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Interim Report on Concrete Degradation Mechanisms and Online Monitoring Techniques

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Interim Report on Concrete Degradation Mechanisms and Online Monitoring Techniques

Sankaran Mahadevan, Vivek Agarwal, Kyle Neal, David Kosson and Douglas Adams

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Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

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ABSTRACT

The existing nuclear power plants in the United States have initial operating licenses of 40 years, though most of these plants have applied for and received license extensions. As plant structures, systems, and components age, their useful life—considering both structural integrity and performance—is reduced as a result of deterioration of the materials.

The research on online monitoring of concrete structures conducted under the Advanced Instrumentation, Information, and Control Systems Technologies Pathway of the Light Water Reactor Sustainability Program at Idaho National Laboratory will develop and demonstrate concrete structures health monitoring capabilities. Assessment and management of aging concrete structures in nuclear plants require a more systematic approach than simple reliance on existing code margins of safety. Therefore, structural health monitoring is required to produce actionable information regarding structural integrity that supports operational and maintenance decisions. Through this research project, several national laboratories and Vanderbilt University propose to develop a framework of research activities for the health monitoring of nuclear power plant concrete structures that includes the integration of four elements—damage modeling, monitoring, data analytics, and uncertainty quantification. This report briefly discusses available techniques and ongoing challenges in each of the four elements of the proposed framework with emphasis on degradation mechanisms and online monitoring techniques.

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EXECUTIVE SUMMARY

The U.S. Department of Energy's Office of Nuclear Energy funds the Light Water Reactor Sustainability (LWRS) Program to develop the scientific basis for extending the operation of commercial light water reactors beyond the current 60-year license period. The LWRS Program has three pathways. This project integrates the research activities performed by the Advanced Instrumentation, Information, and Control Systems Technologies and Material Aging and Degradation Pathways.

A unique challenge to light water reactor sustainability concerns the aging of passive structures (materials). As nuclear power plants (NPPs) continue to age and their structures degrade, it is important to understand the degradation condition and mechanisms, enhance monitoring and predictive data analytics techniques, and be able to quantify the uncertainty introduced at various stages. This can be achieved by developing a structural health monitoring (SHM) framework to assess and manage aging structures. The SHM research needs to produce actionable information regarding structural integrity that supports operational and maintenance decisions. This critical information is individualized for a given structure and its performance objectives.

Among different materials of interest, concrete is investigated in this research project. Reinforced concrete structures found in all NPPs can be grouped into four categories: primary containment, containment internal structures, secondary containments / reactor buildings, and spent fuel pool and cooling towers. These concrete structures are affected by a variety of chemical, physical, mechanical, and irradiation degradation. The age-related degradation of concrete results in continuing microstructural changes (slow hydration, crystallization of amorphous constituents, reactions between cement paste and aggregates, etc.). Changes over long periods of time must be measured, monitored, and analyzed to best support long-term operation and maintenance decisions.

Through the LWRS Program, several national laboratories, and Vanderbilt University have begun to develop a framework of research activities for the health monitoring of NPP concrete structures. A systematic approach proposed to assess and manage aging concrete structures requires an integrated framework that includes the following four elements:

- Damage modeling
- Monitoring
- Big data analytics
- Uncertainty quantification.

Based on the initial review of literature on different concrete degradation mechanisms, the alkali-silica reaction (ASR) has been identified as the degradation mechanism for initial investigation and damage modeling. The research will investigate monitoring of chemical-mechanical coupled degradation in concrete via full-field imaging techniques (thermal, optical, and acoustic). Possible full-field techniques include infrared imaging, digital image correlation, and acoustic. Effective combinations of full-field techniques need to be identified for different types of concrete structures. Dynamic operating conditions (cycle loading, pressure variations, humidity, etc.) may lead to coupled chemical-mechanical degradation such as ASR, cracking, rebar corrosion, and internal swelling. For big data analytics, the project is exploring the Apache^{TM} HADOOP$^{®}$ framework to store, process, and analyze the heterogeneous monitoring data obtained from multiple techniques and sources. Uncertainties

in health monitoring are classified into three categories: natural variability in the system properties and operating environments (aleatory uncertainty); information uncertainty due to inadequate, qualitative, missing, or erroneous data (epistemic uncertainty); and modeling uncertainty induced by assumptions and approximations (epistemic uncertainty). A Bayesian network approach will be investigated to integrate the information from various data and modeling sources and to compute the overall uncertainty in diagnosis and prognosis.

Going forward, this research will focus on data analysis and development of uncertainty-quantified diagnostic and prognostics models that will support continuous assessment of concrete performance. The resulting comprehensive approach will facilitate the development of a quantitative, risk-informed framework that would be generalizable for a variety of concrete structures and can be adapted for other passive structures.

ACKNOWLEDGMENTS

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CONTENTS

FIGURES

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ACRONYMS

AE	acoustic emissions
ASR	alkali-silica reaction
COSTAR	Concrete Structures Aging Reference (Tool)
CO_2	carbon dioxide
DBN	dynamic Bayesian network
DIC	digital image correlation
EPRI	Electric Power Research Institute
FW-PHM	Fleet-Wide Prognostic and Health Management
HDFS	Hadoop® distributed file storage system
INL	Idaho National Laboratory
II&C	Instrumentation, Information, and Control
LTO	Long-Term Operations (Program)
LWRS	Light Water Reactor Sustainability (Program)
MAaD	Material Aging and Degradation
NDE	nondestructive evaluation
NPP	nuclear power plant
ORNL	Oak Ridge National Laboratory
PHM	prognostics and health management
SHM	structural health monitoring
USNRC	United States Nuclear Regulatory Commission

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1. INTRODUCTION

Currently in the United States there are 100 nuclear power plant (NPP) units in operation providing 19% of the total electricity consumed by the nation (World, 2014). The longevity of these plants has become an important topic as many have surpassed their initial operation license. The United States Nuclear Regulatory Commission (USNRC) limits commercial power reactor licenses to an initial 40-year period with operating license renewals available for an additional 20 years. There is no cap on the number of 20-year renewals a power reactor may receive. Of these 100 NPP units, 73 NPP units have renewed their operating license. The remaining 27 are or will be seeking renewal in the near future. As USNRC expects the first application for subsequent license renewal to be submitted as early as 2017, the significant challenges associated with the continuous operation of NPP units upwards of sixty years must be carefully considered; as plant structures, systems, and components age, their useful life—considering both structural integrity and performance—is reduced as a result of deterioration of the materials.

While active components at nuclear power plants receive the bulk of the attention, passive structures such as:

- concrete,
- cable insulation,
- reactor pressure vessel steels,
- core internal stainless steels,
- Ni-base alloy piping, and
- weldments

must also be examined to determine if they are capable of enduring a prolonged life cycle. This research project will focus on concrete structures in NPPs. Reinforced concrete structures found in all NPPs can be grouped into four categories (Naus, 2007):

- Primary containment
- Containment internal structures
- Secondary containments / reactor buildings
- Spend fuel pools and cooling towers.

These concrete structures are affected by a variety of chemical, physical and mechanical degradation mechanisms such as alkali-silica reaction (ASR), chloride penetration, sulfate attack, carbonation, freeze-thaw cycles, shrinkage, and mechanical loading. The age-related deterioration of concrete results in continuing microstructural changes (slow hydration, crystallization of amorphous constituents, reactions between cement paste and aggregates, etc.). Changes over long periods of time need to be measured, monitored, and analyzed in order to best support long-term operation and maintenance decisions. Assessment and management of the aging concrete structures in nuclear plants require a more systematic approach than simple reliance on existing code margins of safety (Christensen, 1990). Current knowledge and ongoing national and international research efforts need to be leveraged and synthesized to advance the state-of-the-art in full-field, multi-physics assessment of concrete structures, particularly with regard to monitoring of its performance in-situ.

