DOI: https://doi.org/10.14256/JCE.2379.2018

Građevinar 1/2019

Primljen / Received: 5.3.2018.
Ispravljen / Corrected: 3.8.2018.
Prihvaćen / Accepted: 15.9.2018.
Dostupno online / Available online: 10.2.2019.

Innovative concrete sensing technologies for nuclear power plants

Authors:

Scott David B., PhD. PE
University of North Carolina at Charlotte, USA
Department of Civil and Environmental Engineering
dscott@epri.com

Prof. **Chen Shen-En**, PhD. PE
University of North Carolina at Charlotte, USA
Department of Civil and Environmental Engineering
schen12@uncc.edu

Scientific Paper - Preliminary note

Scott David B., Chen Shen-En

Innovative concrete sensing technologies for nuclear power plants

Nondestructive evaluation has been used to investigate construction and use of concrete structures for the nuclear power industry. Nuclear concrete often has unique structural characteristics which increase proclivity towards degradation and inhibit analysis and inspection using traditional nondestructive techniques. Modern embedded sensing technologies can provide opportunities for the in-depth evaluation of nuclear reinforced-concrete structures. This paper offers an assessment of emerging embedded and surficial sensor techniques, and critically evaluates sensor applicability in the analysis of concrete structures used in the nuclear power industry.

Key words:

nuclear power plants, concrete, structural health monitoring, nondestructive evaluation, sensors

---

Prethodno priopćenje

Scott David B., Chen Shen-En

Inovativne senzorske tehnologije za beton u nuklearnim elektranama

Postupak nerazornog ispitivanja primjenjuje se za istraživanja tijekom izvođenja i uporabe betonskih konstrukcija koje se koriste za potrebe nuklearne industrije. Beton u nuklearnim elektranama često se odlikuje posebnim svojstvima koja ga čine osjetljivim na propadanje te koja onemogućuju analizu i kontrolu pomoću tradicionalnih nerazornih postupaka. Moderne tehnologije analize unutar betona omogućuju dubinsko istraživanje nuklearnih armiranobetonskih konstrukcija. U radu se analiziraju perspektivne dubinske i površinske analitičke metode te se kritički ocjenjuje primjena senzora u analizi betonskih konstrukcija koje se koriste u nuklearnoj industriji.

Ključne riječi:

nuklearne elektrane, beton, praćenje stanja konstrukcija, nerazorno ispitivanje, senzori

---

Vorherige Mitteilung

Scott David B., Chen Shen-En

Innovative Sensortechnologie für Beton in Kernkraftwerken

Das Werkstoffprüfverfahren wird für die Untersuchung während der Ausführung und Verwendung von Betonkonstruktionen angewendet, die für die Kernkraftindustrie verwendet werden. Der Beton in Kernkraftwerken zeichnet sich häufig durch besondere Eigenschaften aus, die ihn anfällig auf Zerfall machen, und die eine Analyse und Kontrolle mithilfe traditioneller Werkstoffprüfverfahren unmöglich machen. Moderne Technologien der Analyse innerhalb des Betons ermöglichen eine Tiefenuntersuchung der nuklearen Stahlbetonkonstruktionen. In der Abhandlung werden prospektive Tiefen- und Oberflächenanalyseverfahren analysiert und der Einsatz von Sensoren bei der Analyse von Betonkonstruktionen, die in der Kernkraftindustrie verwendet werden, wird kritisch beurteilt.

Schlüsselwörter:

Kernkraftwerke, Beton, kontinuierliche Überwachung der Konstruktion, Werkstoffprüfung, Sensoren

1. Introduction

Nondestructive evaluation (NDE) has been used for the investigation and evaluation of nuclear concrete structures (NCS) for decades [1]. Nuclear structures consisting of reinforced concrete are, in general, unique to most commercial structures. Examples of nuclear related reinforced concrete structures are cooling fluid intakes, cooling towers, containments, spent-fuel pools, and dry-cask storage. Applications of NDE include investigation of aging effects of concrete containments at nuclear power plants for chemical attacks, physical attacks, and degradation factors such as leaching, alkali-aggregate reactions, freeze-thaw, fatigue, vibration, corrosion, elevated temperature, and others [1, 2].

The configuration and sensitivity of certain parts of these structures necessitate limited access to perform NDE. Furthermore, the nuclear industry utilizes copious composite structures (e.g.; steel-lined concrete containments, dry-cask storage and spent fuel pools) which further limit direct NDE access to the concrete structure. At times, this limitation restricts testing to be performed on only one side of the component or is further stunted by an array of penetrations which inhibit the ability to perform NDE. Finally, nuclear structures are robust, containing thick structural members and large concentrations of reinforcing steel, and the access timing (many elements of a nuclear, reinforced concrete structure are only accessible during outages) is an additional critical element associated with maintenance inspection. The combination of these hindrances creates significant complications for conventional NDE and high-fidelity investigations for nuclear applications.

American Concrete Institute (ACI) produces ACI 228.2R [3] which divides traditional NDE techniques into several broad categories: visual, stress waves, nuclear, magnetic and electrical, penetrability, infrared thermography, and RADAR. Other than visual evaluation, these techniques require the imputation of energy into the concrete element, and, subsequently, measuring the responses of the element. These techniques have been directly used in the past on NCSs experiencing delamination in an extent-of-damage survey [4-6]. The techniques may be used to indicate corrosion potential of reinforcement, cracking strength, Young's modulus, voids, bond repair, delamination, honeycomb, member thickness, etc. These techniques may be used individually or in tandem. More recently, innovative technologies such as microwave holography [7] or air coupling (instead of direct contact) ultrasound devices [8, 9] have been developed. Along with traditional NDE, these techniques are often-used tools to provide data on condition assessment of nuclear concrete structures [10]. NDE practices for general concrete applications are well established and documented [11-17].

Alternatively, there is an opportunity for the commercial nuclear power industry to use a suite of innovative sensing techniques which may supplement or, in some cases, replace traditional NDE [18]. These techniques include using sensors made up of single-walled carbon nanotubes [19, 20], piezoelectric ceramics [21-23], fibre optics [24], and electrochemical materials [25, 26]. These sensors are topical or embedded (topical application of sensors is the one in which the sensor is applied on the surface, whereas embedded sensors are internal and can be applied during or after construction of a structural member) [18-26]. The interrogation of these sensors may require contact or be remote [18, 27]. They have been shown to indicate material strength during and after curing, structural strain, and crack development [26].

