic modulus and Poisson's ratio. In case of radar methods, the velocity of electromagnetic waves depends solely on permittivity [16].

2.2.3 Penetration Radiation

There are penetration radiation methods which involve a source of penetrating electromagnetic radiation and a sensor to measure the intensity of the radiation after it has traveled through the object. The method uses short-wavelength electromagnetic radiations to penetrate material; as the amount of radiation emerging from the opposite end of the material can be detected and measured, intensity of this radiation is used to determine the composition of the material. Hanazato et al. [17] discussed the applicability of penetration radiation methods in World Heritage Structures including stone structures. However, the use of this method has been limited by the cost of equipment and the risk factor involved in its application.

In case of radar methods, the radiation used is generally electromagnetic radiation of microwave band with frequencies between 300 MHz and 300 GHz. On the other hand, most electromagnetic waves used in penetrating radiation methods are of much higher frequencies (X-rays of the order of 30 petahertz to 30 exahertz and gamma rays of the order 10 exahertz). This enables them much higher energy and therefore much higher penetrating power.

2.2.4 Physical Methods

Physical methods such as rebound hammer are not generally used for evaluation of stone structures, nowadays. It is the superficial parts of the stone that mostly influence the response of the material. But, this again makes it a method apt for appraisal of cultural stones. However, when used in a combination with UPV, it is observed that for all structures (whether of concrete, stone or brick), the results produced are more reliable than when either of the tests is used alone. Flat-jack technique, another physical strength-based test, is also extensively used and well calibrated to study mechanical properties of various materials.

2.2.5 Thermal Methods

Thermal imaging or thermography is the use of an infrared imaging and measurement camera to show and measure thermal energy emitted from an object. The scanning system measures surface temperatures only. Subsurface configuration effects are based on the principle that heat cannot be stopped from flowing to cooler areas from warmer areas; it can only be moved at different rates by the insulating effects of the material [18]. While analyzing Cenabi Ahmet Pasa Camisi, a mosque in Turkey, using a combination of UPV and infrared thermography (IRT), Akevren et al. [19] observed that during examination of a historic masonry structure IRT can help in detection and imaging of anomalies such as missing, damaged, misplaced or saturated thermal insulation as well as air leakages, cracks, etc. It is also often used to mark wet/damp zones or to investigate moisture problem [3,19,20]. However, IRT actually measures surface temperatures, not moisture content. Moisture can be detected due to the absorption of energy during evaporation [21]. In another comprehensive study, it was observed that the analysis of thermographic data can help in identifying many anomalies which could otherwise go undetected before they evolve into damages of the structure [22]. But, again, it was noted that the data only points at the effects of such damages, and identification of causes of damages is a very complex process.

2.2.6 Other Methods

Apart from these, X-ray tomography has been used to study the microstructure of stone and the symptoms of stone decay [23,24]. For measuring the water-soluble salt content in stone (especially sandstone) structures, Lofvendahl method could be used. Spectrophotometer is used for measuring the color changes in stone [6].

In a different kind of survey, the Government of Australia's State Heritage Office put forward the different arguments for and against the cleaning of Stone Masonry Heritage Structures. Methods such as water cleaning, chemical cleaning and abrasive cleaning were discussed along with their pros and cons when applied to different types of stones [25].

2.3 NDT for Brick Masonry

Brick masonry is one of the most reliable and durable constructions. Many brick masonry structures have remained in service for hundreds of years, often outliving their designers. One of the most important aspects to be considered when evaluating these structures is their strength (as is the case with any structure).

2.3.1 Acoustic Methods

Methods based on acoustic emissions (AE) have been generally considered to be durable and easy to interpret and have been used in the evaluation of masonry structures [26]. The rate of occurrence of AE signals is said to be a direct indication of the internal damage [27]. UPV has also been extensively used. When using UPV for measuring the quality of material in a masonry structure, the moisture content of the structure should be well confirmed. The velocity tends to increase with the increase in moisture content, and therefore, rather than indicating a stronger material a high velocity may indicate a wetter and weaker material [28]. As to solid burnt brick testing, the method is usable in case the brick clinkers are almost free of defects [29]. In another study, Brozovsky [30] confirmed that the method is also applicable to evaluation of calcium silicate bricks. However, the efficiency of the method will be subject to accurately designed test condition to ensure reproducibility of test results. Also, it has been noted that the historic masonry may be too attenuative for UPV methods. Again, UPV only works on individual masonry blocks due to signal attenuation [8].

The impact-echo method can be used to locate cracks, voids and other defects where the bricks or blocks are joined together with mortar. In a review by Harvey et al. [31], the method was shown to give excellent information on crack location and fairly reliable data on cracks movement in masonry structures. The method could also give approximate information on in-place strength, in-place deformability and presence of voids (in grouts as well as in masonry). In a technical note by Kaplan et al. [32], it was noted that with regard to overall condition of the masonry, the denser the material, the higher is the wave velocity response. The results of the method are qualitative in nature. Therefore, the method is less suitable for a holistic evaluation of structure and could be instead used for comparative analysis of structural elements.