Structural health monitoring (SHM) is required to produce actionable information regarding structural integrity that supports long-term and operational and maintenance decision making. Information needs to be conveyed to the decision-maker in a manner that is suitable for risk management with respect to structural integrity and performance. The methods and technologies employed include the assessment of the critical measurements, monitoring, and the analysis of aging. The risk management decisions include sustainment decisions regarding inspection, maintenance and repair, as well as operational decisions regarding the mission demand limits for the system and its operating conditions. In all engineering systems, such decisions are made in the presence of uncertainty that arises from multiple sources. The various types of uncertainty include natural variability (in loads, material properties, structural geometry, and boundary conditions), data uncertainty (e.g., sparse data, imprecise data, missing data, qualitative data, and measurement and processing errors), and model uncertainty (due to approximations and simplifying assumptions made in diagnosis and prognosis models and their computer implementation). An important challenge is to aggregate the uncertainty arising from multiple sources in a manner that provides quantitative information to the decision-maker relative to the future risks for structural integrity and performance, as well as the risk reduction offered by various risk management activities, thus facilitating quantitative risk-informed cost vs. benefit decisions.

The information available in SHM is quite heterogeneous, with the information amassed from a variety of sources in a variety of formats. These heterogeneous sources include mathematical models, experimental data, operational data, literature data, product reliability databases, and expert opinion. In addition to the specific system being monitored, information may also be available from similar or nominally identical systems in a fleet, as well as from legacy systems. Even within the system being monitored, information may be available in different formats (e.g., numerical, text, image). It is also worth noting that information about different quantities may be available at different levels of fidelity and resolution. All of the gathered data needs to be organized and analyzed in such a manner that the resulting information is individualized for a given structure and its performance objectives and compiled into an effective Prognostics and Health Management (PHM) framework. An important challenge in data analytics for PHM is information integration, i.e., fusion of heterogeneous information available from multiple sources and activities.

Health monitoring systems have used either data-driven techniques or model-based techniques for diagnosis and prognosis. An effective framework for health diagnosis and prognosis of aging reinforced concrete structures needs to make use of all the available information through damage modeling, monitoring, data analytics, and uncertainty quantification techniques. This ongoing effort will pursue a dynamic Bayesian network (DBN) approach for integrating heterogeneous information from multi-physics computational models of degradation processes, big data analytics, full-field measurement techniques, as well as for uncertainty quantification in diagnosis and prognosis. The Bayesian network approach enables both the forward problem (uncertainty integration) and the inverse problem (risk management, resource allocation). Methods have recently been developed to integrate various sources of uncertainty in order to quantify the overall uncertainty in health monitoring outcome. Such methods need to be quantitatively linked to decisions regarding appropriate risk management actions through the use of structural reliability theory (Naus, 2007).

Through the Light Water Reactor Sustainability (LWRS) Program, several national laboratories, and Vanderbilt University have begun to develop a framework of research activities for the health monitoring of NPP concrete structures. The goal of this framework is to enable plant operators to make risk-informed decisions on structural integrity, remaining useful life, and performance of concrete structures across the nuclear fleet. This report briefly discusses the available techniques and ongoing challenges in each of the four elements of such a framework, namely, damage modeling, monitoring, data analytics, and uncertainty quantification techniques.

1.1 BACKGROUND

In 2012, the Material Aging and Degradation (MAaD) Pathway under the LWRS Program developed a concrete nondestructive evaluation (NDE) roadmap to define research and development actions to address gaps between available NDE concrete techniques and the technology needed to make quantitative measurements to determine the durability and performance of concrete structures in the current fleet of NPPs (Clayton and Hileman, 2012). To assist in the development of this roadmap, a workshop was held on July 31, 2012, at the Oak Ridge National Laboratory (ORNL) Conference Center with 28 attendees. Several important themes were proposed in the roadmap including:

- Need to survey available samples
- Technique(s) to perform volumetric imaging on thick reinforced concrete sections
- Determination of physical and chemical properties as a function of depth
- Techniques to examine interface between concrete and other materials
- Development of acceptance criteria – model and validation
- Need for automated scanning system for any of the NDE concrete measurement systems.

In 2013, ORNL focused on technique(s) to perform volumetric imaging on thick reinforced concrete sections (Clayton et al., 2013). ORNL performed a comparative evaluation of several ultrasonic techniques using some concrete specimens. Since no concrete specimens truly representative of the reinforced concrete sections found in NPPs were identified, the 6.5 ft. x 5.0 ft. x 10 in. concrete specimen from Florida Department of Transportation's NDE Validation Facility in Gainesville, Florida was utilized for evaluation. ORNL chose to evaluate seven different ultrasonic techniques:

1. Ultrasonic linear array device (Germann Instruments MIRA Tomographer Version 1)
2. Ultrasonic linear array device (Germann Instruments MIRA Tomographer Version 2)
3. Shear wave ultrasonic array (Germann Instruments EyeCon)
4. Ground-penetrating radar (GSSI SIR3000 with 2.6 GHz antenna)
5. Air-coupled impact-echo
6. Air-coupled ultrasonic surface wave
7. Semi-coupled ultrasonic.

The evaluation study concluded that each technique has some limitations and shortcomings, i.e., each technique has situations where it performs very well and other situations where it is somewhat lacking in performance.

1.2 PROJECT OBJECTIVE

The long-term research objective of this project is to produce actionable information regarding structural integrity that supports operational and maintenance decision making, which is individualized for a given structure and its performance goals. The project will support the research objectives of the MAaD Pathway and the Advanced Instrumentation, Information & Control (II&C) Systems Technologies Pathway under the LWRS Program.

Idaho National Laboratory (INL) and Vanderbilt University, in collaboration with ORNL and Electric Power Research Institute (EPRI) will develop a probabilistic framework for health diagnosis and prognosis of aging concrete structures subjected to physical, chemical, environmental, and mechanical degradation, by integrating modeling, monitoring, data analytics, and uncertainty quantification techniques. Current knowledge and ongoing national/international research efforts in individual directions will be leveraged and synthesized in order to advance the state-of-the-art in full field, multi-physics assessment of concrete structures. The framework will be generalizable for a variety of aging passive components in NPPs.

In the first year of the project, INL and Vanderbilt reviewed existing non-destructive monitoring techniques and degradation mechanisms. It was observed that ASR is currently of interest among the nuclear utilities. Several monitoring techniques are under investigation to identify and monitor ASR degradation in concrete structures. Therefore, this report will summarize ASR and associated monitoring techniques.

2. CONCRETE STRUCTURE HEALTH MONITORING FRAMEWORK

The purpose of SHM is to provide information to the decision-maker in a manner that is suitable for risk management with respect to structural integrity and performance. Risk management decisions include sustainment decisions regarding inspection, maintenance and repair, as well as operational decisions regarding the mission demand limits for the system and its operating conditions. The information available in SHM is quite heterogeneous, since the information comes from a variety of sources in a variety of formats. The heterogeneous sources include mathematical models, experimental data, operational data, literature data, product reliability databases, and expert opinion. In addition to the specific structure being monitored, information may also be available from similar or nominally identical structures in a fleet. Even within the structure being monitored, information may be available in different formats (e.g., numerical, text, image). It is also worth noting that information about different quantities may be available at different levels of fidelity and resolution.

Through the LWRS Program, several national laboratories, and Vanderbilt University have begun to develop a framework of research activities for the health monitoring of NPP concrete structures. A systematic approach proposed to assess and manage aging concrete structures requires an integrated framework that includes the following four elements, as shown in Figure 1:

- Damage modeling
- Monitoring
- Big data analytics
- Uncertainty quantification.