These embedded and/or topical sensors (ETS) may be able to overcome limitations unique to NCS. The following offers considerations which may be made for the upcoming and continued advancements in sensing technologies and application of these technologies to NCS. There are also external sensing techniques with devices detached from the monitored structures including radio detection and ranging (RADAR), light detection and ranging (LIDAR), infrared thermography, synthetic aperture RADAR (SAR), etc. But they are outside of the scope of this paper. Though the nuclear industry does not currently and broadly apply these sensing technologies, there is opportunity for these sensing techniques to provide valuable monitoring opportunities for existing and to-be constructed nuclear power structures.

2. Damage and degradation of reinforced concrete

The source of damage induced into NCS varies: whether under construction, nearing end-of-service, or somewhere in between, nuclear structures may potentially have damaged conditions that need to be investigated.

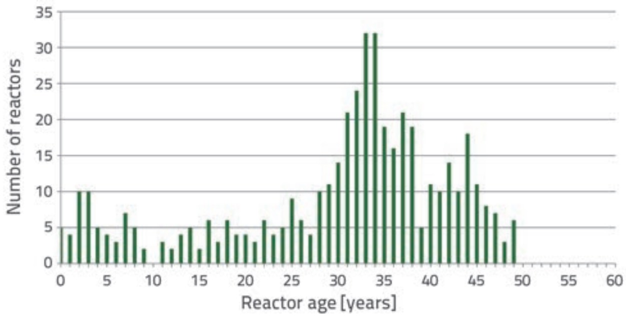

Figure 1. Global age of nuclear reactors used for energy (data from [2])

At the time of this writing, there are 57 new nuclear power plants under construction and, at the same time, hundreds of operating plant structures proceed to age throughout the world. The majority of the world's 448 reactors are older than 20 years – more than a half of the typical 40-year license age [2]. Figure 1 shows the aging nuclear plant population. At the end of 2012, fifteen units in the US had been in operation for at least 40 years, and license-extension applications are regularly submitted to extend use beyond the original 40-year licenses.

The evaluation of nuclear concrete structures must include inspection of in-service structures, forming a technical basis for continued operation, and determining necessary remedial action to extend service of these nuclear assets. Table 1 offers an inventory of potentially

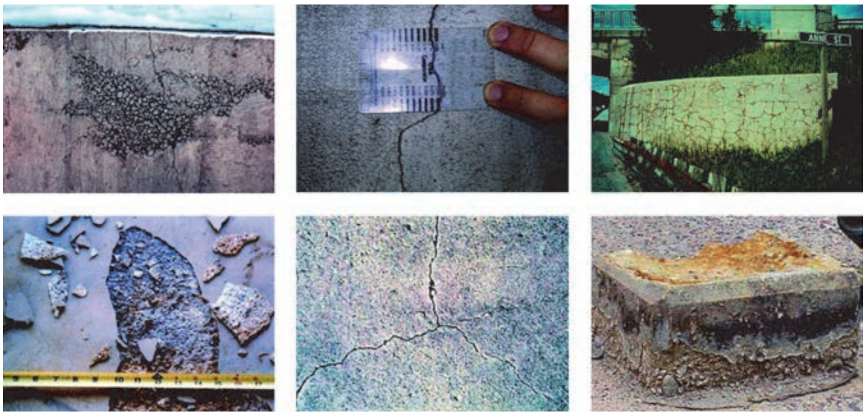

Figure 2. Common degradation for reinforced concrete on nuclear structures [28]

Table 1. Defect and mechanism inventory

Defect category	Defect type/impetus	Life-cycle stage it may occur	Defect scope (structural/ material)
Environment induced	Alkali-aggregate reactivity (AAR)	Intermediate, LTO (long term operations)	Material
	Carbonation	Intermediate, LTO	Material
	Chloride Ingress	Intermediate, LTO	Material
	Deformed bar reinforcement corrosion	Intermediate, LTO	Material
	Corrosion of steel liner	Intermediate, LTO	Material
	Delayed Ettringite Formation (DEF)	Intermediate, LTO	Material
	Irradiation	LTO	Material
	Radiation	New-build, Intermediate, LTO	Material
	Sulphate attack	Intermediate, LTO	Material
Construction induced	Crack	New-build, Intermediate, LTO	Structural and material
	Delamination	New-build, Intermediate, LTO	Structural
	Freeze-thaw	New-build, Intermediate, LTO	Material
	Honeycomb/void	New-build, Intermediate, LTO	Structural
	Shrinkage	New-build, Intermediate, LTO	Material
Steel related	Creep	Intermediate, LTO	Structural
	Debonding of liner and steel	New-build, Intermediate, LTO	Structural
	Fatigue	LTO	Structural
	Lack of bond at Nelson studs	New-build, Intermediate, LTO	Structural
	Rupture of tendon and/or tendon heads	New-build, Intermediate, LTO	Structural
Extreme Operation (Or other)	Coating Failure	New-build, Intermediate, LTO	Material
	Fire	New-build, Intermediate, LTO	Material
	High temperature exposure	Intermediate, LTO	Material
	Inclusions (embedded during construction)	New-build, Intermediate, LTO	Structural
	Missile impact	New-build, Intermediate, LTO	Structural
	Moisture intrusion	New-build, Intermediate, LTO	Material
	Thermal differentials	New-build	Material
	Leak rate failure	New-build, Intermediate, LTO	Structural
	Erosion and/or abrasion	Intermediate, LTO	Material

damaging mechanisms for reinforced concrete, which can be differentiated into environmental, construction, and extreme operations. The compilation of images in Figure 2 indicates the varying ways in which degradation is revealed.

2.1. Environment induced problems

Many of the defects identified in Table 1 are further complicated by the unique characteristics of NCS. For example, corrosion in metals may result in volumetric increases, which produces additional stress on surrounding concrete and significantly cracks and weakens the concrete [29]. Concrete spalling often ensues. Metal corrosion is, in part, environmentally induced, and is especially critical for NCSs because of the massive amount of embedded steel arrangements, as detailed further in Section 2.4.