2.3.2 Physical Methods

Physical methods such as Schmidt Hammer tests are used as first-level indicators of masonry strength [33]. But, it is compulsory that the hammer blow must be gentle not to cause damage at the point of impact. A similar method, Waitzmann Hammer method, was applied and found to be useful for determination of compressive strength covering built-in solid bricks [29].

2.3.3 Thermal Methods

Thermal imaging is another method which has been used to study adobe structures [34]. The increasing sensitivity toward the conservation of cultural properties is looking IRT as an excellent aid [35]. It is usually used for testing large areas. Most anomalies will be detected in the image areas showing cooler temperatures than adjacent areas [36]. Therefore, it is ideal to be used inside a building structure.

2.3.4 Radar Methods

Ground-penetrating radar technology has also been used to study the defects and other parameters of masonry buildings [37–39]. Hamrouche et al. [38] used a sensitivity study by means of numerical simulations to enhance the use of GPR in brick masonry. In a report by Hanna et al. [40] on brick walls, however, it was noted that geophysical methods such as GPR senses a property or combination of properties if and only if the property appears as a sufficiently strong contrast to that of the surrounding material. In the study conducted by McCann et al. [8], it was noted that to understand data from a GPR study, high skill is required. In another study by the same authors, it was further noted that GPR can be used only to evaluate near surface defects but not deep defects [41].

2.4 NDT for Reinforced Cement Concrete

Concrete became a popular building material across the globe in the twentieth century. A vast majority of the buildings constructed in the twentieth and twenty-first centuries are reinforced cement concrete (RCC) structures.

Unlike other building materials, the major challenge or the major cause of concern in RCC structures is the corrosion of reinforcement. Concrete material is strong in compression, but weak in tension. Therefore, steel rods (which are strong in tension and form strong bonds with the concrete material) are used in conjunction with concrete. Corrosion of reinforcement is generally unavoidable and thermodynamically spontaneous reaction. In RCC structures, because of the high alkalinity of the pore solution and the barrier provided by cover concrete against the aggressive species from outside environment, the reinforcement has been believed to be non-corrodible, i.e., the corrosion rate of reinforcement has been believed to be too slow to be of any concern. However, with the passage of time, some cover concretes would not be able to provide adequate protection to the reinforcement due to degradation of concrete and ingress of corrosive species from the environment [42]. Hence, many techniques have been developed to evaluate the impact of corrosion in RCC structures. Concrete structures exhibit other physical flaws such as fall in strength, cracks, delamination and surface erosion. The quality of the concrete material is usually expressed as a function of its compressive strength. To evaluate the compressive strength of concrete, a number of techniques have been adopted which have been mentioned for stone and brick masonry as well.

2.4.1 Methods to Diagnose Corrosion

Generally, two kinds of mechanisms induce corrosion in RCC structures—chloride ingress and carbonation. Among the two, chloride ingress produces the more damaging reaction. Carbonation, on the other hand, is a milder and slower process. In carbonation, the loss of alkalinity of concrete material due to reaction with CO_2 leads to depassivation of steel. A brilliant and comprehensive study of available techniques for determination of chloride-induced corrosion of reinforcement in concrete was provided by H.C. Gran in 1992 [43]. In the study, Gran mentioned a number of techniques including chloride penetration test, Quantab test and Volhard test, etc. With the help of the results, Gran concluded that Quantab test, which is based on the reaction of silver dichromate with chloride ion, shows poor accuracy. When the concentration of chloride ion was high, Volhard test, which is an indirect determination of chloride, gave the most satisfactory results. Rapid chloride permeability test, which was developed in the 1980s and standardized by ASTM in 1991, has also been extensively used [44,45]. Half-cell potential is another prominent method which has also been extensively used and discussed [46–49]. The method does not give quantitative information on the actual corrosion rate of rebars, but should be interpreted in the context of complementary data from the concrete structure by specialists or skilled engineers experienced in the field of corrosion testing and structural evaluation [46]. However, the method only indicates the probability of corrosion at the time of testing and gives no clue about the rate of corrosion. Also, under the following conditions, it is recommended that the test results should be interpreted by experts: (a) The concrete is saturated with water; (b) the concrete is carbonated; and (c) the steel is galvanized. Polarization resistance techniques have been widely used for determination of rate of corrosion. Polarization resistance (Rp) can be measured by several methods such as ac impedance spectroscopy, transient techniques or potentiostatic/galvanostatic measurements. However, linear polarization technique is the most widely used in the field to determine Rp. In linear polarization resistance technique, the polarization resistance is obtained as the ratio of the amplitude of linearly scanning potential and the change in current responding to the linearly scanning potential. This polarization resistance can then be related to the corrosion rate by means of the Stern–Gary equation [50]. According to this equation, the rate of corrosion is inversely proportional to the polarization resistance. The technique is rapid and requires only localized damage. However, the measurements are affected by temperature and humidity [51]. Carbonation is determined in terms of carbonation depth which is generally, most primarily, evaluated by means of phenolphthalein indicator test. The element is drilled and the pH indicator is sprayed at different depths. The solution becomes colorless where the material is acidic, thus indicating the depth of carbonation.