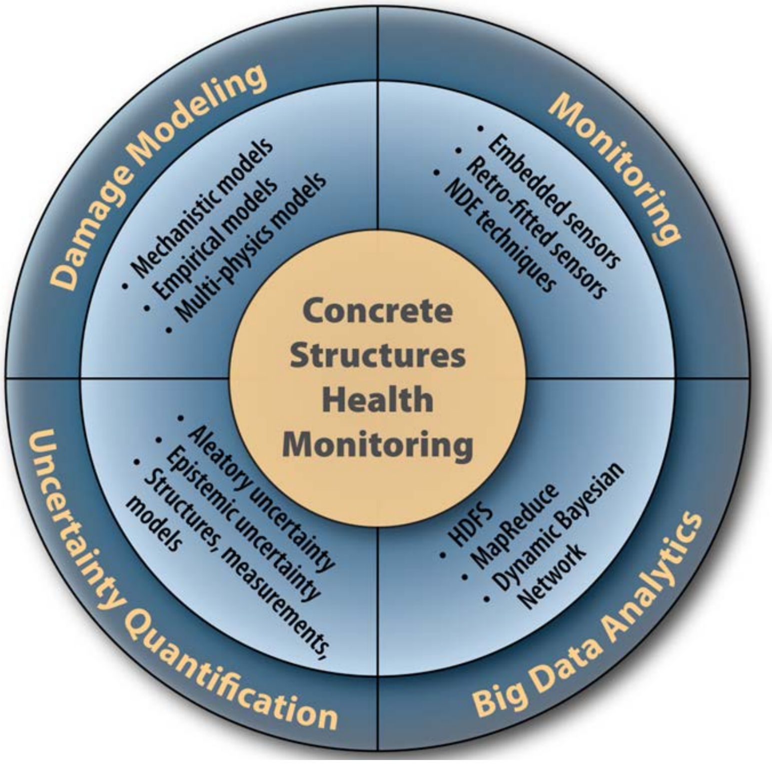


Figure 1. Elements of concrete structural health monitoring.

2.1 Damage Modeling

As plant concrete structures age, incidences of degradation of concrete structures may increase due to a variety of degradation mechanisms. The conventional classification of concrete degradation in NPPs (acknowledging that the degradation mechanisms may be coupled) is physical, chemical, mechanical, and irradiation with an increase in temperature.

Physical degradation includes thermal expansion/contraction, moisture shrinkage/expansion, and freeze-thaw cycles (as shown in Figure 2). Even though the nuclear containment vessel is in close proximity to the nuclear reactor, the concrete containment vessel is not exposed to large doses of radiation because a steel liner surrounds the reactor. Radiation exposure in excess of 1×10^{19} neutrons/cm^2 or 10^{10} Rads of gamma radiation was found to have damaging effects on concrete (Pomaro, 2009).

Mechanical contraction or expansion produced due to moisture transport, sustained or cyclic loading, pressure variations, and tensile stresses lead to the following types of degradation:

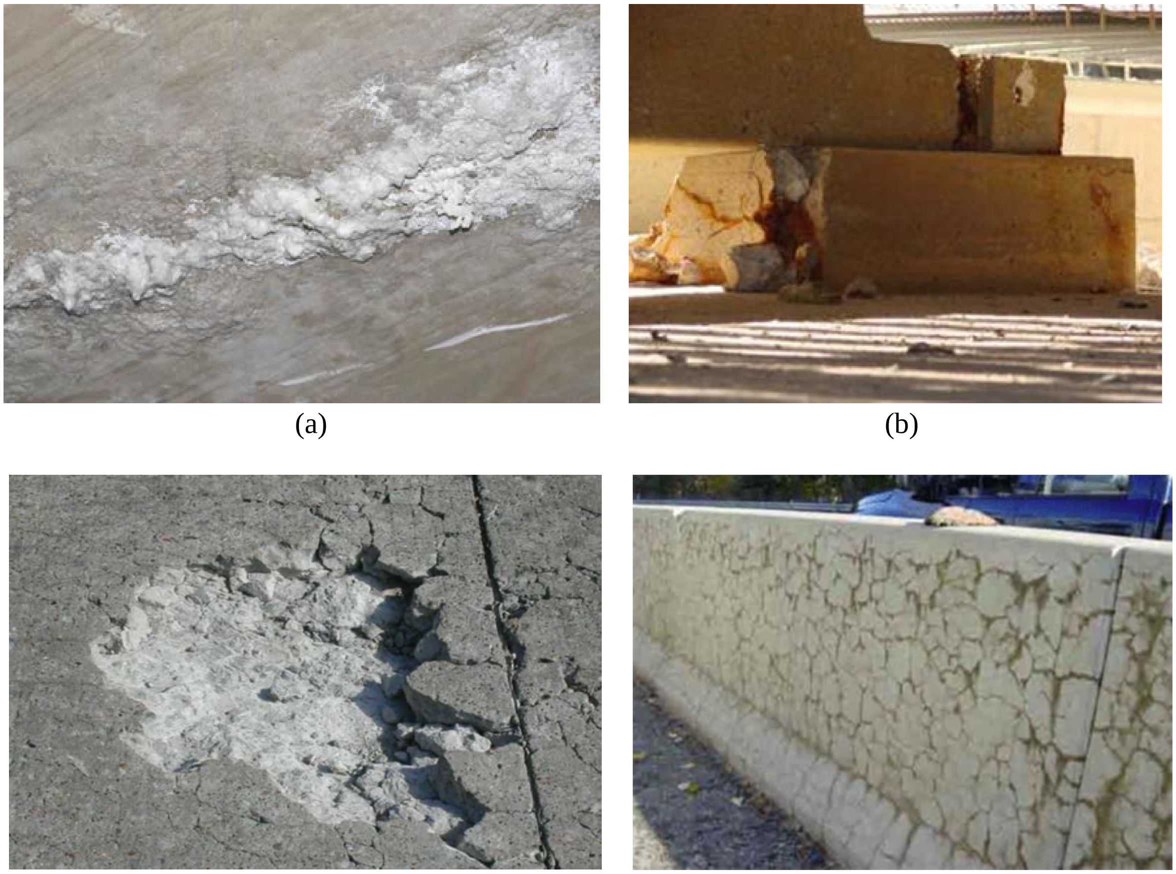
- Shrinkage
- Creep
- Fracture
- Internal swelling reaction.

The chemical reactions between the environment and the cement paste or the coarse aggregate typically occur at concrete surfaces and between cracks. The effect of chemical reactions could lead to following types of degradation (as shown in Figure 3):

- Chloride penetration
- Carbonation
- Corrosion of reinforcing steel
- Leaching
- Acid attack
- Alkali-silica reaction.


(a) (b)

Figure 2. Generic examples (not from a nuclear plant) of physical degradation of a concrete structure (a) freeze-thaw cycle and (b) cracking.



(a) (b)

(c) (d)

Figure 3. Generic examples (not from a nuclear plant) of different types of chemical degradation that can be observed in a concrete structure (a) leaching, (b) corrosion, (c) sulfate attack, and (d) alkali-silica reaction.

There are two possible causes of damage to concrete by irradiation. One is the change in the material properties caused by the radiation interactions with the material. Such damage might result from the breaking of bonds in the material or embrittlement of the material. The second possible cause might be the localized heating of the concrete caused by the absorption of the radiation energy.

All of these sources of degradation can alter the porosity and permeability of concrete, cause or aggravate various material flaws (such as scaling and spalling, swelling and debonding, cracking and disintegration), impair the integrity and tightness of concrete structure, and lower the loading capacity of structural members.

A major current challenge is how to develop an integrated computational methodology to quantitatively assess the durability of reinforced concrete structures subjected to a variety of coupled degradation processes that are acting simultaneously. A related issue is that damage under different degradation processes accumulates at different rates; thus multi-physics degradation analysis also needs to account for different time scales in different processes. In the case of concrete degradation under coupled physical/chemical processes, governing differential equations that characterize the mass/energy balance and thermodynamic/chemical equilibrium of coupled heat conduction, ionic diffusion, moisture transport and chemical reaction have been developed. A variety of multi-scale methods and continuum finite element/difference methods have been utilized to solve the interactive and nonlinear governing equations.

