Light Water Reactor Sustainability Program

Survey of Models for Concrete Degradation

August 2014

DOE Office of Nuclear Energy

Light Water Reactor Sustainability Program

Survey of Models for Concrete Degradation

Benjamin Spencer[1] and Hai Huang[2]

[1]Fuel Modeling and Simulation
[2]Energy and Environment Science & Technology

August 2014

Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov/lwrs

Executive Summary

Concrete is widely used in the construction of nuclear facilities because of its structural strength and its ability to shield radiation. The use of concrete in nuclear facilities for containment and shielding of radiation and radioactive materials has made its performance crucial for the safe operation of the facility. As such, when life extension is considered for nuclear power plants, it is critical to have predictive tools to address concerns related to aging processes of concrete structures and the capacity of structures subjected to age-related degradation.

The goal of this report is to review and document the main aging mechanisms of concern for concrete structures in nuclear power plants (NPPs) and the models used in simulations of concrete aging and structural response of degraded concrete structures. This is in preparation for future work to develop and apply models for aging processes and response of aged NPP concrete structures in the Grizzly code. To that end, this report also provides recommendations for developing more robust predictive models for aging effects of performance of concrete.

This report provides an overview of a variety of aging mechanisms potentially of concern for concrete structures in nuclear power plants. Aging mechanisms that can degrade concrete include freeze/thaw cycles, high temperature and thermal cycles, radiation, abrasion, fatigue, and a variety of chemical processes, including calcium leaching, chloride attack, carbonation, sulfate attack, salt crystallization, and alkali-aggregate reactions. In addition to degradation of concrete, degradation of reinforcing steel and prestressing tendons is also of concern. Embrittlement, loss of cross-sectional area, and loss of prestressing can all have a major impact on the load-bearing capacity of these structures.

A comprehensive approach for modeling effects of aging in concrete structures should provide the capability to represent the various aging processes, the effects of aging mechanisms on the strength of concrete and steel, and the response of structures damaged by aging to a variety of insults.

As described in this document, accurate modeling of the aging process of concrete structures would require a nonisothermal, multiphase, multicomponent thermodynamically-based reactive transport model coupled with solid mechanical model that can appropriately model pre- and post-damage mechanical behaviors of aging concrete. The strong nonlinearity and tightly coupled nature of this problem requires solving a fully coupled set of partial differential equations describing thermal, porous flow, reactive transport, and mechanical processes. The Grizzly code has existing capabilities for multiphysics coupling, reactive porous flow, heat conduction, and solid mechanics can be leveraged to provide a unique capability to address concerns related to life extension of aged concrete structures.

Contents

Abbreviations

AAR   Alkali-aggregate reaction

NPP   Nuclear Power Plant

XFEM   Extended Finite Element Method

1   Introduction

Concrete has been used in the construction of nuclear facilities because of two primary properties: its structural strength and its ability to shield radiation. Concrete structures have been known to last for hundreds of years, but they are also known to deteriorate in very short periods of time under adverse conditions. The use of concrete in nuclear facilities for containment and shielding of radiation and radioactive materials has made its performance crucial for the safe operation of the facility. The goal of this report is to review and document the main aging mechanisms of concern for concrete structures in nuclear power plants (NPPs) and the models used in simulations of concrete aging and structural response of degraded concrete structures. This is in preparation for future work to develop and apply models for aging processes and response of aged NPP concrete structures in the Grizzly code. To that end, this report also provides recommendations for developing more robust predictive models for aging effects of performance of concrete.

2   Aging mechanisms of concrete structures

Long-term degradation of concrete structures in nuclear power plants (NPPs) is mainly influenced by interacting physical (freeze/thaw, elevated temperature, radiation etc.), chemical (e.g., slow hydration, leaching, volume expansion reactions) and mechanical (e.g., cracking) processes leading to the changes of the microstructure of cement constituents and the propagation of micro-cracks [1, 2, 3, 4]. Mechanical damage accelerates the chemical degradation as a consequence of improving transport properties of water and reactants (e.g., porosity, permeability, reactive surface area). The durability of concrete structures can be limited as a result of adverse performance of its cement-paste matrix or aggregate constitutes (including reinforce wires, rebars and strands) under either physical or chemical attack, In practice, these different processes may occur concurrently to reinforce each other. In nearly all chemical and physical processes influencing the degradation of concrete structures, dominant factors include transport mechanisms within the pores and cracks, and the presence of water.

Cracking occurs in virtually all concrete structures and, because of concrete's inherently low tensile strength and lack of ductility, can never be totally eliminated [1]. Cracks are significant from the standpoint that they can indicate major structural problems, provide important pathways for the ingress of hostile environments, and reduce their capability for shielding radiation [5, 6]. Cracking occurs within each material constituent (e.g., cement-paste matrix, aggregates), and can occur while the concrete is in either a plastic (initial setting) or hardened state [7]. From an aging management perspective for existing structures, causes of concrete degradation due to either chemical and(or) physical attacks during the life of service are of primary interest.

2.1   Physical processes

Physical attacks involve the degradation of concrete due to external influences and generally involves cracking due to exceeding the tensile strength of the concrete, or loss of surface material. Concrete attack due to overload conditions is not considered as an aging mechanism. The primary types of physical attacks to concrete material are:

- freezing and thawing cycles;

- high temperature and thermal cycling;

- irradiation;

- abrasion, erosion, and cavitation; and

- fatigue and vibration.

2.1.1   Freezing and thawing cycles

Concrete materials that are saturated or nearly saturated with water can be damaged by the repeated freezing and thawing cycles. The water within the concrete pores expands as it freezes, causing an increase in hydraulic pressure within the concrete. In the northern U.S., the freeze/thaw cycles occur up to 50 times per year. Damage to concrete structures usually takes the form of scaling or flaking, spalling, and pattern cracking [8]. The concrete's resistance to freeze/thaw damage can be increased by controlling the size and space of air bubbles in cement paste, minimizing the presence of large pores and limiting the water saturation in concrete.

2.1.2 High temperature and thermal cycles

Elevated-temperature exposure and thermal gradients are important to concrete structures in that they affect the concrete's strength (i.e., ability to carry loads) and stiffness (i.e., structural deformations and loads that develop at constraints). The mechanical property variations result largely because of changes in the moisture content of the concrete constituents and progressive deterioration of the cement paste and aggregate (especially significant where thermal expansion values for cement paste and aggregate are markedly different). Significant deterioration of the concrete strength does not generally occur until the exposure temperature reaches 400 °C, at which point dehydration of calcium hydroxide occurs [9]. Reference [10] suggested that concrete exposed to temperatures of 90 °C may lose up to 10 percent of its room-temperature strength and stiffness. The response of concrete to elevated-temperature exposure depends on a number of factors (e.g., type and porosity of aggregate, rate of heating, permeability, moisture state, etc.). In addition to potential reductions in strength and modulus of elasticity, thermal exposure of concrete can result in cracking, or when the rate of heating is high and concrete permeability low, surface spalling can occur. Long-term exposure to high temperatures can cause changes in compressive strength, modulus of elasticity, creep resistance, conductivity, diffusivity, and shrinkage/expansion characteristics [10]. The effect of temperature is even more pronounced on the tensile strength of concrete. A temperature increase from 20 to 100 °C may cause a reduction of the tensile strength of concrete by as much as 50 percent [4].

Thermal cycling, even at relatively low temperatures (<65 °C), can have some deleterious effects on concrete's mechanical properties (i.e., compressive, tensile and bond strength, and modulus of elasticity are reduced) [11, 12]. At higher temperatures (200 to 300 °C), the first thermal cycle causes the largest percentage of damage, with the extent of damage markedly dependent on aggregate type and is associated with loss of bond between the aggregate and matrix. Temperature variations, or thermal cycles, also can become important if the deformation of the structure resulting from the temperature variations is constrained (see [1] and references therein). A report on an extensive experimental study on the effects of elevated temperatures on concrete is provided in [13].

2.1.3 Radiation

There are two sources for irradiation-related damage of concrete:

- the bombardment the material by fast and thermal neutrons from the reactor core; and

- the gamma rays from the reactor core and those produced when neutrons are captured by steel in the vicinity of concrete.

The fast neutrons can cause atomic displacements within the concrete matrix, resulting in significant growth of certain aggregate such as flint. The gamma rays produce radiolysis of the water in cement paste, which can affect the creep and shrinkage behavior of concrete to a limited extent [14, 15, 1, 4]. The approximate levels of irradiation necessary to cause measurable damage in concrete were reported to be 1×10^{19} neutrons per square centimeter (n/cm^2) for neutron fluence, and 10^{10} rads of gamma radiation dose [16]. These values indicate that irradiation damage of the primary concrete containment may occur after over 40 years of operation [17]. The researchers indicated that the damage due to irradiation may be reduced by such factors as air gaps and insulation. however, damage to the concrete by irradiation was felt to be less than that caused by related temperature effects [4, 1]. Damage due to excessive irradiation of concrete is manifested through cracking and spalling at exposed surfaces and as a loss of tensile and compressive strength and stiffness.

3

2.1.4   Abrasion, erosion and cavitation

The forces and processes of abrasion, erosion, and cavitation cause the progressive loss of material at the concrete surface. [1, 3] Abrasion is the dry attrition of the concrete. Erosion is the wear due to flowing fluids. Cavitation is the loss of material due to the rapid formation and collapse of vapor bubbles in flowing water. Concrete structures can be made to resist abrasion and erosion by improving the quality of the concrete mixture. High quality concrete mixtures are those that produce low porosity and high strength. Cavitation can be avoided by adjusting the pump speed.

