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Review

Recent advances in non- destructive testing of concretes and structures: An outlook

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Non Destructive Testing (NDT) of materials and structures is one of the most common forms of quality control. The Nigerian infrastructure systems continue to deteriorate due to lack of integrity checks on some identified projects in both public and private sector. Analysis of various sectors in Nigeria revealed that there are abandon projects in building and constructions industry while major oil and gas facilities projects have been put in hold due to political instability and corruption, and lack of capacity development in research and development amongst others. Opportunities arising from the adoption of specialist approaches such as the Internet of Things (IoT) solutions and Artificial Intelligence (AI) are being understood and embraced in industries by many companies to extend the use of conventional NDT to advanced validated NDT methods and beyond. This study highlighted the steps used in choosing an effective NDT methods in the industry, introduced briefly the current approaches and methods adopted for structural integrity management of concretes, challenges faced in the industry due to lack of utilization of NDT methods including an outlook and future of NDT technology in the industry. It is expected that the study will stimulate innovative research and technology transfer aimed at bolstering the performance of NDT in the management of critical national assets.

Key words: Non-destructive test, structural integrity management, quality assurance, defect detection.

INTRODUCTION

Over the last few decades, a lot of work has been done regarding infrastructure monitoring, inspection, repair and design code specifications. Maintaining safe and reliable civil infrastructures for daily use is important for the well-being of mankind. Operation and maintenance have become more complex with the increased age of the structures. Health monitoring is the process of determining and tracking structural integrity and assessing the nature of damage in a structure (Rehman et al., 2016; Chang et al., 2003).

Concrete degradation, steel corrosion, change in boundary conditions, and weakening of connections in structures over time are major concerns in most civil engineering structures. If a damaged bridge remains unattended, the structural integrity and service capability of the bridge would deteriorate over time thereby necessitating frequent condition assessment and health monitoring of the system (Islam et al., 2014). Therefore, the safety, reliability and integrity management of these systems are very important to ensuring resiliency in

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their operations. The Nigerian economy is heavily dependent on the effective operation of these critical assets. When they do not have the robustness and integrity to perform their operations under uncertainties, they would fail leading to the disruption of their operations with long term consequence. Therefore, these critical assets are analyzed in terms of their interdependences which include infrastructure systems' characteristics, operational relationships, environmental impacts, technical efficiency, failure types and states of operations that provide insight into the complexity of the systems while enabling a collaborative modelling to take place.

The integration of NDT techniques and risk assessment tools is seen as an efficient method of managing safety and ensuring performance effectiveness of these assets. In light of the above, the aim of this paper is to carry out brief review of NDT methods used in the industry, highlight the defects and quality assurance issues associated with concretes, highlight challenges faced in the industry due to lack of NDT utilization, present risk governance of this critical infrastructure and present future outlook of NDT in concretes for structural integrity management.

NDT METHODS USED IN THE INDUSTRY

NDT technology was used in the industry as a quality control tool with the details of their processes set out in standards. The various methods of NDT were accepted because they could demonstrate their capability in practice through flaw detection of pores, cracks, inclusions, lack of fusion amongst others. Experience has shown that the type and size of the defect is a major factor for the NDT method to be deployed. The steps for choosing an effective NDT method are (Shull, 2002):

(1) Understanding the physical nature of the material property or discontinuity to be inspected
(2) Understanding the underlying physical processes that govern the NDT methods
(3) Understanding the physical nature of the interaction of the probing field with the test material
(4) Understanding the potential limitations of the available NDT technology
(5) Considering economic, environmental, regulatory and other factors

There are several emerging NDT methods which are validated and classified into conventional and advanced methods. Each of the methods has its peculiar characteristic advantages and limitations (Duaka, 2016).