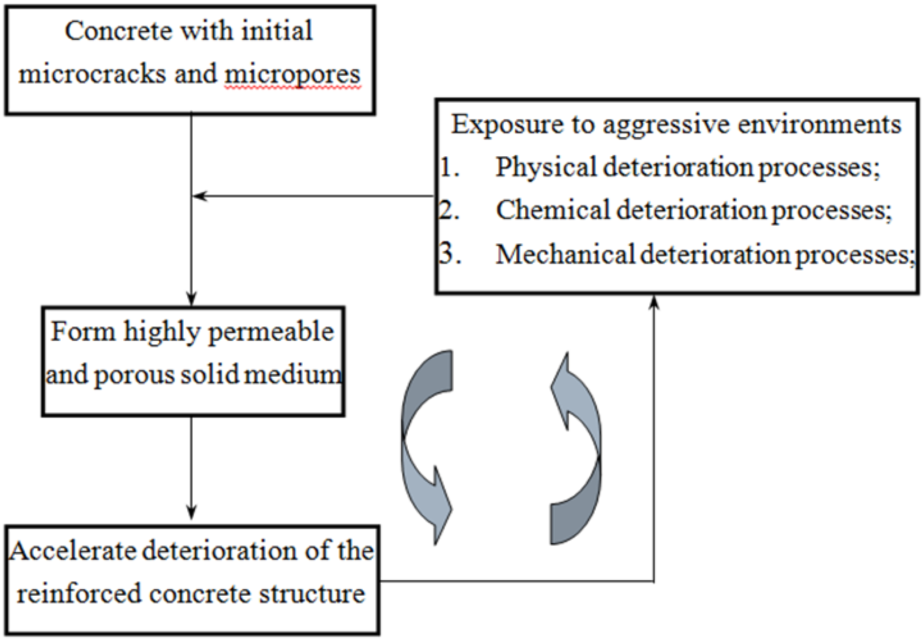


Figure 4. Multi-physics degradation of concrete (Chen, 2008).

Methods have also been pursued to connect chemical reaction products to the mechanical response of concrete (e.g., stress, displacement, crack density).

Under degrading environments, initially discontinuous micropores and microcracks grow, coalesce and finally form an interconnected network of multi-scale pores and cracks. As a result, the permeability of concrete increases, thus further accelerating the deterioration processes of the concrete structure, as shown in Figure 4 (Chen, 2008).

Thoft-Christensen (2003) classified various degradation models of concrete structures into three levels. Level 1 models are empirical models, which are established on the basis of direct observations on existing structural elements and do not consider the degradation mechanism. Level 1 models have been adopted extensively in current design codes as a means of producing a rough estimate of the durability level of existing concrete structures. Level 2 models are medium level models from a sophistication viewpoint; these are based on semi-empirical or average “material parameters” (e.g., concrete permeability) and average “loading parameters” (e.g., average chloride content applied on the surface of concrete). Degradation mechanisms are assumed to follow some formulated physical principles like Fick’s law. Level 2 models have usually limited their scope to individual degradation mechanisms. Level 3 is the most advanced level, where the modeling of the degradation profile is based on fundamental physical, chemical and mechanical principles. Detailed information on concrete microstructure and applied environmental loading is required, and multiple coupled deterioration processes are taken into account.

A few examples of multi-physics degradation modeling, namely ASR (Levels 1, 2 and 3), carbonation and chloride penetration (Level 2), and sulfate attack (Level 3), are described next for the sake of illustration.

2.1.1 Alkali-Silica Reaction

Of particular interest to the nuclear energy sector is ASR that occurs when the alkaline cement paste reacts with non-crystalline silica in the aggregates in the presence of water. The reaction produces an expansive gel that creates micro-cracking in the concrete. This damage mechanism was first discussed by Stanton (1940). In 2012 micro-cracking was discovered in subgrade concrete of the containment vessel at Seabrook Nuclear Plant (USNRC, 2014). The micro-cracking was determined to be caused by ASR. The intrusion of groundwater was facilitating the ASR.

Extensive research, experimental, modeling, and monitoring techniques have been reported in literature. Several factors affect ASR, such as size and mineral composition of the aggregate, alkali content in the pore solution, relative humidity, temperature, confining stress, etc. (Pan et al., 2012). The modeling efforts have been reported at multiple scales, at the level of chemical reactions, and at micro-, meso-, and macro-scales for the mechanical effects of ASR. Some of the prominent studies in recent years are mentioned here. These include mathematical modeling of chemical reaction kinetics (Bazant and Steffens, 2000), who also argued that the cracking of concrete is caused by expansive pressure accumulated in the interface between aggregate and surrounding cement paste due to the formation of the hydrated gel, which leads to cracking of the cement paste. However, other authors have argued that expansive pressure is accumulated inside the aggregate, thus causing cracking of both the aggregate and the cement paste (Goltermann, 1995).

Microscopic level models consider a representative volume element consisting of a spherical aggregate and surrounding cement paste. Reaction kinetics and gel swelling are considered inside the representative volume element (Multon et al., 2007). Meso-scale models take into account multiphase of aggregate, cement paste, void and gel, and ASR is represented by the expansion of aggregate particles or the expansion of gels randomly distributed in the aggregate (Comby-Pyrot et al., 2009). Macro-scale models have been developed to compute the effects of ASR on the structural scale, typically employing finite element models (Leger et al., 1996). Multi-scale modeling approaches that link the models at various scales have also been reported (Dunant and Scrivener, 2010).

As mentioned earlier, concrete damage mechanisms are often coupled. Thus modeling efforts for the coupling of ASR with other damage mechanisms have also been reported. For example, Grimal et al. (2008) studied the combination of creep and shrinkage with ASR. A large application area for ASR modeling has been hydraulic structures, especially dams, and may studies have been reported in this direction (Grimal et al., 2010).

2.1.2 Carbonation

Unlike physical deterioration processes such as the heat transfer and moisture transport, carbonation of concrete is essentially a chemical process. As the hydration product of Portland cement, calcium hydroxide in concrete may react with carbon dioxide (CO_2) dissolved in pore solution, neutralize its high alkalinity environment, and finally result in depassivation of the passive layer and initiation of reinforcement corrosion — one of the major deterioration mechanisms for reinforced concrete structures. On the other hand, as the main product of the carbonation reaction, calcium carbonate will not dissolve in water but precipitate in the pores of concrete, thus decreasing the porosity of concrete and altering its microstructure. In this case, carbonation reaction may be favorable to maintain the durability of plain concrete. Thus carbonation has opposing effects on different constituents of the material.

Based on an assumption that the carbonation front advances after the alkaline material (i.e., calcium hydroxide) has been neutralized completely, the carbonation process is dominated by the diffusion of CO_2 through the porous microstructure of concrete, where the concentration gradient of CO_2 acts as a driving force. As a neutralization reaction, the carbonation process generates a specific amount of moisture, which may affect the temporal and spatial distribution of moisture content in concrete and should be considered in the simulation of previous moisture transport process. To develop a numerical model for carbonation, several coupled processes, namely the diffusion of CO_2, moisture transport, heat transfer, formation of calcium carbonate, availability of calcium hydroxide in the pore solution etc., need to be considered. A popular approach is the multifactor equation, where the diffusivity of CO_2 is assumed to be dependent on the pore relative humidity, temperature and the carbonation-induced reduction of porosity as:

$$D_C = D_{C,0} \cdot F_1^*(h)F_2(T)F_3(\varepsilon)\pi r^2 \tag{1}$$

where F_1, F_2, and F_3 represent the effects of humidity, temperature and carbonation, respectively. Refer Saetta et al. (1995) for details of models for F_1, F_2, and F_3. Saetta et al. (2004) also proposed a similar numerical model for the carbonation reaction rate (ϑ_r) as:

$$\vartheta_r = \vartheta_0 \cdot f_T f_h f_c f_R \tag{2}$$

where ϑ_0 indicates an ideal carbonation rate at which the carbonation reaction takes place in specified ideal conditions, and f_T, f_h, f_c, and f_R represent the influences of temperature, relative humidity, concentration of free CO_2, and degree of carbonation respectively, on the reaction rate.