2.4.2 Acoustic Methods

The UPV is, once again, the most frequently used technique for testing the quality of the concrete material. In a research conducted by Savaliya et al. [52], the relation between velocities of ultrasonic waves propagating along direct, indirect and semi-direct method was investigated. This was a research of particular importance as the results obtained in each case would be different, and while analyzing an already built structure, it may not be always possible to maintain single kind of orientation of UPV transducers. The access to both sides of a wall may not be necessarily available. However, attenuation of UPV signals due to the presence of reinforcement in RCC is a particular threat. To avoid irregularities, therefore, it is usually used in conjunction with other test procedures such as Rebound hammer, infrared thermography (IRT). Jones and Facaoaru [53] discussed in detail how different parameters of concrete could be correlated with the velocity of ultrasonic waves in concrete.

The impact-echo method, a variant of sonic methods, has also been widely used in the detection of flaws and defects in concrete. The method has also been employed in order to detect damage caused by fire [54]. The method is used most successfully to identify and quantify suspected problems within a structure, in quality control applications and in preventive maintenance programs. In each of these situations, impact-echo testing has a focused objective, such as locating cracks, voids or delaminations, determining the thickness of concrete slabs or checking a post-tensioned structure for voids in the grouted tendon ducts. In a work presented by Zhu and Popovics [55], an air-coupled impact-echo was successfully employed for evaluation of concrete. The results produced were similar to that of conventional impact-echo results. However, the direct echo-waves needed to be suppressed and for this the leaky surface wave pulse was isolated and extracted by applying a Hanning Window. Attenuation and interference of signals is therefore a major limitation. Also, as with other sonic methods, experience is required to interpret impact-echo results.

2.4.3 Physical Methods

Generally, the strength obtained through Schmidt rebound hammer test varies from actual data by up to 25%. But, it is still widely used because it is easy to use and convenient. Attempts have been made to improve the accuracy of rebound hammer by interpreting the results through various interpretation algorithms [56]. Still, it is considered to be only a rough tool for estimating material homogeneity inside a specific concrete type [57].

2.4.4 Radar Methods

Ground-penetrating radar is another technique which is widely used even in concrete structures. Typically, GPR studies are used to accurately locate or delineate rebar, tension cables, grade beams, conduits, voids, dimensions of voids, moisture variations, depth of concrete cover and slab thickness [58–60]. The frequency content of the emitted and recorded GPR signal is mainly defined by the antenna. As a general rule of thumb, it can be said that the higher the center frequency of the antenna, the better the resolution but the lower the depth of penetration of the GPR signal and the possible depth of investigation [61]. GPR is applied to structures such as bridges as it causes the least obstruction.

2.4.5 Thermal Methods

IRT technique is especially of use in Historic Structures as it requires no access and generally no surface treatment. Also, the method provides a pseudo-color coded image of the object and a visual manifestation of results [62]. The recorded data can be monitored and processed on a standard personal computer running dedicated imaging software [63]. However, the pore content of cement matrix and porosity of aggregates have a clear influence on the thermal properties and thus on the experimental data obtained in the IRT analysis [64]. Another perceived limitation is that in temperate climates, it is too cold to use this technique [65]. The cost of cameras is also a deterrent presently [59].

2.4.6 Penetrating Radiation Methods

Radiography can be applied to buildings in order to evaluate their properties, functions and the efficiency, thus covering a wide range of data [66]. It can be used to measure a number of parameters including concrete quality, cracks, defects, voids, concrete cover, location of reinforcements and rebar diameter. In crack identification, digital processing drastically improves the crack visualization [67]. Again, the method is not easy to apply and involves great degree of peril. Other methods such as CAPO test, permeability test have also been used by various NDT engineers.

2.4.7 Characterization Methods

Finally, characterization of concrete material is a relatively untapped area which could be further evaluated in order to study the deterioration of the material and to chemically identify the reasons for the deteriorations. X-ray diffraction (XRD) and X-ray fluorimetry (XRF) are methods which could be used. In the past, Ukrainczyk et al. [68] used XRD for characterization of concrete from a hydroelectric power plant's pipeline.

A number of techniques which have been used in the past for evaluation of historic and other structures which could be used for the same purpose are discussed here and summarized in Table 1.

3 National and International Standards for NDT

With the development of software technologies and battery-operated small computers, NDT methods are getting popular among researchers and engineers for quick evaluation and interpretation of results. National and international technical bodies have laid down the standard mechanisms and applications of many of these techniques. Some of these national and international standards (codes) governing NDT techniques in civil engineering are tabulated in Table 2.

As the table would confirm, while a few technical bodies have established nationally accepted or locally applicable standard set of pre-investigation requirements or certified test procedures for a number of conventional and unconventional NDT techniques, others have lagged behind. The result of this growing disparity in standard specifications is that a very few conservators-engineers use modern NDT methods in many countries. As NDT results are complex and provide detailed information, such a set of standards will make it easier for the engineers to understand the results of NDT tests. In this regard, the ASTM International has been able to standardize the usage of a number of conventional, modern and ultramodern NDT test methods in building engineering. However, the above observation is not true of other societies or technical bodies that are authorized to specify such standards (codes). For example, Bureau of Indian Standards (BIS) fails to specify the pre-investigation requirements and test methodologies for application of even the most conventional techniques such as half-cell potential test. Further, the standards governing UPV and rebound hammer tests were last updated in 1992. The technologies have evolved several times since then. The BIS fails to recognize these evolutions in technologies. The result is an overdependence of Indian academia on American and European Standards for the performance of most NDT techniques.