2.1.5   Fatigue and vibration

Fatigue and vibration are mechanical stressors due to the fluctuations in loading, temperature, and moisture content. Concrete deterioration by fatigue begins as microscopic cracks in the cement paste near areas of large aggregate particles, reinforcing steel, or defects where stresses tend to concentrate. Large scale concrete failure due to fatigue is manifested by excessive cracking, excessive deflections, and brittle fracture. Vibration on concrete structures occurs at the supports for piping systems, pumps and turbines.

The nuclear industry has reported no significant fatigue-related concrete failures. Fatigue failure of concrete is unusual because of its good resistance to fatigue, and concrete structures are designed using codes that limit design stress levels to values below concrete's endurance limit [18, 19]. However, as structures age, there may be instances of local fatigue damage at locations where reciprocating equipment is attached, or at supports for pipes that exhibit flow-induced vibrations.

2.2   Chemical processes

Chemical attacks involve the alteration of concrete microstructures and mineralogy through various chemical reactions (all requiring the presence of water) with either the cement paste, or aggregates, or embedded reinforcing steels. Generally chemical attack occurs on the exposed surfaces of concrete, but with the presence of cracks or prolonged exposure, chemical attack can affect entire cross-section of the concrete structure. Reports [3, 1, 2, 4] provide comprehensive summaries of chemical processes related to degradation of concrete materials. Chemical causes of deterioration can be grouped into three categories: (1) hydrolysis of cement paste components by soft water; (2) cation exchange reactions between aggressive fluids and the cement paste; and (3) reactions leading to formation of expansion products [20, 21]. The rate of chemical attack on concrete is a function of the pH of the aggressive fluid and the concrete permeability, alkalinity, and reactivity. A variety of processes, such as transport of fluid and reactants, chemical reactions and reaction-induced mechanical property changes and fracturing, are involved and strongly coupled together. Because of these couplings, simulation of aging due to these processes leads to an extremely challenging nonlinear multiphysics problem. The following subsections summarize the major chemical processes that potentially lead to degradation of concrete.

2.2.1   Calcium leaching and efflorensce

As water infiltrates into and percolates through concrete structures via connected pores and cracks, soluble minerals such as calcium hydroxide in cement paste will dissolve into water and be transported away by the flowing water. This process is called calcium leaching [22, 6]. With time this leaching of calcium and other mineral component will increase the porosity and permeability of concrete, which in turn further accelerates infiltration of water and leaching. The increases of porosity and permeability lead to decreases in the strength and stiffness of concrete.

The calcium leaching rate is largely a function of temperature, concentration of calcium within infiltrating water and pH. For example, calcium hydroxide is more soluble in cold water. The lower the calcium concentration, the higher the degree of undersaturation in terms of calcium hydroxide, indicating faster dissolution kinetics in cement paste. Hydrated cement paste is an alkaline material with a pH of 12.5 or higher. Thus acidic solutions can easily react with calcium hydroxide and other alkaline minerals via dissolution reactions. The dissolved minerals can then be removed from the internals of concrete by water convection.

Efflorescence is more of a surface phenomenon: as water carrying dissolved minerals approaches the surface of concrete and evaporates, the dissolved minerals deposit onto the surface. Efflorescence typically does not affect the structure's durability, but is certainly an indicator that leaching is taking place in the concrete structure.

2.2.2   Chloride attack

Chloride attack is one of the most important aspects for deterioration of concrete structures [23, 24, 25, 26, 27, 28]. Due to the high alkalinity of cement paste, a protective oxide film exists on the surface of steel reinforcement. This protective layer can be lost due to the presence of chloride ions in water and oxygen, inducing corrosion of steel reinforcement. The products of corrosion are greater in in volume (up to 600 percent) than original reinforcing steel, resulting in cracking and spalling of concrete.

There are a number of factors that contribute to the rate at which concrete deterioration can occur as a result of chloride attack. The physical characteristics of the concrete itself are chief among these variables. By its very nature, concrete is a porous material, and its strength and durability are determined largely by factors such as the water/cement ratio, compaction and curing. Because of the nature of the mechanisms of chloride attack, the density of concrete becomes an important influencing factor on the rate of its deterioration: concrete with smaller pores and lower pore connectivity will absorb less water or vapor and inhibit their transport, thus slowing down the ingress of chlorides into the structure.

The physical condition of surface concrete plays an important role in the rate of deterioration. If there is existing surface damage, particularly in the form of abrasions, the resulting cavities and cracks accelerate the transportation of moisture and ions to the steel, which amplifies the rate of corrosion. Freeze thaw cycles can then further exacerbate the process.

In marine environments, reinforcing steel corrodes mainly because of the attack by chloride ions, as sea water is a major source of chloride ions.

2.2.3   Carbonation

Carbon dioxide (CO2) in air can dissolve into water and react with the calcium hydroxide in cement to form calcium carbonate, a process called carbonation [28, 29, 30]. This carbonation reaction can increase the mechanical strength of concrete. However, the carbonation reaction also reduces the alkalinity of cement, which could potentially destroy the passive layer on the surfaces of reinforcing steel and accelerate corrosion of reinforcing steel. The volumetric increase of the corrosion product then causes cracking of concrete, similar to corrosion cracking induced by chloride attack.

Carbonation of concrete is typically a slow and continuous process progressing from the surface toward the interior of concrete, and slows down with increasing distance from the surface. However, cracking can accelerate carbonation since cracking can both provide preferential pathways for reactive fluids and new reactive surfaces. Some numerical models had been developed to simulate and predict migrations of carbonation front in concrete structures [31, 32, 33], mostly focusing on the coupled fluid flow and reaction processes.

2.2.4   Sulfate attack

Alkali sulfates such as sodium, potassium and magnesium sulfates in soils and groundwater can react with the hydrated lime (calcium hydroxide) and calcium aluminate in cement paste when water penetrates into the concrete through connected pores and cracks to form gypsum (calcium sulfate) and ettringite (calcium sulfoaluminate) minerals [34, 35, 36]. These reactions, with the presence of enough water, result in considerable volume expansion of the solid phases in cement paste, leading to cracking of concrete and progressive loss of cohesive strength. The rate of sulfate attack depends on the reactivity of cement paste and the concentration of sulfate in water penetrating into concrete. Research has suggested that sulfate concentrations in water of 1200ppm and higher can aggressively attack concrete in nuclear power plants [2]. Concretes that use cements low in tricalcium aluminate and those that are dense and of low permeability are most resistant to sulfate attack [3].

2.2.5   Salt crystallization

Salt crystallization occurs when the water in the pores of concrete cement contains a large amount of dissolved salts such as calcium sulfate ($CaSO_4$), sodium chloride ($NaCl$) and (or) sodium sulfate (Na_2SO_4). Such salty water can permeate through concrete and evaporate, leaving the salts to crystallize and grow in the pores. The repeated cycles of evaporation and crystallization of salts can drive the growth of salt crystals in confined pores. The continuous growth of salt crystals in confining pores exerts forces onto pore walls and increase the stress level within cement, which eventually leads to concrete cracking [37, 38]. The concrete structures most susceptible to salt crystallization damage are those in contact with fluctuating water levels or with salted ground water [38].

2.2.6   Alkali-aggregate reactions

Alkali-aggregate reactions (AAR) are chemical reactions involving alkali ions (Portland cement), hydroxyl ions, and certain siliceous constituents that may be present in aggregate materials and can form a gel. As the alkali-silica gel comes in contact with water, swelling occurs, causing hydraulic pressure that can cause cracking, and could eventually lead to complete destruction of the concrete [39, 40]. Visible concrete damage starts with small surface cracks exhibiting an irregular pattern (map cracking). The expansion will develop in the direction of least constraint (e.g., patterns parallel to a surface developing inward from the surface of a slab or cracking parallel to the direction of compression forces in columns or prestressed members). Popouts and glassy appearing seepage of varying composition can appear as a result of alkali-silica reactions. Expansion reactions also can occur as a result of alkali-carbonate reactions (i.e., dedolomitization).

Concrete deterioration due to alkali-aggregate reactions typically occurs within 10 years after plant construction, but some structures show no sign of deterioration until 15 to 25 years after construction [1, 3]. This delay indicates that there is a less reactive form of silica to hinder these reactions. This type of deterioration of concrete is manifested in the form of map or continuous cracking, popouts, and spallation. Primary factors influencing alkali-aggregate reactions include the aggregate reactivity (i.e., amount and grain size of reactive aggregate), alkali and calcium concentrations in concrete pore water, cement content (i.e., alkali content), and presence of water.

2.3   Aging of reinforcing steel

Virtually all concrete structures of interest contain reinforcing steel. Because concrete is significantly weaker in tension than compression, reinforcing steel is typically provided for tensile and shear strength, but can also be provided to help resist compressive loads. A minimal amount of reinforcement is required for all structures

to resist tensile stresses due to shrinkage and thermal effects [41]. Potential causes of degradation of the mild reinforcing steel are corrosion, elevated temperature, irradiation, and fatigue. Of these, corrosion is the factor of most concern for aging management of concrete structures in nuclear power plants [1]. Information on the other potential degradation factors is provided for completeness and special situations that might occur.

Corrosion of steel in concrete is an electrochemical process that can assume the form of either general or pitting corrosion. Both water and oxygen must be present for corrosion to occur. The electrochemical potentials that form the corrosion cells may be generated in two ways [42, 43, 44, 45]: (1) composition cells formed when two dissimilar metals are embedded in concrete, such as steel rebars and aluminum conduit, or when significant variations exist in surface characteristics of the steel; and (2) concentration cells formed due to differences in concentration of dissolved ions in the vicinity of steel, such as alkalies, chlorides, and oxygen. As a result, one of two metals (or different parts of the same metal when only one metal is present) becomes anodic and the other cathodic. Other potential causes of corrosion include the effects of stray electrical currents or galvanic action with an embedded steel of different metallurgy. The transformation of metallic iron to ferric oxide (rust) is accompanied by an increase in volume that can cause cracking and spalling of the concrete. In addition, corrosion will result in a reduction in effective steel cross-section and capacity. Depending on the source of the corrosion, local embrittlement may also occur.