2.1.3 Chloride Penetration

Chloride-induced reinforcement corrosion is one of the major deterioration mechanisms for reinforced concrete structures exposed to marine environment, deicing salts or underground environment. It leads to a series of structural degradations, such as loss of the concrete-steel interface bond, reduction of the cross-section area of reinforcement, and cracking and spalling of the concrete cover, thus severely reducing the load carrying capacity of the structure. Considering its unique significance, substantial studies have been carried out on the chloride-induced reinforcement corrosion process for several decades.

Based on Fick's second law, the governing equation of chloride penetration in concrete is expressed as:

$$\frac{\partial C_{cl}(x,t)}{\partial t} = D_{cl} \cdot \frac{\partial^2 C_{cl}(x,t)}{\partial x^2} \tag{3}$$

where $C_{cl}(x,t)$ is the chloride content at spatial coordinate x and time t, and D_{cl} is chloride diffusivity.

Chen and Mahadevan (2008) proposed the modeling of chloride-induced deterioration through a multifactor equation as

$$D_{cl} = D_{cl,0} \cdot F_2(t)F_3(C_{cl,f})F_4(T)F_5(\rho_{local}) \tag{4}$$

where $D_{cl,0}$ is the reference or nominal chloride diffusivity when all influencing factors assume values of unity. F_2 denotes the influence of the age of concrete, which reflects the cement hydration-induced reduction in the concrete porosity with time t. F_3 represents the influence of the free chloride content $C_{cl,f}$, which reflects the hindering effect of high chloride content on the chloride diffusion. F_4 indicates the influence of temperature T, which reflects the thermodynamic effect of high temperature on the chloride diffusion. F_5 reflects the influence of local relative crack density ρ_{local}. Chen and Mahadevan (2008) implemented this approach through a finite element-based computational methodology to link the diffusivity change to structural degradation expressed by the local relative crack density.

The above two modeling approaches use semi-empirical multifactor equations, whose parameters are calibrated using experimental data. These are Level 2 approaches using averaged parameters. An example of a Level 3 approach based on multi-scale modeling is illustrated below for sulfate attack.

2.1.4 Sulfate Attack

When sulfate ions diffuse through a cementitions structure (as shown in Figure 5), they react with the cement hydration products to form expansive products. This induces strain leading to cracking and eventual failure. Sarkar (2010) developed a probabilistic computational model of concrete durability under sulfate attack that considers three processes – diffusion of ions, chemical reactions and mechanical damage accumulation due to cracking. The three processes were modeled through basic differential equations, chemical reactions and mechanics models respectively, based on continuum first principles.

There are several inputs and model parameters in the three parts of the model. Sarkar et al. (2012) pursued a hierarchical Bayesian calibration approach where the parameters of each model component were calibrated using tests that progressively added the processes (i.e., first chemical alone, then chemical and diffusion, then all three). In the geochemical speciation modeling, many mineral sets are possible; their relative proportions were calibrated using experimental data.

The effect of chemical reaction products on mechanical properties such as elastic modulus and strength was computed through multi-scale modeling. Four scales were considered for homogenization and calculation of macro-level structural properties and strength degradation. These were: calcium silicate hydrate, cement paste, cement mortar, and concrete. The macro-level crack density was then connected to effective elastic modulus and diffusivity.

In summary, the above examples of concrete deterioration modeling show attempts at modeling the interactions among multiple chemical, physical and mechanical processes that operate simultaneously across multiple spatial and temporal scales. This presents unique challenges for concrete structures health monitoring. Sensing of physical, chemical and mechanical quantities is one challenge. In addition, since multiple processes are interacting in a coupled manner, it is difficult to link any observed damage to a particular deterioration process or to estimate the proportion of damage contributed by different processes.

Based on the literature, some of the prominent damage mechanisms of interest, and their associated damage signatures that could be detected by NDE techniques, are listed in Appendix A.

2.2 Monitoring

A variety of monitoring techniques have been studied for concrete structures, including embedded sensors in concrete, retrofitted sensors, manual inspection, and external NDE techniques. The discussion in this report is restricted to external sensing considering that the structures are already built.

ORNL, via the LWRS Program's MAaD Pathway, has been researching and evaluating current NDE techniques to identify types of defects that could occur in thick heavily reinforced concrete structures (sample concrete structure is shown in Figure 6). ORNL evaluated and compared five NDE techniques that include:

- Shear-Wave Ultrasound
- Ground-Penetrating Radar
- Impact Echo
- Ultrasonic Surface Wave
- Ultrasonic Tomography.

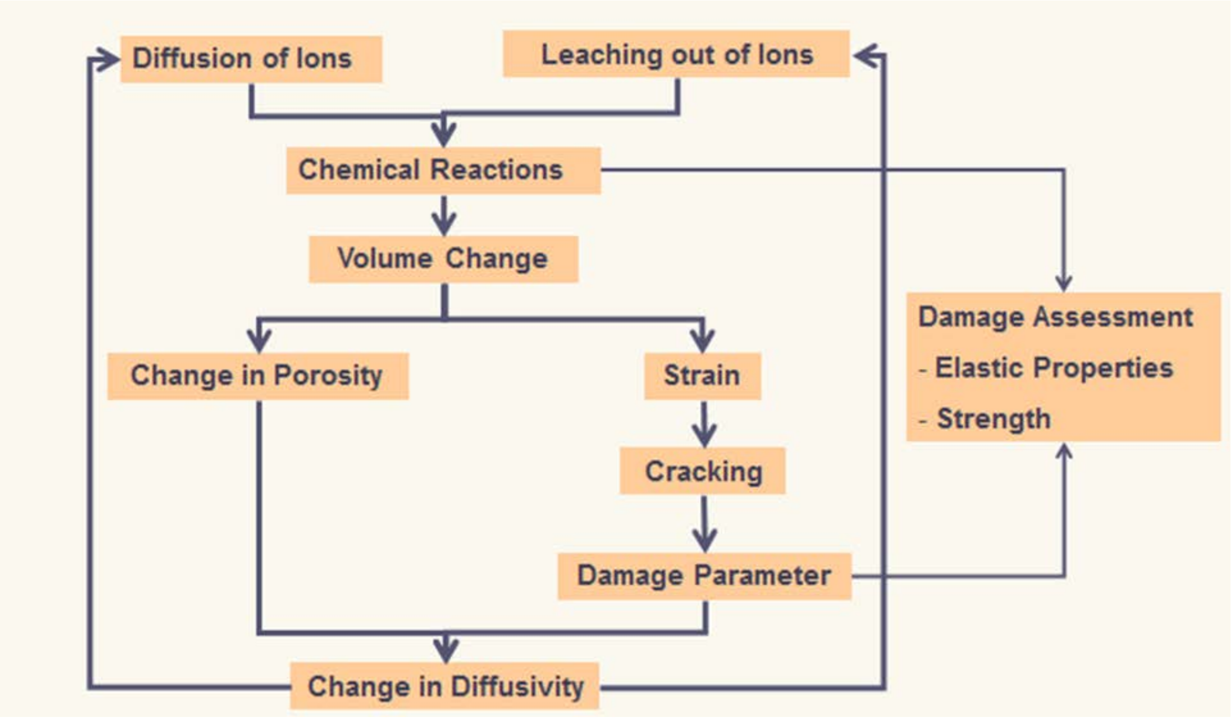


Figure 5. Multi-physics modeling of sulfate attack.