In order to ensure conformity to quality management of engineering systems, codes, regulatory requirements, standards, specifications and recommended practices are used in all aspects of construction, fabrication, manufacturing and inspection. While codes provide a set of rules that specify the minimum acceptable level of safety for manufactured, fabricated or constructed objects. Standards are documents that establish engineering or technical requirements for products, practices, methods or operations. Examples of codes used in the oil and gas industry are the ASME Boiler and Pressure Vessel Code (B&PVC). The AWS D1.1 Structural Welding Code – Steel and that of certification standards are the ANSI/ASNT CP-189, ASNT Standard for Qualification and Certification of Non-destructive Testing Personnel and the ANSI/ASNT CP-105, ASNT Standard Topical Outlines for Qualification of Non-destructive Testing Personnel (ASNT, 2019). Other commonly test methods used for concretes are Standard Test Method for Pulse Velocity through Concrete ASTM C597-16, ASTM C805 and EN12504-2:2001 for Rebound Hammer, ASTM C597, EN12504-42004 for Ultrasonic Pulse Velocity (UPV) amongst others (Hannachi and Guetteche, 2012).

Conventional NDT techniques

The validated conventional methods are techniques that have developed over time and presently have been documented in codes, standards and best practices. Based on industrial application, the setup and procedure of the conventional technique is typically simpler in comparison to advanced methods. These methods are summarised as follows (Duaka, 2016):

(1) Acoustic Emission Testing (AET)
(ii) Leak Testing (LT)
(iii) Electromagnetic Testing (ET)
(iv) Thermal/Infrared Testing (TIR)
(v) Neutron Radiographic Testing (NRT)
(vi) Liquid Penetrant Testing (LPT)
(viii) Magnetic Particle Testing (MPT)
(ix) Radiographic Testing (RT)
(x) Ultrasonic Testing (UT)
(xi) Vibration Analysis (VA)

Advanced Validated NDT Methods: The advanced validated NDT methods include the following:

(1) Phased Array Ultrasonic Testing (PAUT)
(2) Alternating Current Field Measurement (ACFM)
(3) Long Range Ultrasonic Testing (LRUT)
(4) Guided Wave Ultrasonic Testing (GWUT)
(5) Pulse Eddy Current Testing (PET)
(6) Digital Radiography Testing (DR)
(7) Time of Flight Diffraction Testing (TOFD)

During the application of the NDT, the personnel make an interpretation of the indication (signal or image response) to show if the indication is real, that is, a flaw or irrelevant or a false indication. Real flaws are usually evaluated and

Figure 1. Schmidt rebound hammer.
Source: Adapted from Resolutionengineering.com.

compared with the relevant acceptance standards. A flaw is deemed defect if it exceeds the acceptance level as presented in the code or standard (Rummel, 2014).

Overview of NDT for structural integrity management

Many NDT techniques used in the industry are capable of identifying and determining the features of defects such as size, shape, and orientation. Unlike the destructive tests where the part being tested is damaged or destroyed during the inspection process, the NDT inspection of components is done in a safe, reliable and cost effective manner without causing damage to the equipment or shutting down of plant's operations.

Resonant frequency test method

This is a non-invasive NDT method used to determine material properties by assessing their natural frequency of vibration. The two most commonly used methods are resonant frequency by vibration and resonant frequency by impact. The natural frequency of a vibrating structural member is a function of its dimensions, dynamic modulus of elasticity and density. Therefore, measuring either the transverse or longitudinal natural frequency of vibrations of a structural member of known dimensions and material allows the determination of its modulus of elasticity as shown in Equations 1 and 2 (Helal et al., 2015; Rayleigh, 1945).

Equations 1 and 2 were determined based on homogenous, isotropic and perfectly elastic systems. The conditions are not met in the testing of *in-situ* concretes; however, the equations still provide an accurate estimate of material properties,

$$N = (m^2k/2\pi L^2)\sqrt{E}/d \quad (1)$$

$$E = (4\pi^2L^4N^2d)/m^4k^2 \quad (2)$$

Where E = dynamic modulus of elasticity; d = density of the material; L = fundamental flexural frequency; k = radius of gyration; and m = a constant.