In dense concrete with low permeability and porosity, the high alkalinity condition within the concrete (typically with pH > 12) causes a passive iron oxide film to form on the iron surface. However, when the pH of pore water falls below 11, a porous oxide layer (rust) forms on the reinforcing steel due to corrosion. Carbonation and the presence of chloride ions can destroy the passive iron oxide film. For example, carbonation reduces the pH of pore water within concrete, leading to corrosion, and corrosion cracking in turn accelerates the carbonation reactions. The passive iron oxide film on the steel reinforcement can also be destroyed in the presence of chloride ions in pore water, even at high alkalinities (with pH > 11.5), which promotes corrosion [23, 24, 25, 26, 27, 28].

The influence of elevated temperature on the reinforcing steel is considered to be negligible because the operating temperatures of concrete are typically far lower than the threshold temperature of 200 °C where the mechanical properties of the reinforcing steel are significantly affected [2].

Irradiation can produce changes in mechanical properties such as the yield strength and ductile/brittle transition temperature of carbon steel. The effects of irradiation include a reduction of ductility, increasing the risk of brittle fracture. The steel most susceptible to irradiation damage is located in shield walls. The concrete cover over the steel provides shielding from the neutron fluence. According to the report prepared by Do and Chockie [2], irradiation does not appear to be detrimental to the reinforcing steel, but they recommended additional research on its possible impact.

The effects of fatigue on reinforcing steel are similar to the previously described effects on concrete. Some loss in the strength of the bond between steel and concrete is expected due to vibration. Overall, however, failures of steel reinforcement due to fatigue are not likely to occur.

2.4   Aging of prestressing steel

Potential causes of degradation of the prestressing steel tendons include corrosion, elevated temperature, irradiation, fatigue, and loss of prestressing force. Of these, corrosion and loss of prestressing force are most pertinent from an aging management perspective [1, 3].

Corrosion of prestressing systems can be highly localized or uniform. Most prestressing corrosion-related failures have been the result of localized attack produced by pitting, stress corrosion cracking, hydrogen embrittlement, or a combination of these. Pitting is the electrochemical process that results in locally intensified material loss at the tendon surface, potentially reducing the cross section to the point where it is incapable of supporting load. Stress corrosion cracking results in the fracture of a normally ductile metal or alloy under stress (tensile or residual) while in specific corrosive environments. Hydrogen embrittlement, frequently

7

associated with hydrogen sulfide exposure, occurs when hydrogen atoms enter the metal lattice and significantly reduce its ductility. To protect against corrosion, the ducts containing the post-tensioned tendons are filled with organic corrosion inhibitors. These inhibitors include waxes such as petrolatum or Portland cement grout [2].

During construction, a force known as the jacking force is applied to prestressing tendons. When the jack is removed, a number of mechanisms lead to an instantaneous reduction in the prestressing force. These include friction, anchorage deflection, elastic shortening of the concrete as it is placed in compression, stress relaxation in the tendons due to shortening, and anchorage deflection. The prestressing load at this point is known as the initial prestressing force. Over time, the prestressing load is further reduced from the initial prestressing force due to stress relaxation of the tendons and creep and shrinkage of the concrete [46]. Corrosion and anchorage slip could also contribute to prestressing loss. This time-dependent relaxation is considered to be aging-related degradation processes [2]. The extent of stress relaxation depends on material properties, initial stress level, temperature, and time under loading. Concrete creep and shrinkage are changes in volume that occur over the process of curing and aging of the structure, resulting in a contraction of the concrete in the direction parallel to the prestressing, and an accompanying decrease in the prestressing force.

Prestressing is used to achieve improved characteristics in the design of a concrete structure. Because concrete is primarily a compressive load-bearing material, prestressing optimizes the performance of concrete by minimizing the portion of the concrete that is in tension. This can result in increased stiffness, more efficient use of materials, and minimal deflection and cracking under design loads. A loss of prestressing results in a loss of the benefits intended to be provided by the prestressing in the design of the structure. Loss of prestressing results in increased cracking and deflection under loading.

2.5 Summary of aging mechanisms most important to NPPs

Concrete deterioration generally stems from more than one aging mechanism, and it is usually very difficult to identify the initial reason why the concrete has no longer able to resist external or internal attack. However, published literature [1, 2, 3, 4], shows that the most important cause of degradation is corrosion of the reinforcing steel, followed by the effect of frost in cold climates, and the physical-chemical effects of external as well as internal phenomena on the hydrated cement paste. Damage to concrete structures due to corrosion of the reinforcing steel is generally apparent from the loss of concrete cover and from the loss of the bond between the concrete and steel. Obviously, marked corrosion does not develop unless the concrete is permeable from the beginning or becomes permeable in service, due to microcracking consequent to various physical and chemical attacks. In fact, if the concrete quality and cover thickness are adequate, the three basic conditions for corrosion, i.e., iron available in the metallic state for the anode process, oxygen and moisture available for the cathode process and a low electrical resistivity for the electron flow, do not occur during service life. With regard to the anode process, the alkalinity of the cement paste near the reinforcing steel must be reduced and the protective film of iron oxides or hydroxide must be destroyed before metallic iron becomes available (first condition). In saturated conditions with moisture available, the coefficient of oxygen diffusion is very low and oxygen is not readily available for corrosion; on the other hand, in dry conditions, when gas diffusion is facilitated, moisture is not available for the cathode process; moreover, dry conditions are inappropriate for a reduction in electrical resistivity.

Much research has been devoted to the identification of the influence of various factors (e.g., cement type and content, water/cement ratio, depth of cover, crack widths, environmental conditions) on corrosion phenomena of reinforcing steel. The corrosion initiation period depends on the rate of CO_2 diffusion in both the air and pore water (carbonation to reduce pH of pore water near reinforcing steel) and the diffusion rate of chlorides through pore water (responsible for depassivation of the steel). The availability of pore water near steel and the permeability of the cement play key role in determining the corrosion rate of reinforcing

steel.

3   Numerical models for aging mechanisms

Accurate prediction of degradation of aging concrete structures is of great concern in many fields including nuclear power plants and civil engineering. However, as described in the previous sections of this report, concrete degradation generally stems from more than one cause. These various aging processes, including flow of fluids, transport of chemicals and heat, freeze-thaw cycles, expansive chemical reactions, mineral dissolution and precipitation and corrosion of reinforcing steel, typically act together closely to introduce microcracks (often referred to as damaging) in concrete structures. The damaging of concrete in turn usually facilitates water flow and transport of reactive chemicals, which further accelerate damage. Therefore, accurate predictions of aging behavior of concrete structure would require fully coupled therm-hydro-mechanical-chemical multiphysics models. Extensive work has been done over the past few decades on theoretical and experimental analysis to identify the influence of various factors (such as cement type, water/cement ratio) and aging mechanisms on degradation behavior of concrete. However, most of the numerical models developed to deal with degradation phenomena are based on fluid flow and transport theory of porous media [47, 48], and only consider the effect of one or a small subset of the aging mechanisms [32, 49, 30, 50, 6, 5, 33, 51, 21, 22, 52, 53, 31, 54, 55, 56, 57, 58, 59, 60, 61, 62].

For example, finite element based models for carbonation of concrete have been presented over the past two decades [32, 29, 33, 31], all treating concrete as a porous medium and coupling moisture, heat and CO2 flow together, with simplified reaction network. The main purpose of these studies is to provide a theoretical approach capable of predicting the depth of carbonation as function of time and external boundary conditions. The changes of porosity and permeability due to carbonation reactions within concrete were included in these models. However, these models were not coupled with mechanical models (no mechanical-chemical coupling). One of the most important consequences of carbonation in concrete is the reduction of pH of pore water, which potentially leads to accelerated corrosion of reinforcing steel and microcracking.

Similarly, finite element models were also developed for analysis of concrete swelling due to alkali-aggregate reactions [52, 63] without incorporating solid mechanics coupling. Ulm et al. [64] presented a chemoelasticity model to study internal stress build up in concrete due to alkali-aggregate reactions, similar to poroelasticity model. However, the details of chemical reactions were highly simplified and the volume expansion is approximated by a first-order reaction kinetics, without considering concrete damaging and feedback of damaging to transport and reaction processes. The model of [65] for AAR includes coupling with solid mechanics.

Coupled chemo-mechanical models for degradation of concrete due to calcium-leaching reaction [6, 5, 66] have included coupling to phenomenological solid mechanics models based on damage mechanics approach [67, 68, 69, 22, 70]. Empirical constitutive relationships were typically used to related the mechanical and transport properties of concrete with reaction kinetics and damaging coefficient.

More recently, Coussy and Monterio [71] presented a linear poroelasticity model for study internal stress buildup within unsaturated concrete subject to freezing temperatures by extending the classic poroelasticity theory for saturated porous media [72] for unsaturated conditions. Although there is no damage mechanics included in their mechanical model, it does provide a method for quantitative analysis of stress and strain developed due to freezing of pore water, and provides an efficient method to analyze the influence of entrained air-voids on the frost resistance of porous materials. Coupled thermo-chemo-mechanical models using a finite element approach were also developed by Cervera at al. [60, 61] to study the behavior of concrete at early ages. The coupled model allows simulation of the observed phenomena associated with hydration, aging, damage and creep of concrete during curing and hardening stages. This model allows predictions of the evolution in time of the hydration degree and heat production. The evolution of compressive and tensile strengths and elastic moduli are in turn related to the hydration degree. The short- and long-term mechanical behavior are modeled by a viscoelastic damage model. However, fluid flow and transport (dif-

fusion and convection) of chemicals are not in this model. Furthermore, the hydration reaction, despite of its complexity in reaction network and kinetics, is simplified as a phenomenological reaction model with a temperature dependent Arrhenius-type rate equation. Furthermore, this is no feedback of damaging on chemical processes.