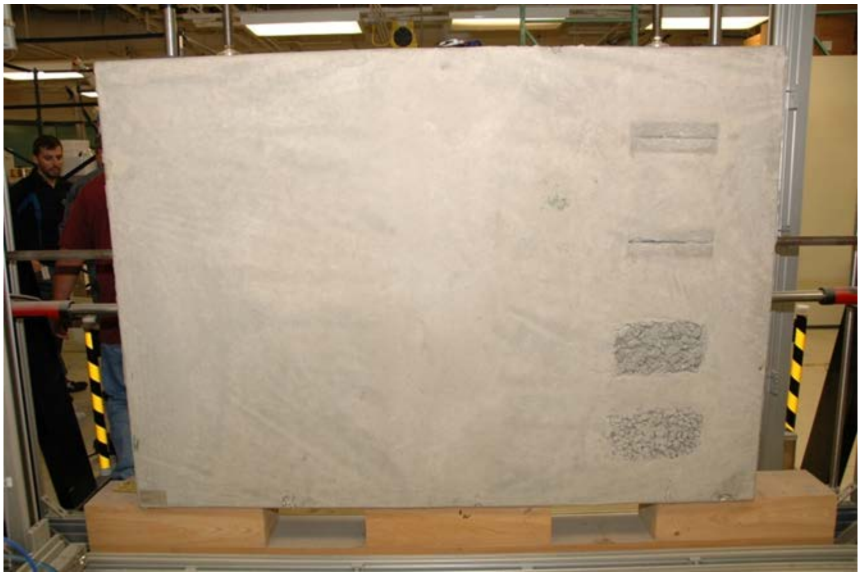


Figure 6. A concrete test specimen from the Florida Department of Transportation's State Materials Office NDE Validation Facility in Gainesville, FL with simulated cracking and non-consolidation flaws (Clayton, 2014).

The techniques were compared in terms of ease of use, time consumption, and defect detection capability, and different techniques showed different advantages and disadvantages. For example, ultrasonic tomography appeared to have the best detection especially at larger depths under the surface, but was very time consuming. The first two (shear-wave ultrasound and ground penetrating radar) were found to have above average performance but some disadvantages as well.

In this research, INL and Vanderbilt University collaborate with ORNL to advance NDE-based monitoring techniques. The concrete samples proposed to be prepared by ORNL with different age-related defects will be used to test promising monitoring techniques and collect information on the concrete structure. Different types of techniques—optical, thermal, acoustic, and radiation-based—are available, and practically feasible and useful combinations of these techniques for NPP concrete structures need to be identified. When data from multiple techniques is combined for damage inference, the information is expected to be heterogeneous in nature. Possible full-field techniques include infrared imaging, digital image correlation (DIC), and acoustic.

2.2.1 Infrared Thermography

Infrared thermography maps the thermal load path in a material. In the case of concrete, cracking, spalling, and delamination all create a discontinuity in the thermal load path. Additionally, rebar and tensioning cables can be easily detected due to the difference in thermal conductivity coefficients between steel and concrete. Thermography has even been shown to detect debonding between the reinforcing steel and concrete. Infrared thermography can be either an active or passive monitoring technique. When heat is locally added to the structure to create a temperature gradient, it is referred to as active. If the sun is used to provide heat to produce the temperature gradient, it is considered passive. Passive infrared thermography is preferred because it is less energy intensive. EPRI showed the feasibility of infrared thermography by mapping a 450,000ft^2 dam. During the two days that EPRI spent mapping the dam, numerous potential delamination sites were identified (Renshaw, 2014).

Kobayashi and Banthia (2011) combined induction heating with infrared thermography to detect corrosion in reinforced concrete. Induction heating uses electromagnetic induction to produce an increase in temperature in the rebar. When corrosion is present, it inhibits the diffusion of heat from the rebar to the surrounding concrete. Infrared thermography is then used to capture the temperature gradient. It was concluded that the temperature rise in corroded rebar is higher than that in a non-corroded rebar, a more corroded rebar yields a smaller temperature rise on the surface, and the technique is more effective with larger bar diameters and smaller cover depths (Kobayashi and Banthia, 2011). Further research may be in order to evaluate the combination of induction heating and infrared thermography as a means to identify debonded rebar.

2.2.2 Digital Image Correlation

Digital Image Correlation is an optical NDE technique. It can be conducted quickly, which allows it to be used as a screening method. DIC is capable of measuring deformation, displacement, and strain of a structure (Bruck, 2012). During a NPP routine pressure tests on the containment vessels, when the internal pressure reaches 60 psi, it would provide an ideal condition to use DIC to determine the deformation of the concrete containment. DIC is capable of detecting surface defects such as cracks, micro-cracks, and spalling, but is unable to detect any subsurface defects. DIC is commercially available.

2.2.3 Ultrasonic

Ultrasonic testing utilizes high-frequency oscillating sound pressure waves. In a recent study led by ORNL, five NDE techniques were evaluated, including shear-wave ultrasound and semi-coupled ultrasonic tomography. The shear-wave ultrasound consisted of a 4x12 array that was capable of producing real time 3D imaging. The semi-coupled ultrasonic tomography was excellent at identifying internal void areas and unbonded, embedded rebar. Both techniques did show some limitations; the semi-coupled ultrasonic tomography was unable to detect well-bonded rebar, and the shear-wave ultrasound is in need of post-processing of the data. The shear-wave ultrasound is currently in commercial production, but the semi-coupled ultrasonic tomography is not (Clayton, 2014).

Nonlinear ultrasonic testing is gaining significant attention in the diagnosis and prognosis of ASR (Qu et al., 2014). Researchers are researching correlation between the acoustic nonlinearity parameter and ASR (if any), developing chemo-mechanics models to interpret the measurement data, and conducting numerical simulations for prognosis. The research is still in its early stages and will need some time before their product will be ready for commercialization. The available resources on nonlinear ultrasonic testing and ASR will be utilized in the proposed framework.

2.2.4 Acoustic Emission

Acoustic emission (AE) has great potential as a monitoring technique for areas where degradation is believed to be occurring. It is a passive method that can detect and characterize fracture by the sound produced from the release of strain energy. AE can only detect damage if it is monitoring a location when the damage occurs; previous damage is not detectable. AE sources are located via triangulation (Larosche et al., 2014). Microcracking caused by ASR as well as fracture due to delamination would be detectable. AE has the ability to recognize both the type and severity of damage. One challenge with AE is there is a lot of noise in the data, so data filtering is required. AE is not suited for monitoring concrete structures on a scale similar to the size of a nuclear containment vessel due to the sheer number of AE devices that would be required, but in conjunction with other NDE methods, AE could serve as an effective point source monitoring technique for areas of high probability of degradation.

Effective combinations of full-field techniques and acoustic emission need to be identified for different types of concrete structures. Dynamic operating conditions (cycle loading, pressure variations, humidity, etc.) may lead to coupled chemical-mechanical degradation such as ASR, cracking, corrosion, and internal swelling. The forward analysis of the evolution of concrete degradation is a challenging task in itself, which requires the combination of reactive transport modeling with mechanical degradation models. The inverse problem of damage inference in the presence of multiple damage mechanisms is even more challenging, and requires development of damage signatures that have to be effectively connected to monitoring data.

Going forward, this research will focus on data analysis and development of uncertainty-quantified diagnostic and prognostics models that will support continuous assessment of concrete performance. The resulting comprehensive approach will facilitate the development of a quantitative, risk-informed framework that would be generalizable for a variety of concrete structures and can be adapted for other passive structures.

Based on the literature review, some of the prominent NDE techniques and their suitability to detect prominent concrete degradation mechanisms of interest are listed in Appendix B.

2.3 Big Data Analytics

The information gathered from health monitoring results in high volume, velocity, and variety (heterogeneity) of data, which are the three main characteristics of Big Data, as shown in Figure 7.