In addition, nuclear related structures use heavy amounts of, or are often near, large bodies of water in order to cool the heat generated from nuclear processes. This water sometimes includes chlorides which were used to treat the water, or the plant is near the sea, which introduces a harsh chloride environment. The ingress of chlorides into the concrete will be a catalyst for corrosion of reinforcing steel. In addition to the proclivity towards corrosion of reinforcing steel, chemical attack may occur such as in the form of alkali-aggregate reactivity. The alkali-aggregate reactivity is subcategorized into two forms, namely: alkali-silica reaction or alkali-carbonate reaction [30]. Environmentally induced degradation may be stunted through the use of coatings consisting of paints, mortars, liquefied rubbers, and resins' [31]. Nonetheless, improper selection of coatings or exposure to extreme conditions may still lead to peeling, blistering, or flaking.

2.2. Construction induced problems

Many concrete related problems start at the construction phase and include honeycombing, internal voids, and cracking oriented perpendicular and/or parallel to the concrete surface. The thick members of NCS are prone to excessive temperature differences between concrete core and surface areas, which may result in delayed ettringite formation, potentially leading to map cracking. Map cracking is a series of interconnected cracks that encompass large concrete surface areas, and is especially significant for mass concrete found in NCS.

Heavy reinforcement and use of prestressed tendons are also problematic for NCS. Many nuclear concrete structures are reinforced with post-tension tendons that extend both horizontally (hoop tendons) and vertically. The tendons are designed to keep concrete in compression which requires the tendons to endure very high stresses. This may result in tendon stretching and subsequent concrete cracking and tendon rupture. Debonding between the concrete and steel may occur between composite materials due to shrinkage or external loading. The areas of debonding are more susceptible to intrusion of contaminants, which leads to degradation.

2.3. Steel related problems

In recent years, various steel alternatives have been utilized to reinforce concrete. However, steel, either in form of deformed bar steel or high-tension tendons, remains the material of choice to provide greater tensile capacity for concrete. Unfortunately, the use of steel provides additional degradation mechanisms which induce a range of issues, from aesthetic considerations to structural failure. The most common degradation issue associated with steel is corrosion, as described above. ACI (American Concrete Institute) defines corrosion as the destruction of metal by chemical, electrochemical, or electrolytic reaction within its environment [29]. Corrosion can be initiated through several means: chlorides found in the concrete, carbonation, stray current, and, in some cases, galvanic induction through localized dissimilar metals [32-34]. At best, if corrosion were to occur then it will eventually protrude through pores and joints to the surface and be an eye-sore. It is usually reddish, brown in colour and may protrude as hardened flakes or a gel-like by product.

More importantly, corrosion of a high-stressed tendon could cause sudden collapse of a structure. During the chemical reaction, corrosion products replace the consumed steel with a larger volume of corroded material. The increased volume produces additional stress on the surrounding concrete, and significantly cracks and weakens the concrete. Traditional testing of corrosion involves electrochemical techniques that are used to indicate potential rate of corrosion. This does not however provide evidence of the extent of corrosion that has previously occurred. One research possibility is to investigate the ability of non-destructive testing techniques, to determine the extent of corrosion.

Additional degradation mechanisms associated with steel reinforcement within concrete is creep, lack of bond (during or after construction), fatigue, and rupture [35]. These are all related to mechanical relationship between the reinforcing steel and concrete when subjected to load. They are heavily affected by design and construction practices. For instance, if a tendon anchor has insufficient cover then the anchor will be overcome by the stress transferred from the tendon and will fail violently.

Alternatively, concrete is susceptible to creep when subjected to long-term loading. This may occur in case of post-tensioned and prestressed structures, and also in case of regularly reinforced concrete structures.

2.4. Extreme operation conditions

According to ACI 349.3R [36], neutron irradiation affects the crystalline structure of the cement matrix and the mechanical properties of reinforcing steel such that the ductility of the steel is reduced [37]. It is reported that radiation exposures > 10^{10} rads of gamma can result in a significant increase in concrete volume and reduction in strength [38].

For nuclear power plants, steam is generated by harnessing the extreme heat developed through nuclear reactions between radioactive materials. Temperatures reach hundreds of degrees Fahrenheit (> 315 °C). These high thermal loads desiccate and reduce the elasticity of concrete. Additionally, prolonged exposure to high temperatures may cause loss of ductility to post-tension tendons found in NCS. Leak Rate (LR) tests are typically required for verification of the pressure or leakage limited boundaries of nuclear containment structures [39].

3. Mechanics associated with nuclear structures

The initiation of the damages associated with nuclear concrete described previously is mostly characterized as material damage and not considered as structural damage. Hence, classical mechanical descriptions of material damages such as fracture, fatigue, and corrosion, can be applied. Mechanical descriptions of material damages are based on the constitutive behaviours of materials as described in Table 2. Some of the constitutive models may be rate dependent. The constitutive models rely primarily on the assumption of a continuum and the material properties such as elastic constants can be described as spring elements and dashpots. Damage parameters associated with constitutive models require measurements such as deformation rate (in case of plastic or inelastic deformations), stress fields and crack tip opening and fracture process zone (in case of fracture), etc. [40, 41].

Pre-existing defects that can help qualify damage at a later stage may also be essential, e.g. the extent of micro-cracking in concrete and initial anisotropy of material. In damage mechanics, these are described as internal variables. The damage affects the constitutive behaviour, and the changes in internal variables become an essential requirement for the sensors. For example, [40] defines the extent of microcracks within a material as an internal damage variable, calling it microcrack density distribution. Rules of evolution must be defined to describe formation and progressing of pre-existing damage; these can be described as constitutive damage laws. The correlation between constitutive material constants and damage variables and traditional sensor measurements, such as strain gauge and displacement gauge measurements, has been well defined. However, new sensing techniques described in the following text have not yet been defined.

4. Embedded and/or topical sensors

Technologies utilizing ETS include sensors made up of carbon nanotubes [42], nano-oxides, piezoelectric ceramics, fibre optics [43], etc. The following sections introduce some specific ETS technologies. It is important to identify the stage of development of a sensor in order to ensure proper application for concrete. Table 3 provides a summary of sensor technology that may be used for various defects and degradation mechanisms for reinforced concrete highlighted in Table 1. Table 3 indicates sensor type, resulting measurement, and characteristics. The sensors identified herein may be topical or embedded. Interrogation of these sensors may require contact or remote detectors. Also, it can be observed that the sensor technology indicated here requires electrical connectivity; therefore, it is very important to consider using components that are durable when embedded in harsh NCS environments. These sensors can indicate material strength during and after curing and structural strain. The range and sensitivity levels found in Table 3 are not intended to indicate exhaustive information of existing sensor technology. It is intended to provide general reference of these levels. Figure 3 provides a basic rubric of NCS characterization based on likely concrete defects and available ETS technologies. The following sections detail the different types of sensors that may be utilized in/on NCSs.