Although much progress has been made in modeling concrete aging behavior due to various physical and chemical processes, largely due to the complex interactions among various processes, the majority of the developed models are typically limited to (1) a simplified model for fluid flow (vapor, dry air, liquid water) in which fluids filling the pores are modeled as an equivalent fluid [73, 74, 75]; and (2) use of phenomenological reaction models (single species) to account for volumetric expansion, without detailed chemical reaction networks and phase partitioning between aqueous and gaseous phases,coupled with transport process of reactants (both diffusion and convection). These simplified models, though facilitating numerical implementations and reducing computational burden, should be used with caution and only under particular conditions, due to the incomplete set of physics represented. It is now widely recognized that modeling of concrete as a variably saturated porous medium and multiphase system is a more rigorous approach for the mass and heat transport processes that occur in concrete exposed to environments [54]. Thus, more general three-field flow models for flow of vapor, air and liquid water in variably saturated porous media were also developed based on multiphase flow and transport theory of unsaturated, deformable, porous media [76, 77, 78, 49], mostly using a finite element approach. It is worthy to mention the model presented by Gawin et al. [56, 62], in which the multiphase flow model (air, vapor and water) and heat transport (both convection and conduction) model were coupled with a damaging solid mechanics model, with two-way coupling among transport/flow properties (i.e., permeability and porosity) and mechanical damage coefficients. Only hydro-thermo-mechanical processes were included in their model to study concrete degradation at elevated temperature, however, the concomitant transport of reactants with fluid flow and reactions and their effects on concrete degradation were not considered in these models.

In the chemical-transport simulations of degradation of concrete materials, reactive transport models have varying levels of complexity [79, 80, 81, 82, 83, 84]. The simplest reactive transport model is that of calcium leaching, which only involves one reactant-calcium in pore water [80], without considering complex solution-mineral reactions and aqueous speciations and often assuming some type of phenomenological reaction and kinetics. Many coupled chemo-mechanical models cited previously in this section belong to this category. A more complex reactive transport model involves multiple reactive species in aqueous phase, such as those for carbonation and sulfate attacks [85]. More advanced multi-species reactive transport models that involves full aqueous speciations and pore water-mineral reactions were also developed for predicting spatial and temporal distributions of reactive species in concrete cement [83, 84, 86]. These full multi-species reactive transport models allow more accurate predictions of the spatial-temporal evolution of cement mineralogy and solution chemistry, which is critical in terms of understanding the coupling effects between reactions and mechanical damage on concrete degradation. This is especially crucial in the case of complex aggressive solutions containing multiple dissolved ions and reactions with pH buffering (i.e., carbonation reaction). Some reactive transport models ignore fluid flow and associated convective transport of reactive species in the aqueous phase, and only considered molecular diffusion of reactive species [86]. Such an assumption is only valid in the case where there is no significant fluid pressure gradient within and across concrete structures, or the permeability of concrete is too small to allow fluid flow. Permeability and porosity of aging concrete often increase over time due to calcium leaching or microcracking induced by expansive chemical reactions. Under such circumstance, both convective transport and hydrodynamics dispersion need to be considered in reactive transport models.

In modeling chemical aging of concrete structure, thermodynamic geochemical modeling were also adopted in order to better understand reaction networks within the cement of concrete and identify important reactions [86, 82]. Such geochemical models do not include any transport process of reactive species. Instead, they tend to compute equilibrium mineral assemblage, fluid phase equilibrium, aqueous speciation

in a complex chemical system from its total bulk elemental composition, based on minimization of Gibbs free energy [87, 88, 89]. Although such thermodynamic geochemical modeling is crucial to understand the reaction network and helps better understand the chemical aging mechanisms, these geochemical models need to be coupled with nonisothermal, multiphase, multicomponent reactive transport models to provide accurate predictions for degradation of concrete under chemical attacks. However, based on our review of existing models, such general purpose nonisothermal, multiphase, multicomponent reactive transport models for concrete under all relevant chemical aging mechanisms are still in the early development stage. In the field of subsurface hydrology and groundwater contaminant transport, much experience and success has been gained in developing such general purpose nonisothermal, multiphase, multicomponent reactive transport models and their applications for many geotechnical applications such as remediation of contaminated groundwater, geothermal reservoirs and CO2 geological storage [90, 91, 92, 93, 94, 95]. All these subsurface reactive models include full fluid phase equilibrium, aqueous speciation and solution-mineral chemistry. Although these subsurface reactive transport models primarily deal with porous geomaterials, they can be readily adapted for modeling reactive transport process in concrete.

4   Mechanical behavior of degraded concrete

Reinforced concrete is a complex composite material. The concrete itself consists of a mix of hydrated cement, sand, and aggregate. In addition, almost all concrete structures of interest contain significant amounts of reinforcing steel, some of which has prestressing forces applied in many important applications. To accurately predict the behavior of reinforced or prestressed concrete, the response of the individual constituents and their interactions as part of a composite system with must be considered.

An ability to model the nonlinear mechanical response of reinforced and prestressed concrete, including damage processes, is important for the current effort for two major reasons:

- Mechanical deformation and damage of concrete are key physical aspects that must be considered in multiphysics models of aging processes.

- The nonlinear response of the constituents of the reinforced concrete system is needed to predict the ability of an aged structure to withstand a variety of insults that it may be subjected to.

The need for including the damage behavior of concrete in multiphysics models of aging processes has been discussed extensively in the previous section. Many of the important aging processes are highly dependent on the porosity of the concrete, which is affected by those aging processes and by stress-induced damage mechanisms. Once the extent of damage due to aging processes has been predicted at a certain point in time, the critical question to be answered is whether the aged structure can still adequately withstand the full range of loading that it has been designed to resist. To answer this question, the nonlinear response of the structure in its aged condition must be evaluated. These two regimes of behavior place competing demands on the material models used to represent concrete behavior, and there are few examples in the literature of models that can be used in both regimes.

4.1   Overview of concrete behavior

As a man-made geological material consisting of bonded aggregates, concrete is a quasi-brittle, frictional material. As such, its behavior is defined by the following important characteristics [61, 96, 97]:

- Concrete behaves as an isotropic elastic material behavior prior to damage.

- Concrete has significantly different behavior under tension and compression. The strength of concrete under uniaxial tensile loading is roughly 1/10 its strength under compressive loading. Concrete has residual tensile strength when loaded in tension past its peak strength, but it has much less ductility than in compression.

- The strength of concrete is highly dependent on the multiaxial stress state. As a frictional material, concrete has significantly increased strength under compression. The function proposed by [98] is a widely accepted description of the shape of the yield surface. It represents the weak brittle behavior in tension and the transition into more ductile material with increased deviatoric strength under increasing pressure. It also includes a cap on the surface under high pressure.

- Loading of concrete into the nonlinear regime, past the yield function, results in significant inelastic deformation. Much of the strain experienced beyond that point is irrecoverable.

- As a frictional material, concrete experiences significant dilatancy, or volumetric expansion, under loading past the elastic limit under low confining pressures. Nonassociated flow rules are commonly employed in plasticity models to include this effect.

13

- Concrete experience significant reduction in both strength and stiffness under loading past its elastic limit. It has a significantly more ductile response under compression than under tension. While its behavior under tension is fairly brittle, it does have some residual strength, The strength does not immediately drop to zero under continued tensile loading, but rather, the concrete undergoes a decohesive process in which the stress gradually drops from the tensile strength to zero when a finite tensile strain is reached. Under higher higher confining pressures, there is a finite residual strength. The degradation in stiffness can be observed by cyclically loading and unloading the concrete once it has been loaded past the peak strength.

- As a softening material, concrete experiences localization under tensile and compressive loading past its limit strength. To properly capture this effect, models must ensure that the concrete has a constant fracture energy, or area under the traction/separation curve, independent of the mesh size used.

- Load reversals between tension and compression result in stiffness recovery. This is because different mechanisms cause a loss of stiffness under tensile and compressive loading. Tensile loading beyond the limit results in cracking. Reversing the loading on cracked material to put it in compression results in closure of the crack, at which point the stiffness returns to a value close to the value for undamaged material.

- Under high hydrostatic compression, concrete experiences irreversible pore collapse, leading to a cap in its yield surface. Loading beyond the yield surface under high pressure results in pore collapse and hardening. The hardening due to this mechanism is influenced by the shear stress.

- Concrete's compressive strength is highly rate sensitive. Under quasistatic loading, the loading rate does not significantly influence the strength, but at higher strain rates, it has a significant effect. At a strain rate of 1/s, the strength can increase around 50%. At strain rates of 100/s, the strength can be doubled.

In addition to the characteristics of concrete, the response of the reinforced concrete system depends on the behavior of the reinforcing bars embedded in the concrete matrix. Because of the inherent weakness of concrete in tension, concrete structures rely heavily on steel reinforcement for ductility and resistance of tensile and shear loads. Reinforcing bars with small cross-sectional area generally be idealized as providing resistance only to axial loading. In some situations, buckling behavior of reinforcement must be considered. It can become important to consider the resistance of larger reinforcing bars to bending and shear deformation. Being made of mild steel, reinforcing bars experience a plateau in strength after initial yielding, followed by significant hardening and ductility in both tension and compression.