Rebound (Schmidt) hammer method

Rebound Schmidt Hammer can be used to evaluate the quality of concrete near the surface. These methods attempt to highlight the empirical correlations between strength properties of concrete and surface hardness. While test results do not directly correlate with strength of concrete, a site-specific calibration on concrete cores can be used to predict the concrete strength on-site. Industrial application of the hammer reveals that upon impact with the concrete surface, the rebounded hammer (Figure 1) records a rebound number which presents an indication of strength properties by referencing established empirical correlations between strength properties of concrete (compressive and flexural) and the rebound number (Helal et al., 2015). Rebound hammer is easy and fast to perform in the field. Test results can be used for comparative assessment of concrete quality at different locations (McCann and Ford, 2001).

Penetration resistance methods

This is an invasive NDT procedure that explores the strength properties of concrete using previously established correlations. The method involves driving probes into concrete samples using a uniform force; the probes depth of penetration provides an indication of concrete compressive strength by referring to correlations. Windsor probe system (Figure 2) is the most commonly used penetration resistance method and also

Figure 2. Windsor probe system.
Source: Adapted from James Instrument Inc.

Figure 3. Typical setup for pull-out resistance NDT method.
Source: Adapted from Helal et al. (2015)

refers to non-destructive despite the disturbance of the concrete during penetration.

Pull-out resistance methods

Pull-out resistance methods measure the force required to extract standard embedded inserts from the concrete surface. Using established correlations, the force required to remove the inserts provides an estimate of concrete strength properties. The two types of inserts, cast-in and fixed-in-place, define the two types of pull-out methods. Cast-in tests require an insert to be positioned within the fresh concrete prior to its placement. Fixed-in-place tests require less foresight and involve positioning an insert into a drilled hole within hardened concrete. Pull-out resistance methods are non-destructive yet invasive methods which are commonly used to estimate compressive strength properties of concrete. The most commonly used pull-out test method (Figure 3) is the LOK test developed in 1962 (Kierkegaard-Hansen, 1975).

Pull-off resistance method

The pull-off test was developed with the aim of determining the strength of concrete *in situ* due to problems associated with high alumina cement. The test has the ability to evaluate the resistance of concrete and to verify the adhesion strength of the concrete repairing materials (Pereira and Medeiros, 2012; Lung and Murray, 1983).

Maturity test method

The maturity method is a NDT technique for determining strength gain of concrete based on the measured temperature history during curing. The maturity function is presented to quantify the effects of time and temperature. The resulting maturity factor is then used to determine the strength of concrete based on established correlations. The maturity method has various applications in concrete construction such as formwork removal and

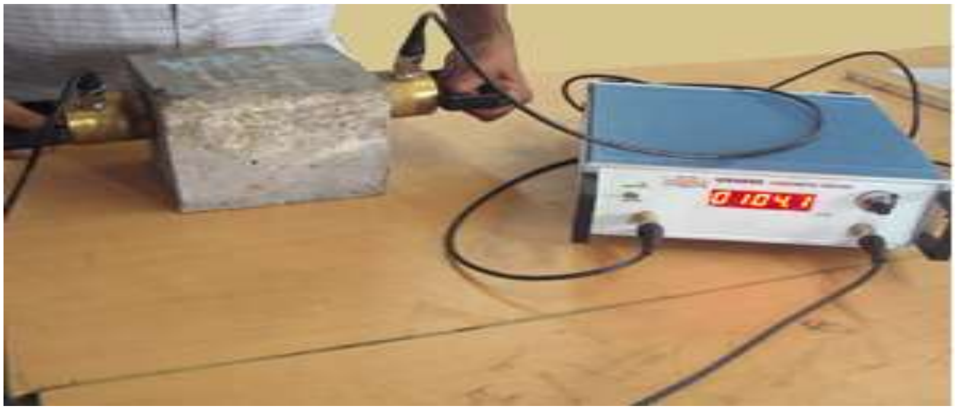

Figure 4. Ultrasonic pulse echo method.
Source: Adapted from indiamart.com.

Figure 5. NDT of Concrete using GPR.
Source: Adapted from www.fprimec.com.

posttensioning (Helal et al., 2015).