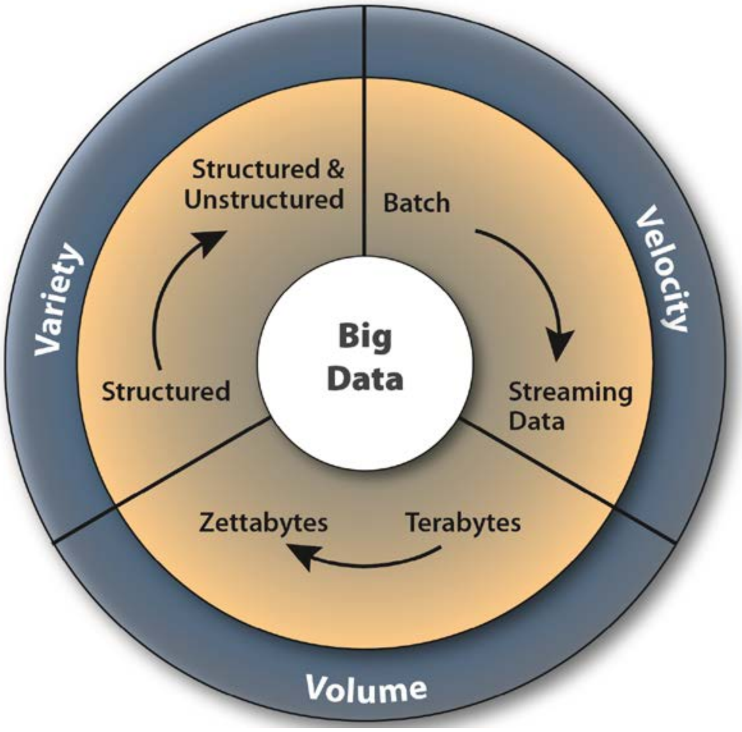


Figure 7. Characteristics of big data.

Data (big or small) is of little value without proper analytic tools. Therefore, Big Data Analytics, a combination of big data and analytic tools, presents an opportunity to store, process, and access heterogeneous (structured, unstructured, and binary) data. The effective application of big data analytics would support decisions related to operations, maintenance, and risk reduction. Owing to the advancements in data storage and processing power, big data analytics have a wide range of applications in science and technology, health care, transportation, education, and other consumer industries.

The development of the concrete structural health-monitoring framework would require tools to store, process, and access the data. Some of the tools developed to date and studied for other applications are as follows:

- **NoSQL**. Database MongoDB, CouchDB, Cassandra, BigTable, Hypertable, Voldemort,
- and Hbase
- **MapReduce**. Apache™ Hadoop®, Hive, Pig, Cascading, Cascalog, S4, MapR, Greenplum
- **Storage**. S3, Hadoop® Distributed File System (HDFS)
- **Servers**. EC2, Google App Engine, Elastic, Beanstalk, Heroku
- **Processing**. R, Yahoo! Pipes, Elasticsearch, Datameer, BigSheets, and Tinkerpop.

This research activity will initially focus on the Hadoop® distributed file storage system (HDFS) and MapReduce, and DBNs. As shown in Figure 8, the HDFS has master/slave architecture and is suitable for large data sets. HDFS is scalable, fault tolerant, and provides high throughput access to application data. MapReduce is a parallel processing framework that has two functional routines: Map and Reduce. Map accesses large data sets, subdivides the data sets, and assigns them to slave nodes. The Reduce routine aggregates the results from slave nodes to obtain the final result.

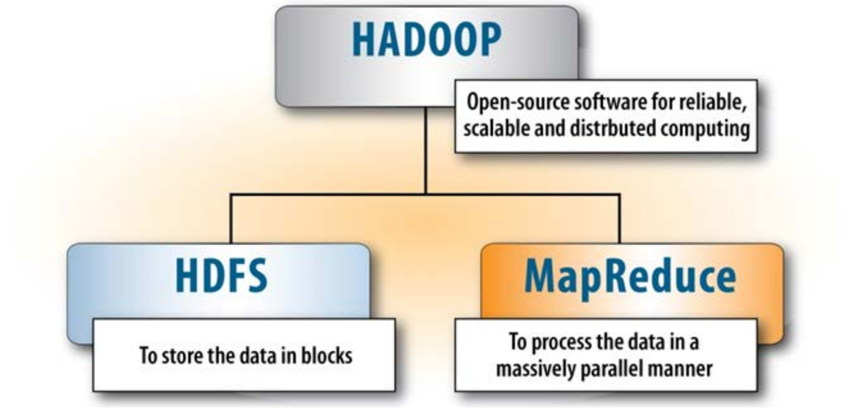


Figure 8. Big data analytics via Hadoop®.

Probabilistic graphical models for machine learning such as Bayesian networks (Jensen, 1996) have shown much effectiveness in the integration of information across multiple components and physics in several application domains. The DBN have been used for systems evolving in time, and recent work has extended DBNs to include heterogeneous information in diagnosis and prognosis (Bartram and Mahadevan, 2014). The Bayesian network is able to include asynchronous information from different sources. Also, Bayesian networks can be built in a hierarchical manner, by composing component-level networks to form a system-level network.

Big data presents many issues such as data quality, relevance, re-use, decision support, etc. In particular, uncertainty of inference due to data quality, data sparseness and incompleteness, as well as due to the approximations and assumptions in the models used for inference, needs to be addressed. This leads naturally to the next element of this research: uncertainty quantification.

2.4 Uncertainty Quantification

Uncertainty sources in health monitoring may broadly be classified into three categories: natural variability in the system properties and operating environments (aleatory uncertainty); information uncertainty due to inadequate, qualitative, missing, or erroneous data (epistemic uncertainty); and modeling uncertainty induced by assumptions and approximations (epistemic uncertainty). Considerable previous work has focused on variability, but a systematic approach to include data and model uncertainty sources in structural health monitoring still awaits development.

2.4.1 Data Uncertainty

Sensor information may be inadequate, due to sparse, imprecise, qualitative, subjective, faulty, or missing data. Alternatively, one may be confronted with a large volume of heterogeneous data (big data), involving significant uncertainty in data quality, relevance, and data processing. In the context of a probabilistic framework, both situations may lead to uncertainty in the distribution parameters and distribution types of the variables being studied, and the Bayesian approach is naturally suited to handle such data cases and update the description with new information. Flexible parametric or non-parametric representations can be developed within the Bayesian framework to handle such epistemic uncertainty (Sankararaman and Mahadevan, 2011). An important recent development is the extension of global sensitivity analysis to quantify and distinguish the relative contributions of aleatory uncertainty versus epistemic uncertainty (Sankararaman and Mahadevan, 2013) to the overall uncertainty in the analysis output.

2.4.2 Model Uncertainty

There are significant challenges in developing a multi-physics computational framework for concrete degradation modeling that mathematically represents the interactions among the multiple degradation processes and their effect on to the quantities being measured by sensors. The models for various processes could be based on first principles or regression of empirical data. For some components there may not even be any mathematical models available, but perhaps reliability data from past experience or literature. Quantification of the model uncertainty resulting from such heterogeneous information could be studied with respect to three categories, namely, model parameters, model form, and solution approximations; and the corresponding activities to quantify them are calibration, validation, and verification, respectively. Model parameters are estimated using calibration data, and Bayesian calibration constructs probability distributions for the model parameters. Model form uncertainty may be quantified through either a validation metric, based on validation data, or as model form error (also referred to as model discrepancy or model inadequacy). Model form error can be estimated along with the model parameters using calibration and/or validation data, based on the comparison of model prediction against physical observation, and after accounting for solution approximation errors, uncertainty quantification errors, and measurement errors in the inputs and outputs (Liang and Mahadevan, 2011). The Bayesian network offers a systematic approach to integrate the information from various data and modeling sources and to compute the overall uncertainty in diagnosis and prognosis.