The concrete/steel system relies on a strong bond between concrete and steel to behave as a composite system. Reinforcing bars are deformed to minimize bond slippage, but when they carry significant axial loads, slippage can occur between the bars and the concrete. This can have a significant effect on the overall response of the system, and on the cracking patterns and energy dissipation. The influence of bond slippage on energy dissipation can have a significant effect on the dynamic response of reinforced concrete structures.

4.2   Constitutive models for concrete

To numerically simulate the behavior of reinforced concrete structures requires a material constitutive model that represents the relevant aspects of concrete. Starting in the late 1960s [99, 100], numerous constitutive models have been proposed to represent the nonlinear behavior of reinforced concrete. Since that time, numerous constitutive models for concrete have been proposed based on a variety of numerical theories.

The majority of concrete models are based on a representation of concrete as a continuum, discretized using the finite element method. Rather than representing concrete as a continuum, a number of researchers

have represented it other ways, including as a lattice [101], and using the peridynamic theory [102]. Finite elements that use beam theory to represent the composite behavior of reinforced concrete beams have also been developed [103, 104] for frame structure applications more appropriately modeled with beams than with continuum elements. For the present application, a continuum representation of concrete is likely most appropriate. This permits application to a wide range of structural geometries that could not be readily represented with beam elements, such as containment vessels and spent fuel pools. This also facilitates coupling with continuum models of aging processes.

The continuum mechanics models proposed over the years have been based on a variety of theoretical frameworks to represent the complex aspects of concrete described in the previous section. These frameworks include nonlinear elasticity, plasticity, continuum damage mechanics, and fracture mechanics. Because of the large number of models proposed, this report cannot present an exhaustive summary of all models, but these frameworks will be summarized below.

4.2.1 Fracture mechanics

Starting with the original proposed models for reinforced concrete, significant emphasis has been placed on capturing the process of cracking when loaded in tension. This is because this is often the most important regime governing the response of typical lightly reinforced concrete structures to quasistatic or relatively slow dynamic loading, such as would be experienced under a seismic event. Since the beginning of concrete modeling, there have been two major different ways of representing fracture in the finite element method. Rashid [99] proposed a smeared representation of fracture, representing it by decreasing the strength of continuum elements. Ngo and Scordelis [100], on the other hand, proposed a discrete representation of cracks, using interface elements inserted at the boundaries between solid elements.

The addition of a tension softening curve to fracture models to represent the behavior of the fracture process zone of concrete was originally proposed by Hillerborg [105]. This was a significant development, as it ensures that the process of crack growth releases a consistent amount of fracture energy. This concept was extended to smeared cracking models by Bazant and Oh [106] with the crack band theory, which modifies the softening curve as a function of element size to obtain a fracture energy release that is independent of mesh size.

Since the initial works on concrete modeling, the smeared and discrete representations have been competing approaches to represent fracture. The smeared approach has the advantage that it is easier to implement and use in engineering analyses because cracks can form anywhere in the solid finite element mesh used to represent the concrete structure, without modifications to the mesh. The downside of the smeared crack approach is that while dependencies on mesh size can be minimized using the crack band theory, there are still dependencies on mesh orientation, as pointed out in detail in [107]. These orientation dependencies can prevent proper crack localization, especially for shear cracks. Discrete approaches for modeling cracks, on the other hand, do not suffer from the mesh orientation and size dependencies of smeared crack models. They are not often used in practice, however, because they are cumbersome to use. They either require the crack to follow finite element boundaries, or require the use of other more advanced techniques to represent cracks crossing through elements. As demonstrated in [108], discrete cracks can capture shear failures that smeared crack models do not. A good overview of fracture models for concrete is provided in [109].

More recently, approaches for representing discrete cracks that can arbitrarily pass through the finite element mesh have been introduced. One popular approach, the embedded crack method, originally introduced by [110], enriches the displacement or strain fields within a solid element to permit a localized crack, but does not enforce compatibility of the enriched fields across the boundaries. A good summary of these methods has been provided in [111]. A number of authors, including [112, 113, 114] have successfully applied these methods to concrete fracture. A similar technique, the extended finite element method, or XFEM, also permits arbitrary crack propagation across a solid mesh [115, 116] The main difference between XFEM and

embedded discontinuity methods is that XFEM strictly enforces compatibility of the discontinuous fields across element boundaries. To accomplish this, XFEM adds additional degrees of freedom to the nodes of elements through which cracks pass. An example of the application of XFEM to concrete fracture is in [117].

4.2.2   Plasticity

The fracture mechanics approaches outlined in the previous section are all focused on modeling the behavior of concrete in tension. For a complete model of concrete behavior under all conditions, it is also important to capture its response in the compressive regime. The flow theory of plasticity provides an ideal framework to represent the nonlinear behavior of concrete when loaded past the yield point. Plasticity has been traditionally been applied to represent the flow behavior of metals past the yield point, where behavior is dominated by dislocation movement. It can also be applied to other materials, such as concrete, where nonlinearity is governed by other mechanisms such as microcracking and pore collapse.

Many concrete models are either based entirely on plasticity or use plasticity in conjunction with other theories to model some aspect of concrete behavior. There are numerous examples of such models in the literature. Some examples of models based entirely on plasticity include [118, 119, 120]

Plasticity theory treats the material as linearly elastic when the stress state falls within the yield surface. Loading on the yield surface results in plastic flow, which occurs in the direction normal to the yield surface in the case of associated flow, or in the direction normal to a separate plastic potential function in the case of nonassociated flow. Nonassociated flow rules are commonly used for concrete plasticity to better capture dilatancy. Hardening/softening rules are employed to capture the evolution of the yield surface. These can have a variety of forms to capture the full nonlinear behavior.

A limitation of plasticity theory for representing nonlinear concrete behavior is that behavior within the yield surface is treated as linear elastic. This means that material that has experienced nonlinearity by loading past the yield surface will retain its initial elastic modulus when unloading and reloading. This is not realistic for concrete, as it experiences significant degradation of its elastic modulus when loaded into the nonlinear regime.

4.2.3   Damage

Damage mechanics is an alternative theoretical framework for representing nonlinear material behavior. Instead of decomposing inelastic strains into elastic and plastic portions, as in the theory of plasticity, it represents nonlinear behavior as a reduction of the intact portion of the material. The stiffness is reduced by a damage index that indicates the extent of damage. Examples of concrete models based completely on damage mechanics include [121, 70]

In the simplest case, a single scalar value is used to represent the damage. This results in an isotropic reduction of the material strength, which results in a reduction of strength in all directions due to damage in one direction. More sophisticated models use multiple damage indices to independently represent damage in multiple directions.

Damage mechanics provides a natural framework for representing the reduction of stiffness that occurs during loading in the nonlinear regime. This is particularly important for correctly capturing the hysteretic response that concrete exhibits during cyclic loading, such as would occur during a seismic event. Damage mechanics by itself, however, cannot properly represent irreversible deformations [121, 122]

4.2.4   Other models

A number of other models have been proposed based on other theories. One notable model with widespread use is the microplane model [123], which represents nonlinear behavior of concrete through the behavior of

a set of surfaces at a variety of orientations.

4.2.5   Combined models

Because of the complex nature of concrete response, no one theory is capable of representing its behavior under all regimes of interest. For this reason, many authors have developed models that combine concepts from more than one of the theoretical frameworks described above. Most of the concrete models used in practice for engineering applications contain elements from multiple theoretical frameworks. There are numerous examples of models that combine plasticity and damage, including [67, 124, 125, 122, 96, 126] Combining plasticity and damage allows a model to capture both the inelastic deformation and cyclic behavior of concrete.

There are also benefits to combining plasticity and fracture in a concrete model. A model that successfully combines plasticity and fracture was proposed by [127]. This permits the use of smeared cracking concepts to model cracking behavior in tension with plasticity to represent compressive response. By explicitly representing tensile behavior with a fracture model, this permits capturing phenomena such as crack closure, important for the cyclic behavior of concrete.

4.3   Constitutive models for damaged concrete

Most of the models developed for modeling the constitutive response of concrete in the literature are developed for modeling the response of undamaged concrete subjected to a loading event that may force the concrete into the nonlinear regime. There is much less work in the literature on modeling degraded concrete. Some examples of models that represent the effect of degradation mechanisms on concrete strength include the work of [65, 128] for modeling AAR.

Much of the degradation of concern observed in nuclear power plants has been to the reinforcing steel, prestressing tendons, or steel liners, which are used in containment vessels. The work of [129] and [130] modeled the pressure capacity of degraded reinforced and prestressed concrete containment vessels. In that work, degradation of steel was represented as a reduction of cross sectional area, and in the case of prestressing tendons, a loss of prestressing force. Corrosion of liners was represented by local thinning of the steel, with factors to account for stress risers due to pitting.

5   Proposed modeling approach

A comprehensive approach for modeling effects of aging in concrete structures should provide the capability to represent the various aging processes, the effects of aging mechanisms on the strength of concrete and steel, and the response of structures damaged by aging to a variety of insults.

To describe properly both short and long-term behavior of concrete undergoing various physical and chemical attacks, many researchers have highlighted the importance of coupled models involving heat conduction, liquid and gaseous water flow, and interactions of these fluid phases with the solid skeleton. Traditionally, a Biot-like formulation is employed to reproduce such solid-fluid interactions, leading to complex non-linear coupled systems of equations. The dependence of transport and hydromechanical parameters on cracking is also of great importance and has been investigated in the case of brittle materials by means of damage variables. However, taking into account the detrimental effects of cracking on these physical properties introduces further non-linearity and increases both calculation times and convergence problems in the numerical simulations. In addition, in the case of a partially saturated medium (which is the typical condition for concrete), the saturation of liquid water adds further nonlinearity to the coupled governing equations.