Permeability test method

Permeation tests are non-destructive testing methods that measure the near-surface transport properties of concrete. When concrete is permeable, it can cause corrosion due to the presence of oxygen, moisture, CO^2, SO^{3-} and Cl^-. This formation of rust due to corrosion becomes nearly 6 times the volume of steel oxide layer, leading to cracking and spalling in reinforced concrete. Permeability represents the governing property for estimating the durability of concrete structures (Constructor, 2018).

Ultrasonic Pulse-Echo (UPE) method

Ultrasonic testing of concrete is a NDT method used to assess the homogeneity and integrity of concrete. This is achieved by propagating ultrasonic waves through solids materials while measuring the time taken for the waves to propagate between a sending and receiving point. The ultrasonic pulse test (Figure 4) of concrete can be used to assess the strength of concrete, thickness measurement, degradation in different locations of structural members, discontinuity in cross section like cracks, delamination amongst others within concrete tank wall.

Ground penetrating radar

Ground penetrating radar (GPR) is a NDT method used to scan concrete using pulsed electromagnetic radiation to evaluate structural integrity of concrete. It consists of a transmitter, a receiver antenna, and a signal processing unit. The reflected waves from the subsurface layers and objects are captured by the receiver antenna. The scanning apparatus (Figure 5) can be mounted on a truck or a special vehicle to perform the scan. Due to its suitability, GPR method scans large areas of concrete in a limited period of time and scans steel reinforcement concretes over existing coatings where potential

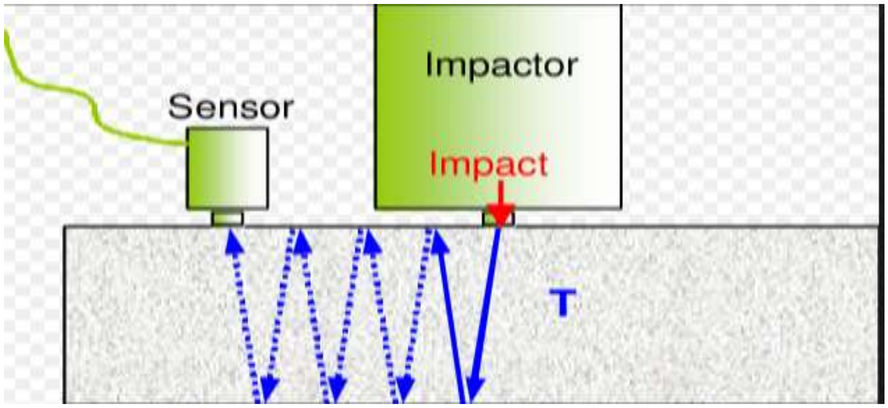

Figure 6. Impact echo method.
Source: Adapted from Grosse et al. (2005).

Figure 7. NDT corrosion mapping.
Source: Adapted from www.fprimec.com.

delamination and other discontinuities are identified. The practice has been standardized by ASTM D6087.

Impact Echo (IE) method

The Impact-Echo method is ideal for measuring the thickness of concrete slabs and for identifying delamination. On a broader level, it is also used for detecting mechanical impedance contrasts, an example of this being delamination, which refers to "sub-horizontal" cracks which are parallel to the side under observation. The process analyzes the reflection signals of impact-generated stress waves that propagate through the testing elements/structures as presented in Figure 6. In recent years, efforts have been made to introduced more advanced data analysis techniques for better analysis of impact echo signals such as the Ensemble Empirical Mode Decomposition (EEMD) used to decompose the IE signals into different spectra components to extract defect signal (Carino and et al.,, 1986; Sansalone and Carino, 1986; Lin et al., 2009; Zhang and Xie, 2012) but full concrete condition assessment using impact-echo method and extreme learning machines was conducted by Zhang et al. (2016) to enhance the structural integrity of the structures under uncertainty. Concrete Thickness Gauge CTG is one amongst several IE methods used in the industry.