As many of the defects present in a structure are direct results of the environment the structure is subjected to, test standards should be accommodative of various localized environmental scenarios. In case of techniques such as IRT, it has been acknowledged that the time of inspection and climatic conditions affect the results. In fact, a material's temperature gradient may vary depending on the location and the orientation with respect to the sun [69]. While carrying out IRT examinations, authors have come up with contradictory observations regarding what time of the day would help researchers find optimum results [59,70,71]. There is a

Table 1 NDT techniques for evaluation of different materials

NDT methods	Parameters to be measured for various materials		
	Stone masonry	Brick masonry	RCC structure
Visual inspection	Macroscopic flaws, cracks, deformation, etc	Macroscopic flaws, cracks, deformation, etc	Macroscopic flaws, cracks, deformation, etc
Acoustic	Strength, modulus of elasticity, flaws	Strength, modulus of elasticity, flaws, surface hardness	Strength, modulus of elasticity, flaws, surface hardness, rate of corrosion
• Ultrasonic pulse velocity			
• Acoustic emission			
• Impact-echo method			
Physical methods	Strength	Strength, surface hardness	Compressive strength, surface hardness
• Schmidt Rebound Hammer			
• Waitzmann Hammer			
• Flat–Jack Hammer			
Radar methods	Flaws, cracks, moisture content, voids, dimensions of voids	Flaws, cracks, moisture content, voids, dimensions of voids	Flaws, cracks, moisture content, voids, dimensions of voids, rebar location, depth of concrete
• Ground penetration radar			
Penetrating radiation methods	Voids, cracks, path density		Surface and subsurface defects, voids, concrete quality
• Radiography			
• Radiometry			
Characterization	Chemical composition of stone, chemical attack, inner structure		Corrosion, reason for corrosion, presence and amount of corrosion inducing chemical phases
• X-Ray tomography			
• X-Ray diffraction			
• X-Ray fluorescence			
Thermal Imaging	Air circulation, cracks, voids, damage to thermal insulation	Voids, cracks, air circulation	Cracks, concrete quality, surface temperatures
• Infrared Thermography			
Methods to diagnose corrosion			Carbonation depth, chloride ingress, rate of corrosion
• Phenolphthalein indicator test			
• Chloride penetration test			
• Haf cell potential test			
• Rapid chloride test			
• Quantab test			
• Volhard test			

dearth of standards specifying the best time for evaluation of structure using IRT. As this would highly depend on the climatic conditions of a place, the standards should also be local in nature or should be accommodative of such variations in local temperatures. In another method, namely neutron radiography, a set of standard specification laying down the safety equipment and procedures required for performing the test would be highly beneficial.

Combining several NDT methods for evaluating structures is now required for better assessment. A number of researchers have worked on this; a number of technical articles have been published [42,72–74]. Yet, even today,

Table 2 National and International Standards Governing Various NDT Techniques

S. No	Methods	Codes
1.	Visual inspection	NDIS 3418:1993
		ASTM C823/C823M
2.	Ultrasonic pulse velocity	IS 13311 (Part 1):1992
		ASTM C597-97
		BS 1881: Part 203: 1986
		BS 4408: Part 5
		BS 12504-4, Part 4 2004
		NDIS 2416-1993
		ISO/DIS 8047, C-26-72
		COST 17624
3.	Impact-echo test	ASTM C1383-15
4.	Acoustic emission techniques	ASTM E2983
5.	Rebound Hammer	IS 13311 (Part 2):1992
		ASTM C805-97
		ASTM D5873
		BS 1881: Part 202: 1986
		EDIN EN 12398 (1996)
		ISO/CD 8045
6.	Radiography	BS 1881: Part 205: 1970
		BS 4408: Part 3
		NDIS 1401-1992
		ASTM E1742/E1742M
7.	IR thermography	ASTM D4788-88, D 4788-03 (2013)
8.	Ground penetration radar	ASTM D6087-08
		ASTM D6432-11
9.	Phenolphthalein indicator test	ASTM C1202
		AASHTO T277
		ASTM C114
10.	Half-cell potential test	ASTM C876-91
11.	Volhard test	ASTM 1411-09
		NT 208
		BS 1881-Part 6
		DS 423.28
		NS 3671
12.	Polarization resistance test	ASTM C803-82

what combinations would best help in evaluating different parameters has been left to the whim and knowledge of the researchers. The different technical societies are unwilling to update the researchers with standard combinations of NDT techniques.