As described in this document, accurate modeling of the aging process of concrete structures would require a nonisothermal, multiphase, multicomponent thermodynamically-based reactive transport model coupled with solid mechanical model that can appropriately model pre- and post-damage mechanical behaviors of aging concrete. The strong nonlinearity and tightly coupled nature of this problem requires solving a fully coupled set of partial differential equations describing thermal, porous flow, reactive transport, and mechanical processes.

The Grizzly code, in which these models will be implemented, is an ideal platform to solve these models. It is built on the MOOSE multiphysics framework [131], which facilitates the solution of coupled partial differential equations of this nature. The development of a nonisothermal, multiphase, multicomponent reactive transport model to accurately simulate all relevant physical and chemical aging processes can heavily leverage work previously done in a porous reactive flow and transport code (RAT), also based on the MOOSE framework, for similar phenomena in geological porous media [95]. RAT provides the capability for fully coupled solutions of general reactive transport problems in geoporous materials, including aqueous speciations, equilibrium/kinetic mineral dissolution/precipitation, sorption/desorption and many other reactions in aqueous. These various chemical reactions in RAT code for geomaterials can be conveniently adopted and modified to develop thermodynamically-based reactive transport models in Grizzly for modeling chemical aging processes of concrete structures.

One of the main new capabilities to be developed to model aging processes is coupling of reactive porous flow with solid mechanics. That will require the development of a model that can both capture the damage due to the various physical mechanisms, and which can provide the effect of the damage on the physics contributing to the damage. For example, if damage is influenced by porous flow, the concrete model must capture the damage due to excessive pore pressure, and in turn, provide the change in porosity as a function of damage.

The degraded structure could be subjected to a wide variety of loadings of potential concern, including the effects of various accident scenarios, such as overpressurization of a containment vessel, or external loads such as wind or seismic loads. For this reason, the models developed for this work must be capable of representing the concrete behavior under a variety of conditions, including monotonic and cyclic loading. All of these are needed to make decisions about extending the life of structures subjected to aging.

Because of the need to represent a wide range of concrete behavior, a successful constitutive model for concrete will require a combination of concepts of plasticity, damage, and fracture. The solid mechanics models in MOOSE can currently have a capability to represent smeared cracking in conjunction with other models such as plasticity, but this has not yet been applied in the context of concrete modeling. A logical

path forward for concrete model development is to develop a plasticity-based model for nonlinear behavior of concrete in the compressive regime that can be combined with this smeared cracking model. This should then also be combined with damage mechanics concepts to correctly capture stiffness degradation.

The first priority for this work is to develop a robust continuum model for concrete. Once this is developed, development work currently underway to represent fractures as discrete discontinuities using XFEM in MOOSE for other applications should be leveraged to improve the representation of fracture localization. The continuum models would represent concrete in the compressive regime and the initial process of fracture localization, and then XFEM would be used to represent mesh-independent localization.

Another important area where development is needed is for modeling reinforcing steel and the interaction with concrete. Representing steel either as a smeared continuum or discrete bars is fairly straightforward, and both techniques may be useful for different structural configurations.

The Grizzly code is an ideal platform for development of models to predict the aging process and for simulating the capacity of age-degraded reinforced concrete structures. A wealth of existing capabilities for multiphysics coupling, reactive porous flow, heat conduction, and solid mechanics can be leveraged to provide a unique capability to address concerns related to life extension of aged concrete structures.

6 References

1. D. J. Naus. Concrete component aging and its significance relative to life extension of nuclear power plants. NUREG/CR-4652, ORNL/TM-10059, Oak Ridge National Laboratory, Oak Ridge, TN 37381, 1986.

2. Mark J. Do and Alan D. Chockie. Aging degradation of concrete structures in nuclear power plants. SKI Report 94:15, Battelle Seattle Research Center, Seattle, WA 98105, 1994.

3. D. J. Naus, C. B. Oland, and B. R. Ellingwood. Report on aging of nuclear power plant reinforced concrete structures. NUREG/CR-6424, BNL-NUREG-13148, Oak Ridge National Laboratory, Oak Ridge, TN 37381, 1996.

4. D. L. Fillmore. Literature review of the effects of radiation and temperature on the aging of concrete. INEEL/EXT-04-02319, Idaho National Engineering and Environmental Laboratory, 2004.

5. Detlef Kuhl, Falko Bangert, and Günther Meschke. Coupled chemo-mechanical deterioration of cementitious materials part ii: Numerical methods and simulations. *International Journal of Solids and Structures*, 41(1):41–67, 2004.

6. Detlef Kuhl, Falko Bangert, and Günther Meschke. Coupled chemo-mechanical deterioration of cementitious materials. part i: Modeling. *International Journal of Solids and Structures*, 41(1):15–40, 2004.

7. Sidney Mindess, J. Francis Young, and David Darwin. *Concrete*. Prentice Hall, Upper Saddle River, NJ, 2nd edition, 2003.

8. Sidney Mindess and J Francis Young. *Concrete*. Prentice-Hall, 1981.

9. ZP Bazant, JC Chern, MS Abrams, and MP Gillen. Normal and refractory concrete for lmfbr applications—vol. 1, review of literature on high-temperature behavior of portland cement and refractory concretes, vol. 2, evaluation of concrete for lmfbr applications. EPRI Final Report NP-2437, Electric Power Research Institute, Palo Alto, CA, 1982.

10. Tasnim Uddin and Charles G Culver. Effects of elevated temperature on structural members. *Journal of the Structural Division*, 101(7):1531–1549, 1975.

11. D Campbell-Allen and PM Desai. The influence of aggregate on the behaviour of concrete at elevated temperatures. *Nuclear Engineering and Design*, 6(1):65–77, 1967.

12. VV Bertero and M Polivka. Influence of thermal exposures on mechanical characteristics of concrete. *ACI Special Publication*, 34, 1972.

13. Effects of long-term exposure to elevated temperature on the mechanical properties of hanford concrete. RHO-C-54, Construction Technology Laboratories, Portland Cement Association, October 1981.

14. TV Blosser, GW Bond, LA Lee, DT Morgan, JF Nichols, RC Reid, AB Reynolds, TOP Speidel, DW Vroom, and MA Welt. A study of the nuclear and physical properties of the ornl graphite reactor shield. , Oak Ridge National Lab., Tenn., 1958.

15. HK Hilsdorf, J Kropp, and HJ Koch. The effects of nuclear radiation on the mechanical properties of concrete. *ACI Special Publication*, 55, 1978.

16. LB Miller, RE Jarka, and DC Kaul. Study of radiation dosage to structural components in nuclear reactors. *Final Report Science Applications, Inc., Rolling Meadows, IL.*, 1, 1976.

17. M. F. Kaplan. *Concrete radiation shielding: nuclear physics, concrete properties, design and construction*. Longman Scientific & Technical, 1989.

18. SP Shah. Predictions of comulative damage for concrete and reinforced concrete. *Matériaux et Construction*, 17(1):65–68, 1984.

19. John M Hanson et al. Consideration for design of concrete structures subjected to fatigue loading. *ACI Journal*, 71(3):97–120, 1974.

20. P.K Mehta. *Concrete: structure, properties, and materials*. Prentice-Hall, 1986.

21. P Kumar Mehta and Ben C Gerwick. Cracking-corrosion interaction in concrete exposed to marine environment. *P. K. Mehta and B. C. Gerwick, Jr., Concrete International: Design & Construction, V. 4,*, (10):45–51, 1982.

22. Franz-Josef Ulm, Eric Lemarchand, and Franz H Heukamp. Elements of chemomechanics of calcium leaching of cement-based materials at different scales. *Engineering Fracture Mechanics*, 70(7):871–889, 2003.

23. Shamsad Ahmad. Reinforcement corrosion in concrete structures, its monitoring and service life prediction—-a review. *Cement and Concrete Composites*, 25(4):459–471, 2003.

24. Adam Neville. Chloride attack of reinforced concrete: an overview. *Materials and Structures*, 28(2):63–70, 1995.

25. Vinod Kumar. Protection of steel reinforcement for concrete-a review. *Corrosion Reviews*, 16(4):317–358, 1998.

26. Arnon Bentur, Neal Berke, and Sidney Diamond. *Steel corrosion in concrete: fundamentals and civil engineering practice*. CRC Press, 1997.

27. Byung Hwan Oh, Soo Won Cha, Bong Seok Jang, and Seung Yup Jang. Development of high-performance concrete having high resistance to chloride penetration. *Nuclear Engineering and Design*, 212(1):221–231, 2002.

28. P Castro, EI Moreno, and J Genescá. Influence of marine micro-climates on carbonation of reinforced concrete buildings. *Cement and Concrete Research*, 30(10):1565–1571, 2000.

29. Anna V Saetta, Bernhard A Schrefler, and Renato V Vitaliani. The carbonation of concrete and the mechanism of moisture, heat and carbon dioxide flow through porous materials. *Cement and Concrete Research*, 23(4):761–772, 1993.

30. DWS Ho and RK Lewis. Carbonation of concrete and its prediction. *Cement and Concrete Research*, 17(3):489–504, 1987.

31. O Burkan Isgor and A Ghani Razaqpur. Finite element modeling of coupled heat transfer, moisture transport and carbonation processes in concrete structures. *Cement and Concrete Composites*, 26(1):57–73, 2004.

32. Anna V Saetta, Bernhard A Schrefler, and Renato V Vitaliani. 2 - d model for carbonation and moisture/heat flow in porous materials. *Cement and Concrete Research*, 25(8):1703–1712, 1995.