Table 2. Mechanical behaviour characterizing material damage

Linear Elastic	Hypoelastic	Hyperelastic	Viscoelastic	Plastic
Isotropic	Nonlinear	Large strain	Time dependent	Irreversible
Non-isotropic	Reversible	Rubber elastic	Temperature	Rate dependent
Orthotropic	Isotropic/Non-isotropic	Stretch		

Table 3. Comparison of different ETS technologies

Sensor type	Measurement	Range/sensitivity	Application issues
Fibre optics	Temperature, strain, corrosion, or stress	Up to several thousand microns, >300 °C [43-47]	Heavy reinforcement environment will restrict placement; sensitive to mechanical vibration during concrete placement
Carbon nanotube composite coating	Strain	Unknown on actual structures [19]	Surface coatings are unable to detecting embedded issues.
Piezoresistive fibres	Stress	0.05 % strain [22-23]	Connectors are required.
Piezoelectric acoustic emissions	Acoustic emissions energy, distance	1.5 mJ, distance 12 cm [53-54]	Detection depth is questionable; useable frequency range is questionable.
Skin-type sensor	Temperature	do 1200 °C [56]	Surface indication only.
Polymer modified self-sensing concrete	Strain	Potentially unlimited [58]	Radioactivity tolerance; heat tolerance; reinforcing steel compatibility; accuracy of damaged concrete is unknown.
Carbon nanotube modified concrete	Strain	Potentially unlimited [60]	Durability
Electrochemical	Electron flow and chemical changes	[62]	Corrosion of reinforcing steel and internal chemistry of concrete; accuracy due to variations in concrete and environment.
Coaxial cables	Strain and electron flow	Varied [65]	Corrosion and cracking.

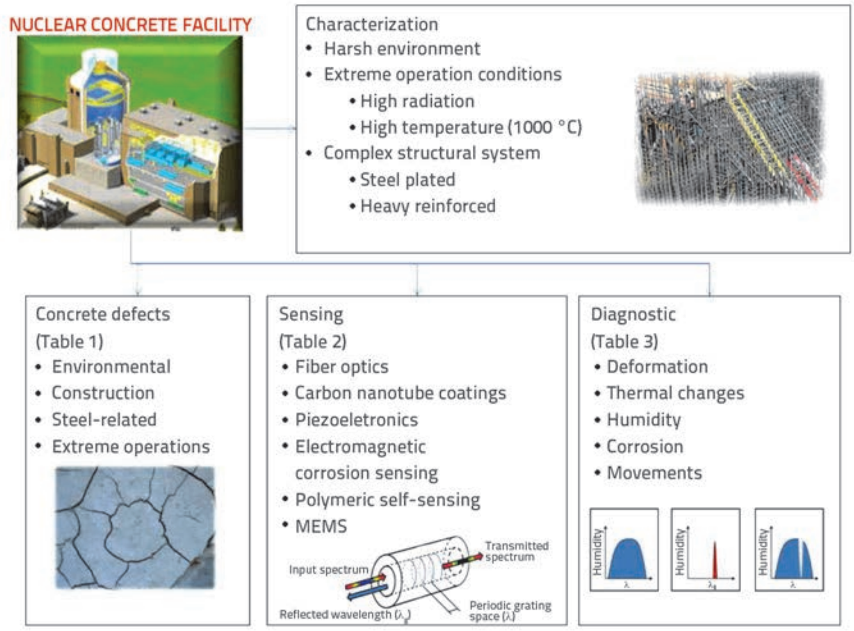

Figure 3. Schematic of sensing applications for NCS evaluation

4.1. Fibre optics

Fibre optic (FO) sensors are popular sensors for structural monitoring because of their increased reliability, autonomy, ease of installation, and increased measurement quality [43]. Fibre optics may be used as a single strand or in a bundle; additionally, fibres may be classified as short gauge (discrete) or long gauge (distributed). They have good sensitivity and resolution with the ability to measure in the level of microns and are resilient to relatively high temperatures [44]. However, FO sensors with this high-temperature resilience may require expensive materials such as gold. Often, FO sensors are used to provide a measurement across 20 mm or less. Distributed FO sensors are used to cover distances up to kilometres [45]. Depending on the FO sensor, they can be used to indicate a variety of physical parameters: temperature, pressure, strain, displacement, rotation, magnetic / electric field, and corrosion. They measure through different means and are classified as intensity-based fibre optic sensors, interference-based point sensors, polarization-based sensors, and Bragg Grating-based fibre optic strain gauges [46]. In [47], the authors measured strain ranging "from 1,000 to 3,000 με for temperatures as low as -253 °C."

Fibre Optic sensors are especially ideal for NCS since they are not influenced by electric saturation of the surrounding environment and will not be affected by chemical attacks because they are essentially chemically inert. However, the placement and installation of FO sensors can be a challenge for existing NCS in areas where the concrete is not directly accessible.

4.2. Carbon nanotube composite coatings and modified concrete

Carbon nanotube composite coatings consist of very small tubes of bonded carbon atoms. The bond between adjacent carbon atoms is covalent (sharing of electrons between atoms) and the tubes may be open-end or closed-end. The atoms are predominantly linked in a hexagonal shape with the closed-end tubes having a pentagonal shape near the ends [48]. Single cylinder tubes are labelled as SWCNT (single-walled carbon nanotubes); however, multiple tubes may be concentrically placed within each other and are labelled as MWCNT (multi-walled carbon nanotubes). The diameters are in the nanometre range with lengths of up to several centimetres. Carbon nanotubes have the "highest strength-to-weight ratio" of any known material with a total strength reported to be up to 150 GPa [48]. As such, they have reinforcing functions for the material in which they are embedded. The sensitivity of carbon nanotubes is reported to vary depending on the application. Carbon nanotubes can be used as a functional filler material of a coating that can then be applied topically. As a coating, it can be used to indicate the strain occurring in the substrate on which the coating is applied. This occurs because the electronic structure of the carbon nanotubes changes when the material stretches and compresses. In [20], the authors indicate that SWCNT using fluorescence spectra will "reveal axial strains below 0.1 %" which is sufficient for large-scale objects. A limitation of application of this highly functional coating is systemic to all coating systems, which is the sufficiency of the bond between the coating and the substrate. Debonding characterized as peeling, scaling, or osmotic blistering, will limit the benefit of the coating impregnated with carbon nanotubes.