It can be fairly said that the standards or codes for performance and validation of NDT tests should be based on local, long-term results and should have room for all aspects of NDT engineering including combination of NDT techniques and safety procedures required. This requires the authorities of concerned technical bodies to conduct authentic experiments from time to time involving latest technology and equipment. Moreover, academes should be encouraged to engage in research in order to identify newer techniques and newer combinations of techniques that would help the researchers optimize costs and enhance test results.

4 Discussion

Of the many steps involved in the condition evaluation of historic structures, identification of an appropriate and efficient technique for studying a given parameter of a given material medium is of utmost importance. This, however, is only one step in a detailed procedure. The flow of steps involved in the condition evaluation of structures constructed of stone

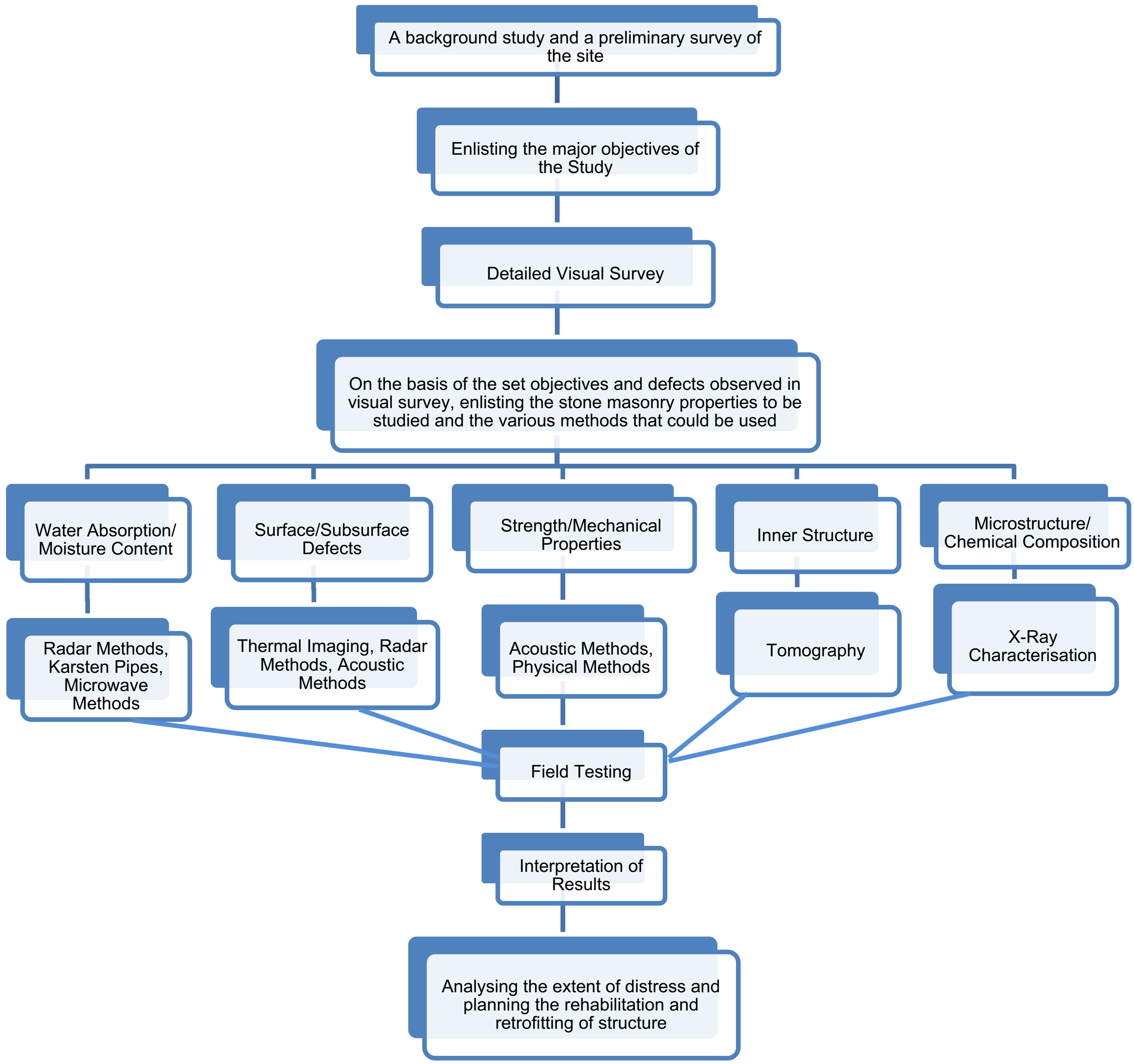

Fig. 1 Flow of condition evaluation procedure for stone masonry structures

masonry, brick masonry and concrete/RCC is provided in Figs. 1, 2 and 3.