33. B Bary and A Sellier. Coupled moisture—carbon dioxide–calcium transfer model for carbonation of concrete. *Cement and concrete research*, 34(10):1859–1872, 2004.

34. Adam Neville. The confused world of sulfate attack on concrete. *Cement and Concrete Research*, 34(8):1275–1296, 2004.

35. Jan Skalny and PW Brown. *Sulfate attack on concrete*. Taylor & Francis, 2002.

36. P Kumar Mehta. Mechanism of sulfate attack on portland cement concrete—another look. *Cement and Concrete Research*, 13(3):401–406, 1983.

37. George W Scherer. Crystallization in pores. *Cement and Concrete research*, 29(8):1347–1358, 1999.

38. Niels Thaulow and Sadananda Sahu. Mechanism of concrete deterioration due to salt crystallization. *Materials Characterization*, 53(2):123–127, 2004.

39. JE Gillott. Alkali-aggregate reactions in concrete. *Engineering Geology*, 9(4):303–326, 1975.

40. Benoit Fournier and Marc-André Bérubé. Alkali-aggregate reaction in concrete: a review of basic concepts and engineering implications. *Canadian Journal of Civil Engineering*, 27(2):167–191, 2000.

41. ACI Committee 318. Building code requirements for structural concrete and commentary. ACI 318-11, American Concrete Institute, Detroit, MI, 2011.

42. Peter Schiessl. *Corrosion of Steel in Concrete: Report of the Technical Committee 60 CSC, RILEM (the International Union of Testing and Research Laboratories for Materials and Structures)*. Chapman & Hall, 1988.

43. K. Tuutti. *Corrosion of steel in concrete*. CBI forskning. Swedish Cement and Concrete Research Institute, 1982.

44. JG Cabrera. Deterioration of concrete due to reinforcement steel corrosion. *Cement and concrete composites*, 18(1):47–59, 1996.

45. Youping Liu and Richard E Weyers. Modeling the time-to-corrosion cracking in chloride contaminated reinforced concrete structures. *ACI Materials Journal*, 95(6), 1998.

46. Arthur H. Nilson. *Design of prestressed concrete*. Wiley, New York, 2nd ed edition, 1987.

47. Jacob Bear and Y Bachmat. A generalized theory on hydrodynamic dispersion in porous media. In *IASH Symposium on Artificial Recharge and Management of Aquifers*, volume 72, pages 7–16, 1967.

48. Jacob Bear. *Dynamics of fluids in porous media*. Courier Dover Publications, 2013.

49. S. Dal Pont, S. Durand, and B.A. Schrefler. A multiphase thermo-hydro-mechanical model for concrete at high temperatures—finite element implementation and validation under LOCA load. *Nuclear Engineering and Design*, 237(22):2137–2150, November 2007.

50. F Bangert, D Kuhl, and G Meschke. Chemo-hygro-mechanical modelling and numerical simulation of concrete deterioration caused by alkali-silica reaction. *International Journal for Numerical and Analytical Methods in Geomechanics*, 28(7-8):689–714, 2004.

51. George Chatzigeorgiou, Vincent Picandet, Abdelhafid Khelidj, and Gilles Pijaudier-Cabot. Coupling between progressive damage and permeability of concrete: analysis with a discrete model. *International journal for numerical and analytical methods in geomechanics*, 29(10):1005–1018, 2005.

52. P Léger, P Côté, and R Tinawi. Finite element analysis of concrete swelling due to alkali-aggregate reactions in dams. *Computers & structures*, 60(4):601–611, 1996.

53. HJ Dagher and S Kulendran. Finite element modeling of corrosion damage in concrete structures. *ACI Structural Journal*, 89(6), 1992.

54. S. Dal Pont, F. Meftah, and B.A. Schrefler. Modeling concrete under severe conditions as a multiphase material. *Nuclear Engineering and Design*, 241(3):562–572, March 2011.

55. Mike B Otieno, Hans D Beushausen, and Mark G Alexander. Modelling corrosion propagation in reinforced concrete structures–a critical review. *Cement and Concrete Composites*, 33(2):240–245, 2011.

56. D Gawin, F Pesavento, and BA Schrefler. Modelling of hygro-thermal behaviour of concrete at high temperature with thermo-chemical and mechanical material degradation. *Computer methods in applied mechanics and engineering*, 192(13):1731–1771, 2003.

57. Alain Millard, Valerie L'Hostis, Karim BEDDIAR, Yves Berthaud, and Sabine Care. Modelling the cracking of a reinforced concrete structure submitted to corrosion of steels-first validation of a damage model based on experimental results. 2004.

58. Zdeněk P Bažant. Prediction of concrete creep and shrinkage: past, present and future. *Nuclear Engineering and Design*, 203(1):27–38, 2001.

59. Y Ichikawa and GL England. Prediction of moisture migration and pore pressure build-up in concrete at high temperatures. *Nuclear Engineering and Design*, 228(1):245–259, 2004.

60. Miguel Cervera, Javier Oliver, and Tomás Prato. Thermo-chemo-mechanical model for concrete. i: Hydration and aging. *Journal of engineering mechanics*, 125(9):1018–1027, 1999.

61. Miguel Cervera, Javier Oliver, and Tomás Prato. Thermo-chemo-mechanical model for concrete. ii: Damage and creep. *Journal of engineering mechanics*, 125(9):1028–1039, 1999.

62. D Gawin, F Pesavento, and BA Schrefler. Towards prediction of the thermal spalling risk through a multi-phase porous media model of concrete. *Computer methods in applied mechanics and engineering*, 195(41):5707–5729, 2006.

63. Zdeněk P BazÌĘant and Alexander Steffens. Mathematical model for kinetics of alkali–silica reaction in concrete. *Cement and Concrete Research*, 30(3):419–428, March 2000.

64. Franz-Josef Ulm, Olivier Coussy, Li Kefei, and Catherine Larive. Thermo-chemo-mechanics of asr expansion in concrete structures. *Journal of engineering mechanics*, 126(3):233–242, 2000.

65. Victor Saouma and Luigi Perotti. Constitutive model for alkali-aggregate reactions. *ACI Materials Journal*, 103(3), 2006.

66. Bruno Gerard, Gilles Pijaudier-Cabot, and Christian Laborderie. Coupled diffusion-damage modelling and the implications on failure due to strain localisation. *International Journal of Solids and Structures*, 35(31):4107–4120, 1998.

67. J.C. Simo and J.W. Ju. Strain- and stress-based continuum damage models—I. formulation. *International Journal of Solids and Structures*, 23(7):821–840, January 1987.

68. Jean Lemaitre and Jean-Louis Chaboche. *Mechanics of solid materials*. Cambridge university press, 1990.

69. Milan Jirásek and Zdenek P Bazant. *Inelastic analysis of structures*. John Wiley & Sons, 2002.

70. Jacky Mazars and Gilles Pijaudier-Cabot. Continuum damage theory-application to concrete. *Journal of Engineering Mechanics*, 115(2):345–365, 1989.

71. Olivier Coussy and Paulo JM Monteiro. Poroelastic model for concrete exposed to freezing temperatures. *Cement and Concrete Research*, 38(1):40–48, 2008.

72. Maurice A Biot. General theory of three-dimensional consolidation. *Journal of applied physics*, 12(2):155–164, 1941.

73. H-P Lien and FH Wittmann. Coupled heat and mass transfer in concrete elements at elevated temperatures. *Nuclear engineering and design*, 156(1):109–119, 1995.

74. Farid Benboudjema and Jean-Michel Torrenti. Early-age behaviour of concrete nuclear containments. *Nuclear engineering and design*, 238(10):2495–2506, 2008.

75. Benoît Bary, Guillaume Ranc, Sabine Durand, and Olivier Carpentier. A coupled thermo-hydro-mechanical-damage model for concrete subjected to moderate temperatures. *International journal of heat and mass transfer*, 51(11):2847–2862, 2008.

76. Roland Wynne Lewis and Bernard A Schrefler. *The finite element method in the static and dynamic deformation and consolidation of porous media*. John Wiley, 1998.

77. BA Schrefler and F Pesavento. Multiphase flow in deforming porous material. *Computers and geotechnics*, 31(3):237–250, 2004.

78. Olivier Coussy. *Poromechanics*. John Wiley & Sons, 2004.

79. J Marchand, E Samson, Y Maltais, and JJ Beaudoin. Theoretical analysis of the effect of weak sodium sulfate solutions on the durability of concrete. *Cement and Concrete Composites*, 24(3):317–329, 2002.

80. F Adenot and M Buil. Modelling of the corrosion of the cement paste by deionized water. *Cement and Concrete Research*, 22(2):489–496, 1992.

81. Y Maltais, E Samson, and J Marchand. Predicting the durability of portland cement systems in aggressive environments—laboratory validation. *Cement and Concrete Research*, 34(9):1579–1589, 2004.

82. Laurent De Windt, Delphine Pellegrini, and Jan Van Der Lee. Coupled modeling of cement/claystone interactions and radionuclide migration. *Journal of contaminant hydrology*, 68(3):165–182, 2004.

83. Micheline Moranville, Siham Kamali, and Emmanuel Guillon. Physicochemical equilibria of cement-based materials in aggressive environments—experiment and modeling. *Cement and Concrete Research*, 34(9):1569–1578, 2004.

84. David Planel. *Les effets couplés de la précipitation d'espèces secondaires sur le comportement mécanique et la dégradation chimique des bétons*. PhD thesis, Marne-la-Vallée, 2002.