Coatings containing carbon nanotubes were previously written about as a means whereby strain could be passively measured using changes in luminescence according to strain of the coating. Similar to this and the piezoelectric nanoparticles, carbon nanotubes may be dispersed within a concrete mix which will allow strain to be measured. One of the benefits of carbon nanotubes is that it has superior piezoelectric properties over traditional piezo-ceramic materials [42]. Historically, the biggest challenge with the use of carbon nanotubes is their tendency to coagulate, which prevents them from fully dispersing within a binding matrix. Anti-covalent techniques are reported to degrade mechanical properties of the carbon nanotubes yet other techniques have shown to successfully provide long-term suspension and dispersion. Carbon nanotubes are expensive and a business case would need to be established for applying carbon nanotubes throughout an entire NCS. Therefore, the application of carbon nanotubes would likely be through discretely patching strategically placed areas of the modified concrete mixture.

4.3. Piezoresistive fibres

Fibre polymers were first used to reinforce concrete in the 1950s with more regular uses beginning in the 1980s [49]. Embedding fibre materials having piezoelectric properties into concrete will give it additional reinforcement (increasing its strength and stiffening) and improve its self-sensing functionality. Besides polymers, these materials can consist of graphite, carbon, and steel [49]. The fibres are randomly oriented when used in bulk manner (i.e. the fibres are expected to be fully dispersed in the concrete). The random orientation of the fibres allows ubiquitous and isotropic strengthening and stiffening of the concrete, while the use of piezoresistive material allows achievement of self-sensing properties [50]. In [51], Wang and Chung suggest that piezoresistive fibres may be used as a coating composite with an epoxy as binder. When used in this manner the orientation of the fibres is in the plane of the thin coating. They may also be used as a sensor system with other piezoresistive materials where six-mm long fibres and copper gauze are embedded in a cement-based material [52]. Given the varying materials that can be used as piezoresistive fibres and the high temperatures found within areas of NCSs, thermal conductivity of the bulk material should be considered. Heat transfer through the member may have affect (positive or negative) on the exhaust of heat in case of an accident. Or, given the larger nature of these fibres, expansion of the material within the concrete may need to be offset by induced air-entraining admixtures as part of the concrete mixture design.

4.4. Piezoelectric acoustic emissions

Techniques involving acoustic emission sensors consist of measuring the elastic waves produced during a mechanical event – strain or fracture – with relatively low sensitivity [53-55]. Though these sensors are passive, a network of these sensors can indicate the location of an "event" through triangulation. A traditional AE sensor consists of piezoelectric ceramic or crystal; however, composite sensors are also used. In [54], the authors suggest that piezoelectric material is not compatible with the concrete in which it is embedded and that the use of composite sensors is superior. The sensor to which they refer is a composite consisting of piezoelectric rods embedded in cement. The cement phase of the composite provides low acoustic impedance and dielectric constant yet the embedded ceramic offers the traditional piezoelectric effects found in like-kind smart materials. Acoustic emission sensors often have a narrow band of frequency to be measured which sometimes doesn"t correlate with the frequency of the "mechanical event" of the concrete and is difficult to distinguish between vibrations occurring from the normal operation of the plant.

4.5. Skin-type sensor

Metal oxides may be used in a solid state as a thermistor because of the Arrhenius relationship between temperature and electrical conductivity. In previous experimentation, these oxides are mixed and then screen printed onto a substrate where they are sintered at a temperature up to a little more than 1200 °C [56]. The sintering temperature and oxide composition affect the electrical properties of the sensor. None the less, the embedment of these thermistors can provide a valuable indication of concrete core and surface temperatures to determine the likelihood of delayed ettringite formation or excessive temperature differentials. Similarly, sensors may be applied in a thin patch-like manner [57].

4.6. Self-sensing concrete

Traditionally, strain is measured through the adhesion of a strain gage on the surface of a material. Self-sensing concrete allows embedment of nanoparticles with piezoelectric and/or electrostrictive properties to be dispersed throughout a concrete material [58]. The nanoparticles consist of various materials that include piezoelectric crystals, piezoelectric ceramic, composite of ceramic and polymer piezoelectric, graphite, carbon, and steel [59]. This material may be used as part of a concrete mixture at proportions on the order of three to ten percent [22] of the cement content. Because of its ubiquitous nature within the concrete component, the strain range and sensitivity would theoretically be bound only by the limitation of the host material, in this case concrete. Once cracked to prevent connectivity, there would be a loss or, at best, reduction of strain sensitivity and accuracy [60]. As the hardened concrete is strained the electrical properties (conductivity/resistivity) of the concrete can be measured to indicate the level and type of strain. For NCS with heavy congestion of reinforcing steel and the need to indicate strain through changes in electrical conductivity, placement of the electrodes to interrogate the conductivity of the bulk material will have small tolerances. The measuring mechanism is not only sensitive to strain but also to the conductivity of the NCS steel which poses difficulty in indicating the disparate causes of changes in electrical resistance.

4.7. Electrochemical sensors

As discussed above, the corrosion of reinforcing steel is an electrochemical process [61]. The process requires development of a corrosion cell, which includes an anodic area (where electrons are lost), cathodic area (where electrons are gained), metallic path (for concrete this is usually reinforcing steel), and an electrolytic path (concrete matrix lacking passivity) [62, 63]. Sensors and sensing techniques used to identify corrosion may be topical or embedded and can include varying techniques called potentiostatic linear polarization resistance, galvanostatic pulse polarization, potentiodynamic cyclic polarization, galvanostatic polarization, and electrochemical impedance spectroscopy [64]. Depending on the technique, sensors require direct access to the reinforcing steel being measured or, at a minimum, electrical connectivity to the steel. The interpretation of electrochemical sensors is often difficult and care should be taken when performing analysis of test results [64]. Traditional electrochemical sensors are not developed to experience the high temperature environment that may be found in parts of nuclear power plants; so, the sensors used in this manner should be upfitted to be more robust or strategically placed away from high-temperature zones.