3. CONCLUSION AND FUTURE PLANS

This research and development activity will:

- Advance the state-of-the-art in each of the four elements to overcome challenges such as feasibility, complexity, and scalability to develop an effective concrete structural health monitoring framework;
- Enable collaboration across different LWRS pathways, universities, utilities, and vendors; and
- Leverage current knowledge and ongoing national and international research efforts (i.e., the application of knowledge and science from LWRS's MAaD and Advanced II&C Systems Technologies Pathways, EPRI's NDE research initiatives, and other sources) in order to advance the science of data analysis, integration of heterogeneous data, development of diagnostic and prognostic models, and uncertainty quantification.

Based on the initial review of literature on different concrete degradation mechanisms and models, research performed by ORNL on NDE techniques, and other external references, this research will investigate monitoring of physical-chemical-mechanical coupled degradation in concrete via full-field imaging techniques (thermal, optical, and acoustic). Possible full-field techniques include infrared imaging, DIC, and acoustic. Effective combinations of full-field techniques need to be identified for different types of concrete structures. Dynamic operating conditions (cycle loading, pressure variations, humidity, etc.) may lead to coupled chemical-mechanical degradation such as ASR, cracking, corrosion, and internal swelling. The forward analysis of the evolution of concrete degradation is a challenging task in itself, which requires the combination of reactive transport modeling with mechanical degradation models. The inverse problem of damage inference in the presence of multiple damage mechanisms is even more challenging, and requires development of damage signatures that have to be effectively connected to monitoring data.

In addition to full-field techniques, research in identifying appropriate aging management toolbox will be performed. The two candidate toolboxes identified include: EPRI-developed Concrete Structures Aging Reference (COSTAR) database (Gregor and Carey, 2001) and Fleet-Wide Prognostic and Health Management (FW-PHM) Suite software (EPRI, 2011).

EPRI developed the COSTAR database, which was designed to assist engineers in developing or modifying aging management program for concrete structures and is intended for use in developing a structural monitoring program or utilizing an existing structural monitoring program. The COSTAR database is, in essence, an interactive database used to cross-reference materials and degradation data from existing NPPs. It assigns severity rankings to degraded concrete structures and recommends supplemental investigation techniques for licensees. The software consists of Microsoft Access database and also contains recommended inspection frequencies for structures and the suggest disposition under the Maintenance Rule in accordance with Industry Guidelines. COSTAR is applicable for both pressurized water reactors and boiling water reactors.

The FW-PHM Suite software is an integrated suite of web-based diagnostic and prognostic tools and databases, developed for EPRI by Expert Microsystems, specifically designed for use in the commercial power industry (for both nuclear and fossil fuel generating plants). The FW-PHM Suite serves as an integrated health management framework, managing the functionality needed for a complete implementation of diagnostics and prognostics (EPRI, 2011). The FW-PHM Suite consists of four main modules: the Diagnostic Advisor, the Asset Fault Signature Database, the Remaining Useful Lifetime Advisor, and the Remaining Useful Lifetime Database. The FW-PHM Suite has the capability to perform diagnosis and prognosis at different hierarchical levels, from the component level to the plant level, across a fleet of power units.

A study will be conducted to assess the compatibility of the COSTAR and FW-PHM Suite to enhance structural monitoring, diagnostic, and prognostic capabilities of FW-PHM to passive structures in NPPs.

In the long-term, this research will focus on data analysis and development of uncertainty-quantified diagnostic and prognostics models that will support continuous assessment of concrete performance. The resulting comprehensive approach will facilitate the development of a quantitative, risk-informed framework that would be generalizable for a variety of concrete structures and can be adapted for other passive structures.

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Appendix A

Concrete Degradation Mechanisms and Fault Signatures

Category of Degradation	Mode of Degradation	Damage Signature	Potential Degradation Sites	Notes on Degradation
Physical	Irradiation	Volume change, cracking, loss of mechanical properties	Structures proximate to reactor vessel	Neutron fluence exceeding 10^{19}n/cm^2 reduces concrete strength.
	Settlement	Cracking, spalling, misalignment	Compacted structures on independent foundations	Proper geotechnical report and construction practices should suffice
	Freeze / Thaw Cycles	Cracking, spalling	External surfaces where geometry supports moisture accumulation	Air-entrainment lessens effects
	Salt Crystallization	Cracking, scaling, loss material	Surfaces subject to salt spray; intake structures; foundations	External surfaces subject to salt spray, e.g. NPPs on the coast
	Thermal Cycling	Cracking, spalling, strength loss, reduced modulus of elasticity	Near hot process and steam piping	Causes changes in moisture content.
Chemical	Alkali-Aggregate Reaction	Disintegration/cracking	Areas where moisture levels are high and improper materials utilized	Most common type of Alkali-Aggregate Reaction is ASR
	ASR	Cracking, gel exudation, aggregate pop-out	Areas where moisture levels are high and improper materials utilized	High moisture content and siliceous compounds in aggregates required
	Sulfate Attack	Volume change, irregular cracking	Subgrade structures and foundations	Sulfate attack causes whitish appearance of concrete
	Chloride	Corrosion of steel reinforcement, delamination, spalling	Surfaces subject to salts, proximate to sea	Chlorides combined with high moisture levels cause steel corrosion
	Carbonation	Reduces pH, strength gain in concrete, corroded steel rebar	Surface of concrete, CO_2 from air reacts with calcium hydroxide	Rebar's layer of surface passivation will dissolve allowing corrosion

Category of Degradation	Mode of Degradation	Damage Signature	Potential Degradation Sites	Notes on Degradation
Chemical (contd.)	Delayed Ettringite Formation	Volume change, reduced compressive strength, cracking	Areas where cements have high sulfate contents	High early temperatures prevent normal formation of ettringite
	Biological Attack	Increased porosity/ erosion	Areas where microgrowth exists	Mosses and lichens produce acid that attacks cement paste
Steel Reinforcement	Corrosion	Concrete delamination, spalling, cracking, change in rebar x-section	Outer layer of steel reinforcement near cracks or other defects	Chlorides and carbonation play important role in rebar corrosion
	Irradiation	Reduced ductility, increased yield strength	Structures proximate to reactor vessel	Irradiation generally below 10^{19} neutrons/cm^2 or 10^{10} Rads dose
	Fatigue (Cyclic Loading)	Loss of bond to concrete; failure of steel under extreme conditions	Equipment supports and piping supports	Fatigue could be caused by pressurization tests

Appendix B

Monitoring Techniques and Associated Damage Signatures

Monitoring Technique	**Active/ Passive**	**Technology Used**	**Damage Signature Measured**	**Degradation Type**
Digital Imaging Correlation	Passive	High resolution optical photography	Surface Microcracks	ASR
			Surface Cracks	Freeze/Thaw, Thermal Cycling
Infrared Thermography	Passive / Active	Temperature gradients are created and load paths can be mapped	Delamination	Rebar Corrosion
			Voids	Construction Practices
			Cracks	ASR
Shear-wave Ultrasound	Active	Pitch and catch method using an oscillating sound pressure wave	Delamination	Corrosion
			Unbonded rebar	Corrosion
			Cracks	Freeze/Thaw, ASR
			Spalling	Corrosion
Ground Penetrating Radar	Active	Electromagnetic waves at high frequencies are detected after reflecting off of subsurface structures	Severe Debonding	Rebar Corrosion
			Voids	Construction Practices
			Severe Cracks	Settlement
Acoustic Emission	Passive	Detect and characterize fracture from the sound (elastic wave) caused by the release of strain energy	Active Microcracks	ASR
			Active Cracks	ASR, Freeze/Thaw
			Active Delamination	Corrosion
			Active Spalling	Corrosion
Sensing Skin	Passive	Electrically conductive coating of paint detects surface changes by change in conductivity	Surface Microcracks	ASR
			Surface Cracks	Freeze/Thaw, Thermal Cycling