85. B Bary. Simplified coupled chemo-mechanical modeling of cement pastes behavior subjected to combined leaching and external sulfate attack. *International journal for numerical and analytical methods in geomechanics*, 32(14):1791–1816, 2008.

86. Barbara Lothenbach, Benoît Bary, Patrick Le Bescop, Thomas Schmidt, and Nikos Leterrier. Sulfate ingress in portland cement. *Cement and Concrete Research*, 40(8):1211–1225, 2010.

87. D Kulik, U Berner, and E Curti. Modelling chemical equilibrium partitioning with the gems-psi code. *PSI Scientific Report*, 4:109–122, 2003.

88. Thomas J Wolery. Eq3/6, a software package for geochemical modeling of aqueous systems: package overview and installation guide (version 7.0). 1992.

89. Craig Bethke. *The geochemist's workbench: A users guide to Rxn, Act2, Tact, React, and Gtplot*. C. Bethke, 1992.

90. Karsten Pruess, CM Oldenburg, and GJ Moridis. Tough2 user's guide version 2. *Lawrence Berkeley National Laboratory*, 1999.

91. M. D. White and M. Oostrom. Stomp subsurface transport over multiple phases; version 2.0; theory guide. PNNL-12030, UC-2010, Richland, WA, 2000.

92. Carl I Steefel, Donald J DePaolo, and Peter C Lichtner. Reactive transport modeling: An essential tool and a new research approach for the earth sciences. *Earth and Planetary Science Letters*, 240(3):539–558, 2005.

93. GT Yeh and VS Tripathi. A critical evaluation of recent developments in hydrogeochemical transport models of reactive multichemical components. *Water resources research*, 25(1):93–108, 1989.

94. Tianfu Xu and Karsten Pruess. Modeling multiphase non-isothermal fluid flow and reactive geochemical transport in variably saturated fractured rocks: 1. methodology. *American Journal of Science*, 301(1):16–33, 2001.

95. Luanjing Guo, Hai Huang, Derek R Gaston, Cody J Permann, David Andrs, George D Redden, Chuan Lu, Don T Fox, and Yoshiko Fujita. A parallel, fully coupled, fully implicit solution to reactive transport in porous media using the preconditioned jacobian-free newton-krylov method. *Advances in Water Resources*, 53:101–108, 2013.

96. Yvonne D Murray. Users manual for ls-dyna concrete material model 159. FHWA-HRT-05-062, U.S. Department of Transportation, FHWA, Washington, DC, May 2007.

97. Kaspar Willam, Eric Hansen, and Hong D. Kang. Performance evaluation of damage and plasticity formulations for concrete. In P. B. Shing and T. Tanabe, editors, *Modeling of Inelastic Behavior of RC Structures under Seismic Loads*, pages 1–19. American Society of Civil Engineers, 2001.

98. P. Menetrey and K. J. Willam. Triaxial failure criterion for concrete and its generalization. *ACI Structural Journal*, 92(3):311–318, 1995.

99. Y.R. Rashid. Ultimate strength analysis of prestressed concrete pressure vessels. *Nuclear Engineering and Design*, 7(4):334–344, April 1968.

100. D Ngo and A C Scordelis. Finite element analysis of reinforced concrete beams. *Journal of the American Concrete Institute*, 64:152–163, 1967.

101. A. Itoh and T. Tanabe. Analysis of rc column experiments at ucsd by an equivalent lattice model. In K. J. Willam and T. Tanabe, editors, *Finite Element Analysis of Reinforced Concrete Structures*, SP-205, pages 81–95. American Concrete Institute, 2001.

102. Walter Gerstle, Nicolas Sau, and Stewart Silling. Peridynamic modeling of concrete structures. *Nuclear Engineering and Design*, 237(12-13):1250–1258, July 2007.

103. E. Spacone, F. C. Filippou, and F. F. Taucer. Fibre beam-column model for non-linear analysis of r/c frames: Part i. formulation. *Earthquake Engineering & Structural Dynamics*, 25(7):711–725, July 1996.

104. E. Spacone, F. C. Filippou, and F. F. Taucer. Fibre beam-column model for non-linear analysis of r/c frames: Part ii. applications. *Earthquake Engineering & Structural Dynamics*, 25(7):727–742, July 1996.

105. Arne Hillerborg, Mats Modéer, and P-E Petersson. Analysis of crack formation and crack growth in concrete by means of fracture mechanics and finite elements. *Cement and concrete research*, 6(6):773–781, 1976.

106. Zdeněk P. Bažant and B. H. Oh. Crack band theory for fracture of concrete. *Matériaux et Constructions*, 16(3):155–177, May 1983.

107. J. G. Rots and J. Blaauwendraad. Crack models for concrete: Discrete or smeared? fixed, multi-directional or rotating? *HERON*, 34(1), 1989.

108. B. W. Spencer and P. B. Shing. Modeling of shear behavior of RC bridge structures. In P. B. Shing and T. Tanabe, editors, *Modeling of Inelastic Behavior of RC Structures under Seismic Loads*, pages 315–333. American Society of Civil Engineers, 2001.

109. Rene de Borst. Fracture in quasi-brittle materials: a review of continuum damage-based approaches. *Engineering Fracture Mechanics*, 69(2):95–112, 2002.

110. Michael Ortiz, Yves Leroy, and Alan Needleman. A finite element method for localized failure analysis. *Computer Methods in Applied Mechanics and Engineering*, 61(2):189–214, March 1987.

111. Milan Jirásek. Comparative study on finite elements with embedded discontinuities. *Computer Methods in Applied Mechanics and Engineering*, 188(1-3):307–330, July 2000.

112. J. Oliver, D.L. Linero, A.E. Huespe, and O.L. Manzoli. Two-dimensional modeling of material failure in reinforced concrete by means of a continuum strong discontinuity approach. *Computer Methods in Applied Mechanics and Engineering*, 197(5):332–348, January 2008.

113. Miha Jukić, Boštjan Brank, and Adnan Ibrahimbegović. Embedded discontinuity finite element formulation for failure analysis of planar reinforced concrete beams and frames. *Engineering Structures*, 50:115–125, May 2013.

114. B. W. Spencer. *Finite Elements with Embedded Discontinuities for Modeling Reinforced Concrete Members*. PhD thesis, University of Colorado, Boulder, 2002.

115. T. Belytschko and T. Black. Elastic crack growth in finite elements with minimal remeshing. *International Journal for Numerical Methods in Engineering*, 45(5):601–620, June 1999.

116. Nicolas Moes, John Dolbow, and Ted Belytschko. A finite element method for crack growth without remeshing. *International Journal for Numerical Methods in Engineering*, 46(1):131–150, September 1999.

117. Elena Benvenuti and Antonio Tralli. Simulation of finite-width process zone in concrete-like materials by means of a regularized extended finite element model. *Computational Mechanics*, 50(4):479–497, February 2012.

118. G. Etse and K. Willam. Fracture energy formulation for inelastic behavior of plain concrete. *Journal of Engineering Mechanics*, 120(9):1983–2011, September 1994.

119. Peter H. Feenstra and René De Borst. A composite plasticity model for concrete. *International Journal of Solids and Structures*, 33(5):707–730, February 1996.

120. Hong D. Kang. *Triaxial Constitutive Model for Plain and Reinforced Concrete Behavior*. PhD thesis, University of Colorado, Boulder, CO, 1997.

121. J Mazars. *Application de la mechanique de lendommagement au comportement non lineare et a la rupture du beton de structure*. PhD thesis, Universite Paris VI, 1984.

122. Peter Grassl and Milan Jirásek. Damage-plastic model for concrete failure. *International Journal of Solids and Structures*, 43(22-23):7166–7196, November 2006.

123. Zdeněk P. Bažant, Ferhun C. Caner, Ignacio Carol, Mark D. Adley, and Stephen A. Akers. Microplane model m4 for concrete. i: Formulation with work-conjugate deviatoric stress. *Journal of Engineering Mechanics*, 126(9):944–953, September 2000.

124. P. Menétrey, R. Walther, T. Zimmermann, K. J. Willam, and P. E. Regan. Simulation of punching failure in reinforced-concrete structures. *Journal of Structural Engineering*, 123(5):652–659, May 1997.

125. G. Meschke, R. Lackner, and H. A. Mang. An anisotropic elastoplastic-damage model for plain concrete. *International Journal for Numerical Methods in Engineering*, 42(4):703–727, June 1998.

126. R. M. Brannon, A. F. Fossum, and O. E. Strack. Kayenta: Theory and user's guide. SAND2009-2282, Sandia National Laboratories, Albuquerque, NM, March 2009.

127. Jan Červenka and Vassilis K Papanikolaou. Three dimensional combined fracture–plastic material model for concrete. *International Journal of Plasticity*, 24(12):2192–2220, 2008.

128. J. Y. R. Rashid, R. J. James, and R. S. Dunham. Modeling and analysis of aging behavior of concrete structures in nuclear power plants. In *Fontevraud 7 Contribution of Materials Investigations to Improve the Safety and Performance of LWRs*, Paper A088 T10, September 2010.

129. J.L. Cherry and J.A. Smith. Capacity of steel and concrete containment vessels with corrosion damage. NUREG/CR-6706, SAND2000-1735, Sandia National Laboratories, Albuquerque, NM, February 2001.

130. B. W. Spencer, J. P. Petti, and D. M. Kunsman. Risk-informed assessment of degraded containment vessels. NUREG/CR-6920, SAND2006-3772P, Sandia National Laboratories, Albuquerque, NM, 2006.

131. D. Gaston, C. Newman, G. Hansen, and D. Lebrun-Grandié. MOOSE: A parallel computational framework for coupled systems of nonlinear equations. *Nucl. Eng. Design*, 239:1768–1778, 2009.