4.8. Coaxial cables

Coaxial cables are used with varying material configurations and they usually consist of two layers of conductive material, one of which is spirally bound; and, they both sandwich another dielectric material [65]. The spiral nature of a portion of the cable is what sets it apart from most coaxial cables and is what helps provide its ability to become a sensor rather than a simpler transmitter of signal. They have been utilized for crack detection and corrosion monitoring on a variety of structural members [66]. For crack detection, its primary mode of indication is electrical time-domain reflectometry (ETDR), which provides indication of strain [67]. The strain is indicated because of discontinuities along the cable as portions of the spiral bound cable are stretched apart. It has also been placed near reinforcing steel found in concrete where corrosion was induced. The cable undergoes the same corrosion as the reinforcing steel and the pitting stifles the connectivity of the cable and indicates the corrosion. It should be noted that sensitivity and resolution of the sensor is a function of cable length. The cable lengths for most NCS applications is expected to be very long and stunt sensitivity and resolution. Additionally, there is no indication that the pitting location of the coaxial cables can be identified, only that signal disruption is present. However, since corrosion of the concrete reinforcing steel causes a large amount of damage to structures, further development of this technology would be very rewarding.

5. Technology readiness and discussion

Table 3 indicates different sensor types, resulting measurement, and characteristics. The sensors can be topical or embedded. The interrogation of these sensors may require contact or remote detectors. Also, it can be observed that the indicated sensor technology requires electrical connectivity. It is therefore very important to consider using components that are durable when embedded in harsh NCS environments. These sensors can indicate material strength during and after curing and structural strain. The range and sensitivity levels found in Table 3 are not intended to indicate exhaustive information of existing sensor technology but, instead, provide general reference of these levels. Figure 3 provides a basic rubric of NCS characterization, likely concrete defects, and available ETS technologies.

Several of the sensors are made up of robust materials that can be discretely placed in concrete and act as functional fillers that are dispersed ubiquitously within the concrete. However, as previously noted, some of these sensors are still limited to being interrogated only by connecting through cables. As such, sensors and their associated connections must be strategically placed in areas that are distant or shielded from high temperatures and radiation load. Fortunately, areas of high radiation are limited to a few distinct areas of the NCS; and, there are many areas and large amounts of concrete used for NCS that do not experience the harsh loading and temperature conditions. Areas of high radiation dose include the pedestal for the reactor pressure vessel, shield containment walls, and dry cask storage containers [68].

6. Conclusion

Due to challenging characteristics including mass materials, extensive steel reinforcements, potential exposures to high temperature and radiation, the application of NDT sensing for NCS extends beyond typical NDE sensor capabilities and innovative sensing technologies are needed. This paper brings awareness of the recent embedded and/or topical sensors (ETS) technologies for nuclear industry. Identified ETS technologies include fibre optics, carbon nanotube composite coatings, piezoresistive fibres, piezoelectric acoustic emissions, skin-type sensors, self-sensing modified concrete, electrochemical sensors, and coaxial cables. The topological advantages of these sensors stem from the fact that they are capable of being embedded or surficial, periodically or continuously monitored, and physically accessible or remotely monitored. However, for actual NCS applications, additional considerations, including the need that signal interrogation methods should be robust for harsh environment, should be taken into account. Nonetheless, many ETS technologies have high potential for unconventional applications such as for NCS systems.

Acknowledgement

The views, opinions, and findings reflected in this publication are the responsibility of the authors only and do not represent official policy or position of their affiliations. The authors would like to acknowledge the American Concrete Institute in awarding the 2016 ACI Barbara S. and W. Calvin McCall Carolina's Fellowship to an author of this work.

REFERENCES

[1] Naus, D.J.: Report No. ORNL/TM-2007/191, Inspection of Nuclear Power Plant Structures – Overview of Methods and Related Applications. Oak Ridge (TN); 2007.

[2] Power Reactor Information System (PRIS) [Internet]: Geneva (CH): International Atomic Energy Agency (IAEA). [cited July 2018]. Available from: https://www.iaea.org/pris/.

[3] ACI Committee 228: ACI 228.2R, Report on Nondestructive Test Methods for Evaluation of Concrete in Structures. Farmington Hills (MI): American Concrete Institute; 2013.

[4] Scott, D.: Internal Inspection of Reinforced Concrete for Nuclear Structures Using Shear Wave Tomography. Energy Convers and Manag., 74 (2013), pp. 582-586, https://doi.org/10.1016/j.enconman.2013.01.041

[5] Muenow, R.A.: Field Proven NDT Methods for Evaluation of Damage and Repair of Nuclear Facilities. Nuclear Plant Journal, 6 (1988), pp. 81-82, 89.

[6] Kim, Kim, Seo, et al.: Feasibility Study of the IE-SASW Method for Nondestructive Evaluation of Containment Building Structures in Nuclear Power Plants. Nucl Engin and Des, 219 (2002), pp. 97-110, https://doi.org/10.1016/S0029-5493(02)00234-0

[7] Ghasr, T., LePape, Y., Scott, D.B., et al.: Holographical Microwave Imaging of Corroded Steel Bars in Concrete. ACI Mater J.,112 (2015) 1, pp. 115-124.

[8] Kee, Fernandez-Gomez, Zhu.: Evaluating surface-breakage cracks in concrete using air-coupled sensors. ACI Mater J., 108 (2011) 5, pp. 558-565.

[9] Bhardwaj, M.C.: Noncontact Ultrasonic Testing and Analysis of Materials. In: Schwartz M, editor. Smart Materials. Boca Raton (FL): CRC Press; 2009: 9.3.

[10] Clayton, D., Hileman, M.: Light Water Reactor Sustainability Nondestructive Evaluation for Concrete Research and Development Roadmap. Oak Ridge (TN): Oak Ridge National Laboratory; 2012, https://doi.org/10.2172/1051451

[11] La Plaine Cedex Association de Normalisation (AFNOR). Methodology for Qualification on Non-Destructive Tests. La Plaine Cedex (FR): AFNOR; 2005.

[12] Non-Destructive Tests on Hardened Concrete. Geneva (CH): International Standards Organization (ISO); 2004.

[13] Technical Committee B/517. Concrete - Determination of Ultrasonic Pulse Velocity. Brussels (BE): British Standards Institute (BSI); 2004.