To identify the right technique in a given scenario, a thorough knowledge of various NDT techniques is a must. Toward this objective, the present paper discusses a number of condition evaluation techniques and their application in evaluating concrete, stone and brick masonry structures. The major observations have been mentioned below:

1. A detailed visual inspection should be carried out as the first step of any NDT survey. It not only helps in bringing down the cost of the entire survey but also helps in identifying the kinds and levels of damages in an existing structure. This helps in identifying the right technique for evaluating a structure.
2. In case of methods such as UPV and acoustic emission which require the construction of analytical models and thereafter optimization of results, their reliance on prior models is a major drawback as there are considerable uncertainties in the validation of such prior data. However, such methods are applicable in determination of a wide range of material parameters in a variety of structures.
3. Physical methods such as the ones which relate the surface hardness of the material to its strength (e.g., rebound hammer test) are generally the cheapest and the easiest to

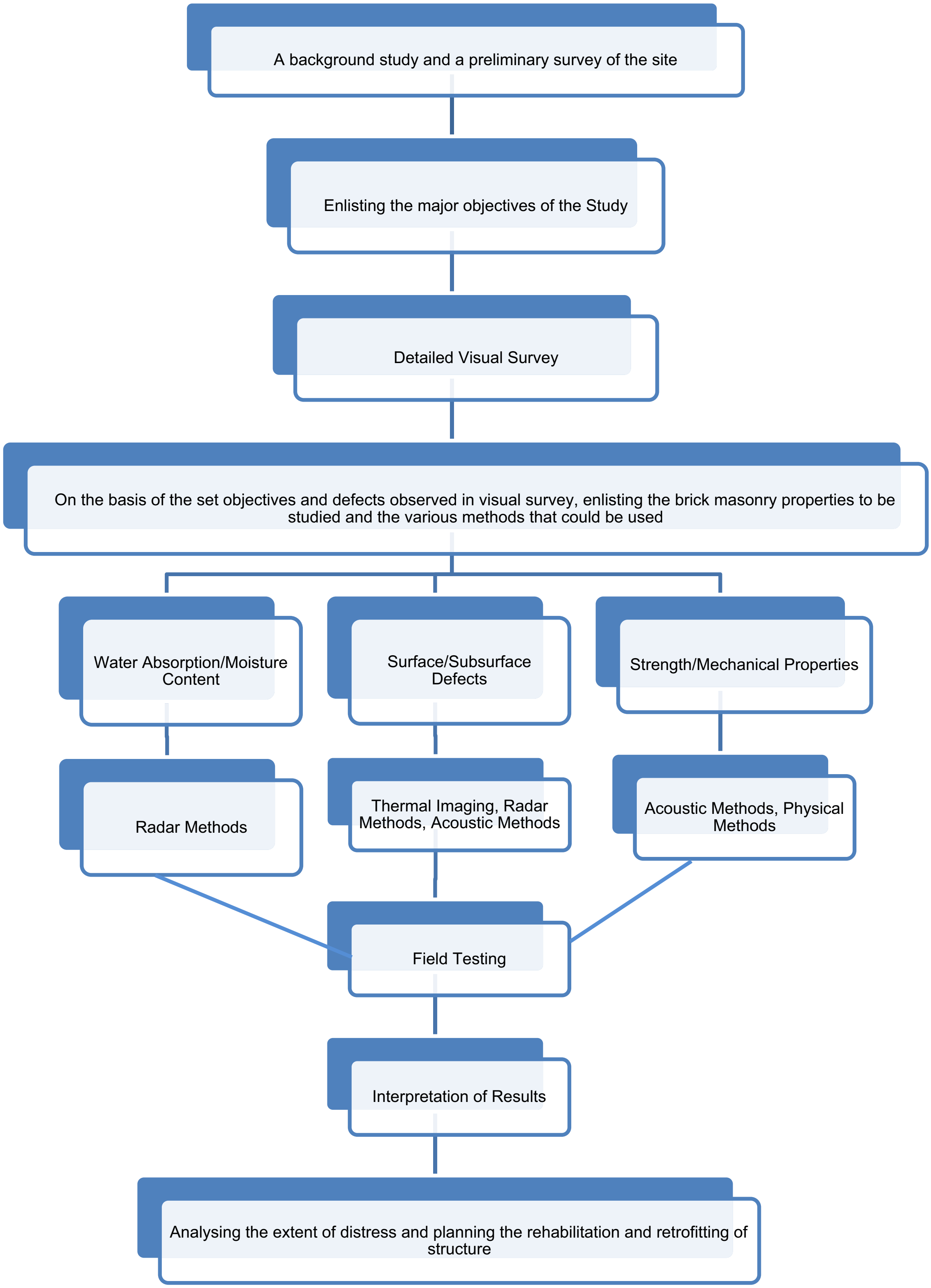

Fig. 2 Flow of condition evaluation procedure for brick masonry structures

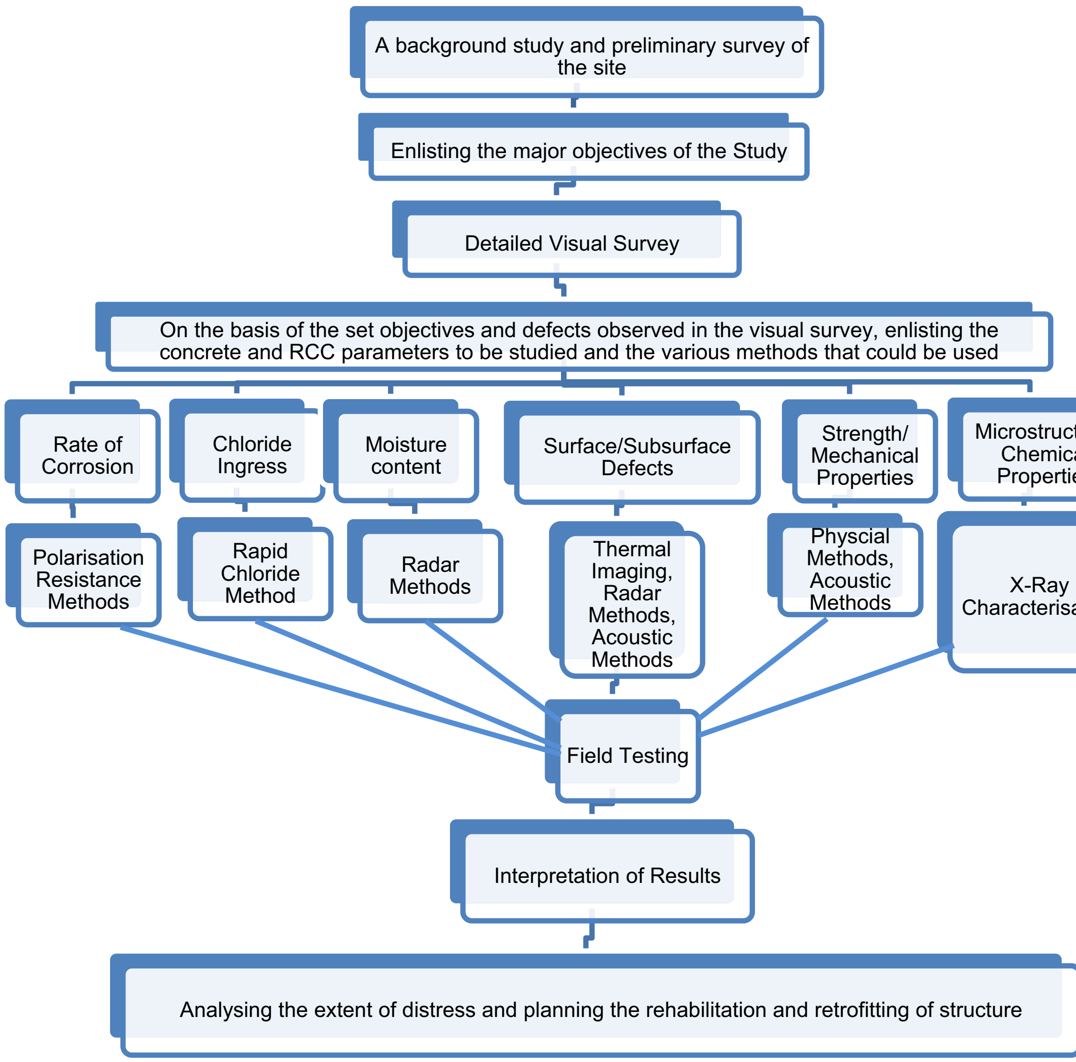

Fig. 3 Flow of condition evaluation procedure for concrete/RCC structures