Half-cell corrosion mapping

Corrosion mapping is a widely used test procedure to identify areas with active corrosion activity. The test (Figure 7) can reveal the locations with high likelihood of corrosion; it can also be used to evaluate the quality of repair. Analysts should consider that any coating or paint residue should be removed before conducting the test.

DEFECTS ASSOCIATED WITH CONCRETE/ STRUCTURAL SYSTEMS

Non-destructive test, inspection and condition monitoring

Figure 8. Disintegration or scaling of concrete.
Source: Adopted from FPremec.com.

Figure 9. Corrosion of reinforcement.
Source: Adapted from concreteprotection.com.

of concrete at regular interval will help to ensure the safety and reliability of this critical national asset. Industrial application of NDT and related approaches will help in detecting and quantifying potential defects and deterioration mechanism at early stage of the structure. Analysts have posited that tests results from the application of NDT will help decision makers in prioritising repairs and maintenance schedules for their assets.

Based on experts' opinion, different defects results from the deterioration of concretes over time and proper understanding of these defect mechanisms will help industrialist develop strategies aimed at mitigating the effect of the defects. The following defects are highlighted based on the research by PCA (2001) and OSIM (2008).

Disintegration or Scaling

This is the physical deterioration or loss of the surface portion of concrete into smaller particles or fragments as a result of freezing and thawing. This defect happens when the pressure from water freezing within concretes exceeds the tensile strength of concrete. Scaling is more common in non-air entrained concrete, but can also occur in air-entrained concrete in the fully saturated condition (PCA, 2001; OSIM, 2008). Mostly, visual method of inspection may be used to identify and implement repair work on the system (Figure 8).

Corrosion of reinforcement

Corrosion of reinforcing steel and other embedded metals is the leading cause of deterioration in concrete as a result of chloride or carbonation inducement. When steel corrodes, the resulting rust occupies a greater volume than the steel. This expansion creates tensile stresses in the concrete leading to cracking, delamination, and spalling. In coastal regions where high chloride concentrations are encountered, chloride-induced corrosion is the major source of environmental deterioration of reinforced concrete structures (Ahmad, 2003) (Figure 9).

Delamination

This is a common problem affecting power-finished

Figure 10. Delaminated concrete.
Source: Adapted from concretedecor.net.

Figure 11. Spalling of concrete.
Source: Adapted from https://cp-tech.co.uk/news/causes-effects-and-repair-of-concrete-spalling.

concrete floor slabs, pavement and beam foundations. It is the detachment of a thin surface layer from the rest of the system (typically 2-8 mm in thickness) and usually manifested by a 'drummy' like-sound. The defect is often caused by trapped air or water content which combines to make larger bubbles during concrete finishing operations thereby causing the separation of the surface from the system. Experience has shown that high air content shows shallow depth while bleed water entrapment reveals deeper depth of defect needing repairs in order to enhance the integrity of the concrete structure (Figure 10).

Spalling

This is sometimes refers to as extended delamination, spalling (Figure 11) describes areas of concrete which have cracked and delaminated from the substrate. It occurs due to freeze thaw cycling, exposure to fire or corrosion of embedded steel reinforcement bars or steel sections. Corroding steel can expand thereby exerting stress on the surrounding concrete. The defect affects a wide variety of structures including concrete framed buildings, multi-storey car parks, bridges, jetties, tanks and bunds with devastating consequences in terms of health and safety, structural integrity and asset value. Unfortunately a sticking plaster approach is often taken to repairing spalling structures, with the underlying causes left untreated (Cp-tech, 2017).

Cracking of concrete

Generally, concrete provides structures with strength, rigidity, and resilience from deformation. Cracking (Figure 12) can occur in this system as a result of volume changes and repeated loading of a member. Experience has shown that deterioration of member may exist before cracks appear. It is important for analysts to understand why cracks occur, the types of cracks formed and its effects on structural integrity on members so as to develop appropriate repair method. The repair method will be selected based on the evaluation of crack and its repair objectives which may include: restoring or increasing strength, restoring or increasing stiffness, improving functional performance, providing water tightness, improving the concrete surface's appearance, improving durability, and preventing the development of a corrosive environment for the reinforcement amongst others.