[14] Nuclear Energy Agency (NEA). Electrochemical Techniques to Detect Corrosion in Concrete Structures in Nuclear Installations. Vienna (Austria): NEA; 2002.

[15] Federal Highway Administration (FHWA). Prediction of Chloride Penetration in Concrete. McLean (VA): FHWA; 2001.

[16] ASTM Committee C09. ASTM C597-16 Standard Test Method for Pulse Velocity Through Concrete. West Conshohocken (PA): ASTM International; 2016.

[17] ASTM Committee C09. ASTM C1740-16 Standard Practice for Evaluation the Condition of Concrete Plates Using Impulse-Response Method. West Conshohocken (PA): ASTM International; 2016.

[18] Sreekala, R., Muthamani, K.: Structural Applications of Smart Materials. In: Schwartz M, editor. Smart Materials. Boca Raton (FL): CRC Press; 2009. 4.

[19] Withey, P.A., Vemuru, V.S., Bachilo, S.M., Nagarajaiah, S., Weisman, R.B.: Strain Paint: Noncontact Strain Measurement Using Single-Walled Carbon Nanotube Composite Coatings. Nano Lett, Am Chem Soc., 12 (2012), pp. 3497-3500, https://doi.org/10.1021/nl301008m

[20] Li, H., Xiao, H., Ou, J.: A Study on Mechanical and Pressure-Sensitive Properties of Cement Mortar with Nanophase Materials. Cem and Concr Res., 34 (2004), pp. 435-438, https://doi.org/10.1016/j.cemconres.2003.08.025

[21] Kim, D.J., Lee, C., Chang, H., et al.: Embedded Piezoelectric Sensor-Based Real-Time Strength Monitoring during Curing Process of Concrete. SPIE 7981, Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems. April 14, 2011; San Diego, CA.

[22] Shen, B., Yang, X., Li, Z.: A Cement-Based Piezoelectric Sensor for Civil Engineering Structure. Materials and Structures, (2006), pp. 1-5.

[23] Suchanek, W.L., Riman, R.E.: Intelligent Synthesis of Smart Ceramic Materials. In: Schwartz M, editor. Smart Materials. Boca Raton (FL): CRC Press; 2009. 2.

[24] Yang, M., Dai, J.: Review on Optical Fibre Sensors with Sensitive Thin Films. Photonic Sensors, 2 (2012) 1, pp. 14-28.

[25] Abu-Yosef, A.E., Pasupathy, P., Wood, S.L., et al.: Detection of Multiple Corrosion Thresholds in Reinforced Concrete Structures Using Passive Sensors. Smart Structures, In Gyekenyesi AL, editor. SPIE 8347, Smart Structures. SPIE. April 5, 2012, https://doi.org/10.1117/12.915164

[26] Yao, Y., Tung, S.T.E., Glisic, B.: Crack Detection and Characterization Techniques - An Overview. Struct. Control and Health Monitoring, 21 (2014), pp. 1387-1413, https://doi.org/10.1002/stc.1655

[27] Renshaw, J., Guimaraes, M., Scott, D.B.: Thermographic Inspection of Massive Concrete Structures. Proceedings of the 2013 QNDE Conference, (2013), pp. 978-984.

[28] ACI Committee 201: ACI 201.1R-08, Guide for Conducting a Visual Inspection of Concrete in Service. Farmington Hills (MI): American Concrete Institute; 2008.

[29] American Concrete Institute (ACI): Concrete Terminology, ACI CT-13. Farmington Hills (MI): ACI; 2013.

[30] Institution of Structural Engineers (ISE). Structural Effects of Alkali-Silica Reaction. London (UK): ISE, SETO Ltd.; 1992.

[31] ACI Committee 515: ACI 515.2R-13 Guide to Selecting Protective Treatments for Concrete. Farmington Hills (MI): American Concrete Institute; 2013.

[32] ACI Committee 222: ACI 222R-10, Protection of Metals in Concrete Against Corrosion (Reapproved 2010). Farmington Hills (MI): American Concrete Institute; 2010.

[33] NACE TG 356: Stray-Current Induced Corrosion in Reinforced and Prestressed Concrete Structures. Houston (TX): NACE International; 2010.

[34] NACE TG 400:. SP0112, Corrosion Management of Atmospherically Exposed Reinforced Concrete Structures. Houston (TX): NACE International; 2017.

[35] Mindess, S., Young, J.F., Darwin, D.: Concrete. Upper Saddle River (NJ): Pearson Education, Inc.; 2004.

[36] ACI Committee 349: ACI 349.3R-18, Report on Evaluation and Repair of Existing Nuclear Safety-Related Concrete Structures. Farmington Hills (MI): American Concrete Institute; 2018.

[37] William, K., Xi, Y., Naus, D., Graves, L.H.: Review of the Effects of Radiation on Microstructure and Properties of Concretes Used in Nuclear Power Plants. Washington DC (USA): US Nuclear Regulatory Commission (USNRC); 2013.

[38] Fillmore, D.L.: Report INEEL/EXT-04-02319, Literature Review of the Effects of Radiation and Temperature on the Aging of Concrete. Idaho Falls (ID): NEEL; 2004.

[39] U.S. Nuclear Regulatory Commission (USNRC): U.S. Nuclear Regulatory Commission Regulations: Title 10, Code of Federal Regulations. Washington, DC (USA): USNRC; 2014.

[40] Barbero, E.J., De Vivo, L.: A Constitutive Model for Elastic Damage in Fibre-Reinforced PMC Laminae. International Journal of Damage Mechanics SAGE, 10 (2001), pp. 73-93, https://doi.org/10.1106/6PQ6-31JW-F69K-74LU

[41] Budiansky, B., O'connell, R.J.: Elastic Moduli of a Cracked Solid. International Journal of Solid Structures, 12 (1975) 2, pp. 1281-1297.

[42] Pammi, S., Brown, C., Datta, S., et al.: Concepts for Smart Nanocomposite Materials. Smart Materials, Structures, and Systems, SPIE 5062, pp. 629-636, 2003.

[43] Fallon, R.W., Zhang, L., Everall, L.A., et al.: All-Fibre Optical Sensing System: BG Sensor Interrogated by Long-Period Grating. Measurement Science Technology, 9 (1998) 12, pp. 1969-1973.

