Abstract

This thesis presents the development and implementation of a robust and computationally efficient multiaxial constitutive model for predicting the thermo-mechanical response of concrete structures subjected to fire. Concrete exposed to fire exhibits strongly coupled thermo-hygro-mechanical (THM) behavior governed by temperature evolution, moisture migration, pore pressure buildup, and the degradation of mechanical properties. To address these complexities while maintaining computational tractability for structural-scale simulations, a phenomenological constitutive framework is adopted. The proposed model integrates a multi-surface plasticity approach (combining Drucker-Prager and Rankine criteria) with continuum damage mechanics to capture the nonlinear inelastic response of concrete under multiaxial stress states at high temperatures.

Temperature-dependent degradation of strength and stiffness is incorporated alongside an explicit formulation for transient thermal creep strain, enabling the model to reproduce the additional deformation observed in concrete under sustained load during heating. A key numerical innovation of this formulation is the implementation of a spectral decomposition-based radial return mapping algorithm for the plasticity model. This approach circumvents the need to evaluate second gradients of potential functions, significantly improving the robustness and efficiency of stress integration under complex loading paths.

In addition to the mechanical formulation, the thesis develops a mathematical framework for coupled heat and moisture transport. The governing equations for energy and mass conservation of liquid water, water vapor, and dry air are solved numerically to obtain the transient temperature, vapor density, and pore pressure fields.

The scope of the proposed modeling framework is validated through a comprehensive series of numerical simulations, ranging from material-level benchmark tests (uniaxial tension, biaxial compression, and triaxial compression under hydrostatic pressures up to 21 MPa) to full-scale structural members (a 3.3 m × 4.3 m reinforced concrete slab and a 4 m axially restrained column) exposed to ISO 834 standard fire curves for up to 3 hours.

Quantitatively, the proposed model demonstrates superior prediction accuracy compared to existing frameworks. Validation against triaxial compression benchmarks showed a reduction in Mean Squared Error (MSE) by up to 88% (e.g., MSE reduced from 49.8 to 5.9 at 8.4 MPa confinement) compared to standard implicit models. Furthermore, comparative studies proved that while thermo-mechanical (TM) models alone can capture the first-order structural response up to 200 °C, the inclusion of hygral effects is critical at higher temperatures. Incorporating pore pressure into the THM model reduced the MSE for high-temperature uniaxial tension (at 400 °C) by over 51% (from 0.013 to 0.006). At the structural scale, the fully coupled THM formulation reduced the deflection prediction error for a fire-exposed reinforced concrete slab by 52% (MSE reduced from 391.2 to 186.4) compared to the uncoupled TM approach.

Overall, the proposed framework provides a highly accurate, computationally efficient tool for simulating the behavior of concrete structures subjected to fire. The thesis concludes by identifying directions for future research, including the influence of pore pressure on transient thermal creep and the potential application of machine learning techniques to accelerate parameter calibration for large-scale structural fire safety assessments.

Keywords: Concrete under fire, Multiaxial constitutive modeling, Thermo-hygro-mechanical behavior, Pore pressure and thermal spalling, Finite element analysis (FEA), Plasticity-damage coupling, Transient creep strain, Spectral decomposition.