

A Coupled VCLM-Conduit Framework for Transport and Fracture in Concrete

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1. Introduction

Containment structures of nuclear power plants (NPPs) constitute the final barrier against the release of radioactive materials; accordingly, preserving their structural integrity and leak-tightness is paramount. Nevertheless, long-term operation and environmental exposure can induce material degradation and damage, potentially compromising performance. The objective of this study is to establish a numerical framework that evaluates degradation induced damage and quantitatively assesses the potential for radioactive release from the containment under such conditions.

2. Numerical Model

2.1 Voronoi Cell Lattice Model (VCLM)

A discrete modeling framework known as the Voronoi Cell Lattice Model (VCLM) or the Rigid-Body-Spring Network (RBSN) is used to analyze the fracture behavior of concrete. The formulation modifies the seminal model proposed by Kawai (1979) [1]. Random nodal seeds are distributed over the analysis domain, followed by a Delaunay-Voronoi dual tessellation; the resulting random lattice serves as the computational mesh. Interactions between adjacent Voronoi cells are defined on their common facet by assigning zero-size spring sets with six degrees of freedom (three translations and three rotations). For each degree of freedom, a damage factor computed from the corresponding fracture criterion is applied multiplicatively to the undamaged spring stiffness, capturing progressive degradation of stiffness and strength at the facet level. This mechanism enables the representation of crack initiation, growth, and coalescence consistent with the intrinsic heterogeneity of quasi-brittle materials such as concrete.

2.2 Conduit Element

To represent moisture diffusion and gas outflow in concrete, a coupled transport-structure framework is formulated by augmenting the VCLM with conduit elements that explicitly model preferential fluid pathways. The Delaunay triangulation generated during the Voronoi-Delaunay meshing procedure is utilized as the background network for matrix diffusion and flow, while additional high-conductivity paths are introduced

along crack surfaces. Specifically on each common facet between adjacent Voronoi cells, a conduit element is placed, as illustrated in Fig. 1, to capture the dominant transport along crack planes. In heterogeneous materials such as concrete, fluid motion along the cracks is substantially faster than through the intact matrix. This is incorporated by assigning to each facet an aperture-dependent equivalent transport coefficient diffusivity of permeability denoted $D_{cr}(w)$, where w is crack opening computed at the facet level by VCLM. The enhanced coefficient $D_{cr}(w)$ increase with w , thereby reflecting accelerated transport along widened cracks relative to the matrix network. Before crack initiation, the transport coefficient was defined as the product of the initial transport coefficient and the degree of saturation(θ), expressed as $D_0 e^{n\theta}$. Once a crack formed, the transport coefficient of the conduit element assigned to the corresponding Voronoi facet was modeled as being proportional to $w^3/12\mu l$, thereby incorporating the effects of crack width and length. This formulation allowed the numerical representation of the dynamic behavior of liquid flow.

The effective geometry of a conduit element is defined using the crack opening w and the facet edge length l_f , yielding a time-evolving cross-sectional area $A_c = w l_f$. This cross-section represents the flow area tangential to the crack surface and is updated consistently with the structural response as cracks initiate and grow. By concurrently accounting for (i) matrix-scale diffusion/flow on the Delaunay network and (ii) crack-surface transport via facet-based conduits, the coupled model enables quantitative evaluation of post-damage diffusion and outflow in cracked concrete, maintaining consistency with the discrete fracture kinematics provided by VCLM.