[44] Glisic, B.: Fibre Optic Methods for Structural Health Monitoring. West Sussex (UK): John Wiley & Sons Ltd., 2007, https://doi.org/10.1002/9780470517819

[45] Mrad, N., Li, H.: Fibre Optic Systems: Optical Fibre Sensor Technology. In: Schwartz M, editor. Smart Materials. Boca Raton (FL): CRC Press; 2009. 14.1.

[46] Huston D. Structural Sensing, Health Monitoring, and Performance Evaluation. Boca Raton (FL): CRC Press / Taylor and Francis Group, LLC: 2011.

[47] Nunes, Olivieri, Kato, Luiz, Braga: FBG sensor multiplexing system based on the TDM and fixed filters approach. Science Direct, Sensor and Actuators, 138 (2007), pp. 341-349, https://doi.org/10.1016/j.sna.2007.05.009

[48] Wille, K., Loh, K.J.: Nanoengineering Ultra-High-Performance Concrete with Multiwalled Carbon Nanotubes. Transportation Research Records, 2142 (2010), pp. 119-126, https://doi.org/10.3141/2142-18

[49] ACI Committee 440: ACI 440R-07, Report on Fibre Reinforced Polymer (FRP) Reinforcement for Concrete Structures. Farmington Hills (MI): American Concrete Institute; 2007.

[50] Han, B., Yu, X., Ou, J.: Self-Sensing Concrete in Smart Structures. New York (NY): Elsevier Inc.: 2014.

[51] Wang, X., Chung, D.D.L.: Short Carbon Fibre Reinforced Epoxy Coating as a Piezoresistive Strain Sensor for Cement Mortar. Science Direct, Sensors and Actuators, 71 (1998), pp. 208-212, https://doi.org/10.1016/S0924-4247(98)00187-3

[52] Han, B., Guan, X., Ou, J.: Electrode Design, Measuring Method and Data Acquisition System of Carbon Fibre Cement Paste Piezoresistive Sensors. Science Direct, Sensors and Actuators, 135 (2006), pp. 360-369, https://doi.org/10.1016/j.sna.2006.08.003

[53] Sakamoto, W.K., Higuti, R.T., Tiago, M.M.: Piezoelectric Composite Film for Acoustic Emission Detection. Ultrasonics Symp, IEEE, pp. 1487-1490, 2009, https://doi.org/10.1109/ULTSYM.2009.5441422

[54] Marin-Franch, P., Martin, T., Tunnicliffe, D.L., et al.: PTCa/PEKK Piezo- Composites for Acoustic Emission Detection. Science Direct, Sens and Actuators, 99 (2002) 3, pp. 236-243.

[55] Qin, Peng, Ren, et al.: Application of cement-based piezoelectric composites in acoustic emission detection for concrete. In: Jinsong L, Anand K, Asundi, et al., editors. Proceedings of SPIE, Second International Conference on Smart Materials and Nanotechnology in Engineering; 7493 (2009), pp. 1-9.

[56] Park, K., Bang, D.Y.: Electrical Properties of Ni-Mn-Co-(Fe) Oxide Thick-Film NTC Thermistors Prepared by Screen Printing. J. Mater Sci Mater Electronics, 14 (2003), pp. 81-87, https://doi.org/10.1023/A:1021900618988

[57] Zhang: Piezoelectric Paint Sensor for Real-time Structural Health Monitoring. In: Tomizuka M, editors. Proceedings of SPIE, Smart Structures and Materials, 5765 (2005), pp. 1095-1103.

[58] Agari, Y.: Functionally Graded Polymer Blend. In: Schwartz M, editor. Smart Materials. Boca Raton (FL): CRC Press, 2009. 3.

[59] Kholkin, A.K., Kiselev, D.A., Kholkine, L.A., et al.: Piezoelectric and Electrostrictive Ceramics Transducers and Actuators. In: Schwartz M, editor. Smart Materials. Boca Raton (FL): CRC Press; 2009. 9.1.

[60] Pacheco-Torgal, F., Gonzalez, J., Jalali, S.: Sustainable Monitoring of Concrete Structures: Strength and Durability Performance of Polymer-Modified Concrete. International J of Sustainable Energy, pp. 1-5, 2011.

[61] Muralidharan, S., Ha, T.H., Bae, J.H., et al.: A Promising Potential Embeddable Sensor for Corrosion Monitoring Application in Concrete Structures. Measurement, 40 (2006), pp. 600-606, https://doi.org/10.1016/j.measurement.2006.09.008

[62] Vennesland, Ø., Raupach, M., Andrade, C.: RILEM TC 154-EMC, Electrochemical Techniques for Measuring Corrosion in Concrete – Measurements with Embedded Probes. Materials and Structures, 40 (2007), pp. 745-758, https://doi.org/10.1617/s11527-006-9219-4

[63] Poursaee, A., Weiss, W.J.: An Automated Electrical Monitoring System (AEMS) to Assess Property Development in Concrete. Automation in Constr., 19 (2009), pp. 485-490, https://doi.org/10.1016/j.autcon.2009.12.016

[64] Andrade, C., Sanchez, J., Castillo, A., et al.: Interpretation of Corrosion Monitoring from Embedded Sensors. In: 15th International Conference on Structural Health Monitoring of Intelligent Infrastructure, SHMII-5; pp. 1-7, 2011.

[65] Muchaidze, I., Pommenrenke, D., Chen, G.: Steel Reinforcement Corrosion Detection with Coaxial Cable Sensors. Tomizuka M, Yun CB, Giurgiutiu V, et al., editors. Proceedings of SPIE, Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems (79811L-1), 7981 (2011), https://doi.org/10.1117/12.879770

[66] Greene, G.G., Belarbi, A., Chen, G., et al.: Distributed Coaxial Cable Crack Sensors for Crack Mapping in RC. Tomizuka M, editor. Proceedings of SPIE, Smart Structures and Materials, Bellingham, 5765 (2005), pp. 407-418, https://doi.org/10.1117/12.600143

[67] Sun, S., Pommerenke, D., Drewniak, J.L., et al.: Signal Loss, Spatial Resolution, and Sensitivity of Long Coaxial Crack Sensors. Shih-Chi Liu, editor. Proceedings of SPIE, Smart Structures and Sensors, 5391 (2012), pp. 786-797, https://doi.org/10.1117/12.540033

[68] Electric Power Research Institute (EPRI): 1023006, Advanced Nuclear Technology: Embedded Sensors in Concrete. Palo Alto (CA): EPRI, 2011.