implement. No complex interpretation is required in these techniques. But, they may have the following disadvantages: (a) It has been proven that the correlation between the strength of material and its surface hardness is imperfect and therefore yields incorrect results; (b) in case of brick masonry, surface hardness-based testing tools such as Schmidt rebound hammer may cause damage to the structure. However, such a technique could be used as an excellent source for preliminary strength evaluation.

4. It has been identified that moisture content influences the results obtained through any non-destructive evaluation. Ground-penetrating radar (GPR) is the most popular method for the determination of moisture variations in a structure. The method also locates voids, dimensions of voids, rebar and depth of concrete cover (in case of RCC structures). However, GPR senses a property or combination of properties if and only if the property appears as a sufficiently strong contrast to that of the surrounding material. The validation of results requires high skill and expertise.
5. There are many unconventional, but useful techniques such as IRT, neutron radiography and X-ray characterization which have great untapped potential. However, the cost of equipment is a great disincentive. As the IRT method is a no-contact method and requires no surface treatment, it is of great use in the evaluation of historic masonry. On the flipside, it does not generate proper results in temperate climates. Radiography is generally avoided by academia as it can be perilous to the person performing the test. Characterization techniques can give details of the microstructural composition of material media in a structure. All these tests require experienced personnel for the performance of test and validation of results.