Honeycomb

This is mostly seen in columns and foundation beams of

Figure 12. Crack in a concrete foundation.
Source: Adapted from www.giatecscientific.com/education/cracking-in-concrete-procedures.

Figure 13. Honeycombs on concrete.
Source: Adapted from the constructor.com.
Other defects found in concretes are Exudations, variable cover, popout, impact damage, tearing amongst others.

concretes and are easily detected after removing the formwork. The defect (Figure 13) looks like a honey-bee-nest and has a rough pitted surface or voids on concrete formed due to improper compaction or incomplete filling. Analysts have posited that Honeycomb is a serious problem of concrete which should be treated in order to avoid failure of the structure with long term economic and environmental consequence (Constructor, 2018). Other defects found in concretes are exudations, variable cover, popout, impact damage, tearing amongst others.

CHALLENGES FACED BY CIVIL INFRASTRUCTURE IN NIGERIA

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 interval of every 5 years. Similarly in Malaysia, The Street, Drainage and Building Act (Amendment 1994, Act A903) was amended as a result of Highland Tower tragedy. The Act stipulates the requirements for the periodical inspection of buildings (Ismail, 2017).

However, the Nigerian material and civil infrastructure continue to deteriorate due to lack of integrity checks on some identified projects in the country both in public and private sector. Analysis of various sector in Nigeria revealed that there are abandon projects in building and constructions industry, major oil and gas facilities projects put in hold due to political instability, lack of capacity development in research and development amongst others leads to the deterioration of key infrastructures (Figure 14).

Global risk governance of concrete and other civil infrastructure

Governance refers to the review and oversight of all activities in any phase of a system's life cycle, which may be in the form of peer reviews, design reviews and independent reviews, especially during the development phase of a technological system (Jackson, 2010). Most safety researchers and analysts agree that risk governance in critical national asset is a key aspect of systems resilience.

Risk governance in a broad context, as defined by International Risk Governance Council (IRGC), is the identification, assessment, management and communication of risks (John and Nwaoha, 2016). The global risk assessment includes a global Likelihood of

Figure 14. Abandoned tank beam foundation for a major oil and gas company in Nigeria.

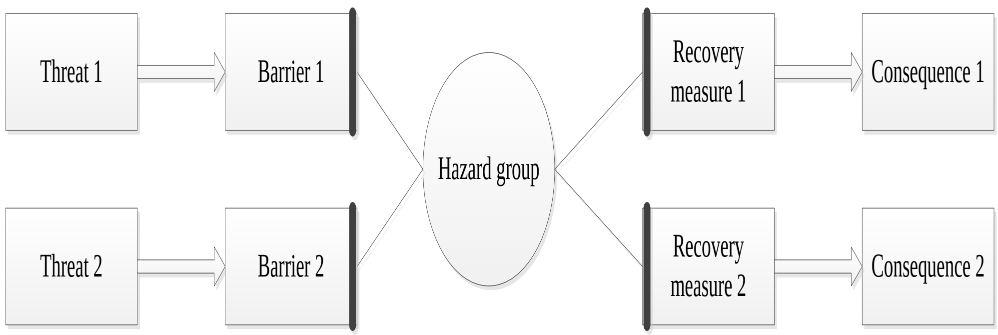

Figure 15. Risk Assessment Bow-tie.
Source: Wang and Trbojevic (2007)

Failure (LoF) and a global Consequence of Failure (CoF) assessment. Based on the global risk assessment definition, Figure 12 can be developed. The global consequence, including safety of life, environmental and financial consequences, is assessed by qualitative method using descriptive criteria or semi-quantitative method using a scoring process while the global likelihood is assessed by semi-quantitative method using a rule-based scoring approach, which uses the available structural analysis results and structural reliability method (Guédé, 2018).

Figure 15 shows the bow-tie diagram. The starting point on the left hand side is a hazard which is defined as a situation or condition with the potential to cause harm. Based on Wang and Trbojevic (2007), these conditions or situations can be technical, organizational or human factor related and can be in any of the following:

(i) Hazardous elements such as corrosion reinforcement, spalling etc.
(ii) Initiating event causing the hazard to occur.
(iii) Threat and target, personnel or a system that is vulnerable to an attack.

