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Multiple Degradation Mechanisms in Reinforced Concrete Structures, Modeling and Risk Analysis

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ABSTRACT:

There are currently 99 commercial nuclear reactors that in operation in the United States. The majority of these reactors are operating under a 20-year renewal of their original 40-year license. The renewed licenses for many of these plants will expire in the near future, and license renewals for beyond 60 years will be considered. To preserve current nuclear generating capacity, there is an urgent need to better understand the effects of degradation during long-term operation to safely extend the service life of these reactors.

Structural concrete performs many roles in Nuclear Power Plants (NPP's), notably foundation, support, and shielding of the primary reactor pressure vessel and the outer containment vessel. Aside from the load bearing function, structural concrete provides physical protection against natural disasters and man-made attacks. Given the requirement to extend operating licenses of the aging fleet of NPP's beyond 60 years, there is a pressing need to inspect the current status and evaluate the long-term performance of structural concrete.

Just as evidenced by deteriorating concrete bridges and buildings, multiple degradation problems have been reported of structural concrete in nuclear power plants. The degradation of concrete structures is caused by mechanical as well as environmental loadings. The effect of environmental loading is critical because of the interaction effects of transport properties of heat, moisture, irradiation and chemical reactants with the mechanical response. The mechanical behavior significantly differs under tension, shear and compression when stress levels exceed the linear elastic regime and approach multi-axial failure where volume expansion takes place in frictional materials such as concrete due to granular action (Reynolds shear dilatancy effect). In other terms, the compactive behavior in axial compression is transformed into lateral expansion when the stress level nears the compressive strength of concrete leading to a drastic increase of porosity and permeability due to expansive micro-cracking. This is especially the case when thermal expansion and irradiation effects are mobilized in addition to the chemical alkali-silica reaction (ASR). These internal swelling processes are further aggravated under freeze-thaw cycles, leaching of calcium hydroxide, chemical attacks, and corrosion of reinforcing steel due to chloride penetration. The environmental loadings are governed by coupled transport processes of heat, moisture, and chemicals which take place in the concrete skeleton subjected to deformations and cracking of the binding mortar matrix of the heterogeneous composite. In summary, concrete is a complex material which deserves our full attention not only at the macroscopic level of observation but also at the meso- and micro-levels of aggregate–mortar-cement paste interaction.

The main focus of the project is to develop novel simulation features for thermos-hygro-chemo-mechanical studies of concrete and integrate them into Grizzly, which is based on the MOOSE finite element framework, to evaluate both mechanical and environmental aging of structural concrete. The goal is to integrate a validated multi-scale and multi-physics approach into Grizzly for risk-informed life cycle analysis of reinforced concrete components in aging NPP's.

The proposed NEUP project brings together two universities with computational research personnel at Idaho National Laboratory (INL). The research team includes two faculty at the University of Houston, one at the University of Colorado Boulder, and two senior scientists at INL. They have worked together in the past and are well positioned to develop advanced simulation features for structural concrete and implement them in MOOSE/Grizzly for computational predictions of realistic life cycle scenarios on NPP components. They will address "Advanced Concrete Materials" under operating and extreme conditions within thrust areas that are organized in four tasks:

Task 1: Multi-Physics Constitutive Platform
The main focus of the project is to incorporate a concrete material model in MOOSE/Grizzly with a wide range of applicability. Henceforth, the constitutive model will encompass a set of partial differential equations for the transport processes of multiple species and a set of equations for damage evolution analysis. The new features of the constitutive model are the coupling among the transport species such as temperature, moisture, and chemicals, and the correlation between the transport parameters and the mechanical damage. The mechanical damage will be characterized by degradation of the elastic stiffness properties in form of anisotropic damage as well degradation of the strength in terms of fracture energy based softening. Cross-correlation functions will be used to link the mechanical damage with the deteriorated transport parameter of concrete.

Task 2: Multi-Scale Modeling of Aging Mechanisms
Durability issues in structural concrete take place at different scales of observation. This task will focus on the transport processes of diffusion, flow and chemical reactions at the scale of particulate composites where mismatch between aggregate and mortar constituents leads to residual stresses and degradation at the meso-scale level of observation that are not included by homogenization at the macro-scale. The multi-phase material models for concrete will account for time dependent chemical reactions such as hydration reactions and ASR and the composition effect of concrete mix designs. For instance, ASR and irradiation heating lead to mechanical swelling of the dense aggregates and thereby to mechanical damage of the surrounding mortar and cement paste. Moreover interaction effects of steel and concrete lead to internal damage due to mismatch.

Task 3: Experimental Program for Validation and Benchmarking Studies
The experimental program of the project will include tests at two levels, (1) at the material level to quantify the coupled transport properties and their interaction with mechanical degradation, and (2) benchmark tests at the structural level to verify the computational implementation and validate the model predictions of MOOSE/Grizzly. The structural level tests will include estimation of the material parameters for transport and the mechanical response behavior in 3-D by well-focused laboratory experiments.

Task 4: Verification, Validation, and Uncertainty Quantification (VVUQ) Studies
The structural tests will involve verification of the computational implementation and validation with two benchmark problems on nuclear concrete that will be used for sensitivity studies to quantify the importance and variability of the principal constitutive parameters within a probabilistic framework.