Table 3 Advantage and disadvantages of various NDT methods when applied to different material media

Method	Stone masonry		Brick masonry		RCC	
	Advantages	Disadvantages	Advantages	Disadvantages	Advantages	Disadvantages
Acoustic methods	Quantitative value which can be directly correlated with properties of stone; high penetrating power and high sensitivity; access to only one surface is required; cost-efficient; portable	Manual operation requires careful attention by experienced personnel; rough, irregular parts are difficult to inspect	Relatively quick; no damage to the brick surface; moderate cost	Manual operation requires careful attention by experienced personnel	High penetration capacity and high sensitivity; access required to one surface only; good accuracy; cost-effective; surface and slight subsurface flaws can be detected	Manual operation requires careful attention by experienced personnel; rough, irregular, non-homogeneous, very small or thin parts are difficult to inspect; affected by moisture of the material
Radar methods	Can detect structural irregularities and presence of multiple leaves in stone masonry; efficient in determining local voids and defects; weak attenuation of the radar waves makes it an ideal tool for evaluating limestone structures	Expensive; choice of antenna can have a significant effect on the results; reliant on the experience of the operator	Water ingress, which is a major source of degradation of the mortar between the bricks, can be quantified; noninvasive; quick	Expensive; defects are detected only if the property appears as a sufficiently strong contrast to that of the surrounding material; poor penetration through salt-contaminated fill; reliant on the experience of the operator	Independent of ambient environment; direct contact may not be requisite; quick	Expensive; tendency to show delamination where sound concrete exists; inability to detect small flaws; results affected by the dielectric constant of the medium; reliant on the experience of the operator; radar waves can never penetrate through metals
Physical methods	Cheap; easy to interpret	Affected by the size, shape, smoothness, rigidity, age, internal moisture of the material	Cheap; easy to interpret	Can cause the material to break	Cheap; easy to interpret	Affected by size, shape, smoothness, rigidity, age, internal moisture of the material
Thermal methods	No requirement of contact with the surface; safe; savings in labor, time and equipment	Equipments are very costly; it alone cannot identify cause and source of defect; quantifiable results will not be produced	No requirement of contact with the surface; safe; savings in labor, time and equipment	Equipments are very costly; it alone cannot identify cause and source of defect; quantifiable results will not be produced	No requirement of contact with the surface; safe; savings in labor, time and equipment	Equipments are very costly; it alone cannot identify cause and source of defect; quantifiable results will not be produced
Penetration radiation methods	Shape of stone does not have an effect on the results; very thick stone surfaces can also be monitored	Costly equipments; risk of radiation hazard	Powerful tool for determination of moisture content; no damage to brick surface	Costly; chances of radiation hazards; generally applied only to very thick layers	Used on dense material, all shapes and forms can be detected	Chances of radiation hazards; costly

6. In case of concrete, reinforcement corrosion has been identified as the major defect. To evaluate the corrosion rate of reinforcement in concrete, a number of methods which are not only efficient but also cost-effective have been developed.
7. For better validation of results and evaluation of a wider array of material parameters, a number of combinations of NDT techniques have been used. Apart from these advantages, the concept of combination of NDT techniques can also help bring down the number of borings required in an NDT investigation.
8. Lack of globally accepted standards for merging new unconventional NDT techniques and an inherent (although pertinent) skepticism toward new methodologies for condition evaluation of structures can be said as serious obstacles in further experimenting with newer techniques or newer combination of techniques.

It was thought imperative by the authors that a comprehensive list of the advantages and disadvantages of all these methods when employed on different kind of structures be made and the same is presented in Table 3.

5 Conclusion

While condition evaluation of structures in itself is a challenging aspect of civil engineering, condition evaluation of historic structures in particular is much more complex. When carrying out the evaluation of such structures, it is important to identify the various material media involved in their construction and the damages associated with each material medium. Being the souvenirs of a country's past, these structures need to be preserved and maintained in their most pristine forms. To achieve this, it is necessary to understand how different condition evaluation tools could be applied to and what results these would produce for different material media. This could be done by analyzing the results of theoretical and practical studies which have been carried out in this field in the past. The authors, in this paper, have endeavored to analyze a comprehensive list of such studies and draw out a comparison of the results obtained in these studies, thereby determining what technique would be best suited for a given material medium.

1. According to the authors, in the examination of stone masonry structures, ultrasonic pulse velocity method or other acoustic-based methods would be the most suited. UPV gives values which could be directly correlated with the stone's properties. The method is of moderate cost. Another advantage is the high penetrating power of the pulses.
2. Another method that could be used quite effectively for evaluation of stone masonry structures is the Radar method. The method is known to be an ideal tool for examining limestone structures.
3. In condition assessment of brick masonry structures, it is necessary to identify the hygric properties of brick and mortar. The authors therefore suggest the use of radar methods and penetrating radiation methods in brick masonry structures.
4. Physical test procedures are not recommended for brick masonry structures as they may damage the test surface.
5. To determine the rate of corrosion in case of RCC structures, the authors suggest the use of polarization resistance techniques. Of the many techniques which could help determine the polarization resistance, the linear polarization resistance technique is the most recommended.
6. To detect the chloride content of in situ material, rapid chloride test is used. It is also used to find out the depth of bad concrete to be removed or replaced in maintenance works. The method provides quick and accurate results.
7. Carbonation is generally detected by means of phenolphthalein indicator test, an inexpensive and uncomplicated test.
8. Various physical methods mentioned in the paper can be employed for evaluation of compressive strength of concrete structures. UPV can be used to identify different physical properties of concrete along with compressive strength. The authors recommend the use of this method for condition evaluation of structures as it offers a reliable and holistic evaluation of structures.
9. Apart from all these methods, non-contact infrared thermography acts as an excellent tool to identify flaws in all the structures mentioned above.

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