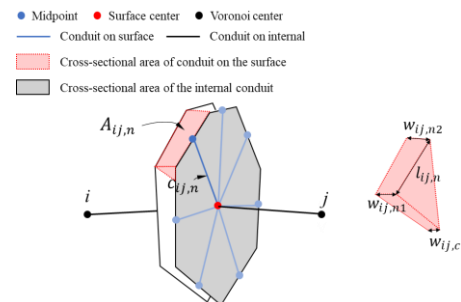


Fig. 1. Internal conduit and facet-based crack conduit configuration

3. Model Verification with Moisture Diffusion Tests

The coupled transport-structure framework was verified against the uncracked-concrete moisture diffusion experiment reported by Zhang et al. (2011) [2]. The specimen had a water-cement ratio of 0.60. Using the reported sorptivity, the reference diffusivity was set to $D_{w0}=9.28 \times 10^{-3} \text{mm}^2/\text{min}$ for the analysis. The bottom face, immersed in water, was modeled with a Dirichlet boundary condition corresponding to full saturation ($\theta=1$). All non-immersed faces (sides and top), sealed with aluminum film in the test, were assigned zero-flux (Neumann) boundary condition. Because the specimen was uncracked, only the internal conduits was activated; facet-based crack conduits were disabled. The maximum water content observed experimentally was $S_{\text{max}}=0.05 \text{g/cm}^3$. For a direct comparison, the moisture state was normalized as $\theta=S/S_{\text{max}}$, so that $\theta=1$ represents the experimental maximum. The predicted penetration height versus time reproduced the measured trend (Fig. 2). Likewise, the computed θ -height profiles showed good agreement with the normalized experimental data (Fig. 3), capturing both the temporal evolution and spatial distribution of ingress. This accuracy reflects the use a saturation-dependent nonlinear matrix diffusivity $D_w(\theta)$ anchored by D_{w0} , which reproduces the experimentally observed faster advance in high-humidity zones relative to drier regions.

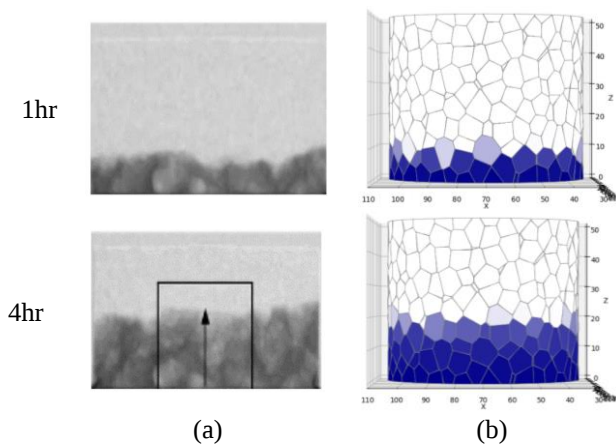


Fig. 2. Results of moisture diffusion analysis without cracks: (a) Experimental results [2], and (b) Numerical results

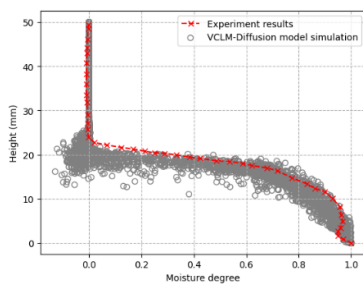


Fig. 3. Comparison of moisture degree-height results after 4 hours [2]

The framework was also exercised on a cracked specimen by activating facet-based conduit elements along the crack surface and assigning an aperture-dependent equivalent diffusivity. As shown in Fig. 4, the model predicts markedly enhanced transport localized at the crack, confirming its ability to represent preferential pathways and the associated acceleration of moisture ingress in damaged concrete.

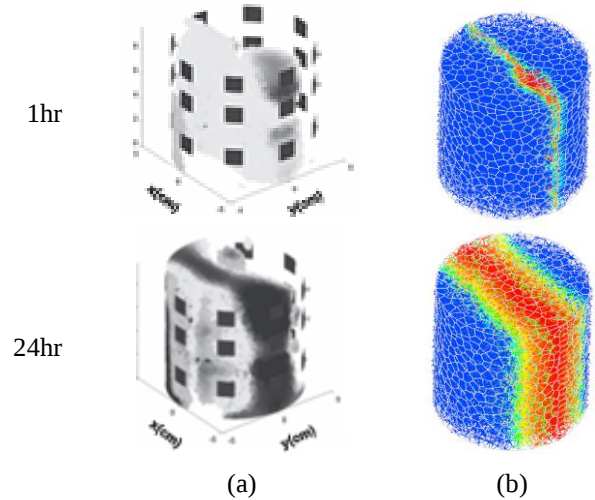


Fig. 4. Results of moisture diffusion analysis with cracks: (a) Experimental results [3], and (b) Numerical results

4. Conclusions

Long-term operation of NPPs containment structures is susceptible to degradation driven by the ingress of moisture, chloride ions, and gases. These transport processes promote reinforcing-steel corrosion and alkali-silica reaction (ASR) induced volumetric expansion, which in turn cause strength reduction and cracking. This study established a foundational numerical framework for representing such degradation in concrete by coupling a discrete fracture model the VCLM with conduit elements that capture preferential transport along crack surfaces. The formulation distinguishes matrix-scale diffusion from crack-surface transport, assigns saturation dependent diffusivity to the matrix network, and employs an aperture-based cubic-law transmissivity for facet-level conduits. In doing so, it provides a consistent means to link evolving fracture kinematics with moisture and species transport. Future work will extend this framework to explicitly simulate degradation product and swelling mechanism e.g. corrosion induced expansion and ASR gel growth as driving sources for crack initiation and propagation. The resulting chemo-hydro-mechanical model is intended to support quantitative assessments of long-term structure integrity.

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