A hazard can be triggered by one or several threats (e.g. mal-function, corrosion, design fault, etc.) which if not checked would lead to an initiating event or loss of control situation (as shown by a circle perimeter in Figure 15). To prevent this, resiliency measures or barriers are put in place. The left hand side of the bow-tie is also called the causation part and requires causation analysis in the global risk assessment or risk governance process (hazard analysis, failure mode and effect analysis, fault tree analysis etc.).

A barrier system based on Figure 12 is to reduce the probability of occurrence of hazards with the aim of buffering the system from major external and internal disruptions, thereby absorbing shocks and reducing system uncertainty. These barriers may include monitoring systems enabled with sensors, connections, feedback loops, action capabilities, etc. The same is true about the recovery measures or resiliency measures at the right hand side, which can include actions in the form of procedures' inspections, and drills that can be standardized as various policies based on the evaluation of the system using event tree analysis, consequence analysis and so on (Mansouri et al., 2010; Wang and Trbojevic, 2007).

The right hand side of the bow-tie depicts the escalation or outcome analysis which could take place if all barriers are breached and the initiating event is released. This event could then escalate to different outcomes, each of which would have specific consequences such as loss of life, fire/explosion, etc. In light of the above, a risk management system can be envisaged as a critical and key aspect for improving resilience in complex systems operations by maintaining barriers and recovery measures. It is important to note that risk assessment can be used as a powerful tool to help infrastructure owners to get a better understanding of hazards affecting their assets, and learn how to maintain their performance. The risks management associated with ageing of infrastructure includes identifying different hazard sources, assessing the risk associated with each hazard source, and finding risk informed solutions for maintenance of these assets in order to improved their life cycle performance and reliability.

OUTLOOK AND FUTURE OF NDT AS APPLIED TO STRUCTURAL INTEGRITY EVALUATION

Concrete defects such as corrosion, cracks, change in pressure and other symptoms of internal deterioration can now be monitored more accurately and cheaply when sensors are placed in concretes next to steel framing in infrastructures to transmit real time data for their assessment and evaluation (GSMA, 2018).

The advent of smart concrete means an addition to the Internet of Things (IoT) technologies which allows challenging NDT inspections to be carried out with ease. This technology makes internal structures to be accurately monitored and maintained while maximizing their lifespan with repairs made at the most cost-effective point of intervention, thereby avoiding potentially disastrous collapses in the system operation. Research has shown that the development of new materials and devices in sensors are paving way for advanced NDT methods to be used in the industries. Data fusion and mining are being developed to integrate several NDT methods with the aim of carrying out effective acquisition of data, processing and interpretation of test parameters in order to bolster the integrity and reliability of structures.

New technology trends such as IoT, wireless sensors and artificial intelligence can support NDT, since NDT traditionally employs computing devices with sensors to assess data from systems. The adoption of these technologies can greatly enhance the integrity management of critical assets in the future with increase in user-friendly devices, higher accuracy in workflows, supporting the user with accurate data interpretation, establishing traceable procedures with less effort and enabling data sharing for collaboration and quality assurance (Meier et al., 2017). It is envisage that the use of specialized and modern NDT tools and risk assessment methodologies will help in broadening the scope and usage of NDT technology for evaluating material integrity and management.

CONCLUSIONS

This paper has attempted to briefly review the methods of NDT being used on concretes and other civil engineering infrastructure. The reliability of non-destructive evaluation of concretes depends on the multitude of different factors deployed to analyze their integrity for resilient performance under high uncertainty. Due to the significance of NDT in advancing economic development, the future achievements of the methods are increasing ease-of-use, user-friendly, higher accuracy, efficiency by reducing errors and rework in workflows, establishing traceable procedures with minimal effort and enabling unobstructed data sharing for collaboration and quality assurance for management of critical civil infrastructure.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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