A Numerical Model for Prediction of Spalling of Concrete Exposed to Elevated Temperatures

H L Zhang[a], C T Davie[a], C J Pearce[b] and N Bićanić[b]

[a] School of Civil Engineering and Geosciences, Newcastle University

[b] Department of Civil Engineering, University of Glasgow

Introduction

A coupled hygro-thermo-mechanical model for concrete exposed to elevated temperatures, together with its finite element implementation, is presented. Then, taking a one-dimensional and a two dimensional benchmark problem as examples, the significance of pore pressure and thermally induced stresses for spalling of concrete with different permeability and moisture content is investigated.

Mathematical Model

Gas phase is governed by

$$\frac{\partial(\varepsilon_G \tilde{\rho}_A)}{\partial t} = -\nabla \cdot \mathbf{J}_A$$

Liquid phase is governed by

$$\frac{\partial(\varepsilon_G \tilde{\rho}_V)}{\partial t} + \frac{\partial(\varepsilon_L \rho_L)}{\partial t} - \frac{\partial(\varepsilon_D \rho_L)}{\partial t} = -\nabla \cdot (\mathbf{J}_V + \mathbf{J}_L)$$

Momentum is governed by

$$\nabla \cdot (\boldsymbol{\sigma}' - P_{Pore}\mathbf{I}) + \mathbf{b} = 0$$

Energy is governed by

$$(\underline{\rho C})\frac{\partial T}{\partial t} - \lambda_E \frac{\partial(\varepsilon_L \rho_L)}{\partial t} + (\lambda_D + \lambda_E)\frac{\partial(\varepsilon_D \rho_L)}{\partial t} = \nabla \cdot (k \nabla T) + \lambda_E \nabla \cdot \mathbf{J}_L$$

Mechanical damage is governed by

$$\omega = 1 - \frac{\kappa_0^{md}(T)}{\kappa^{md}} e^{-\gamma(T)\left(\kappa^{md} - \kappa_0^{md}(T)\right)} \qquad \kappa_0^{md} = \frac{f_t(T)}{E(T)}$$

Thermal damage is governed by

$$\chi = 0.2\theta - 0.01\theta^2$$

Most of the material parameters used here are not constant, e.g., dependent on temperature.

Full details of the model can be found in [Davie et al., In the Proc. of the 5th International Conference for Structures in Fire, May 2008, Singapore.]

Numerical Analysis

As the magnitude of gas pressure build-up is significantly influenced by the initial permeability (which affects the transport of fluids) and relative humidity (which controls the moisture content), a series of analyses are conducted varying these two parameters.

1D problem – wall exposed to fire on one side

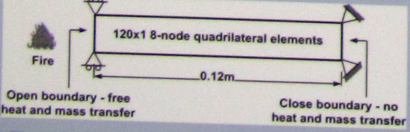

Fig. 1 Schematic diagram of 1D problem

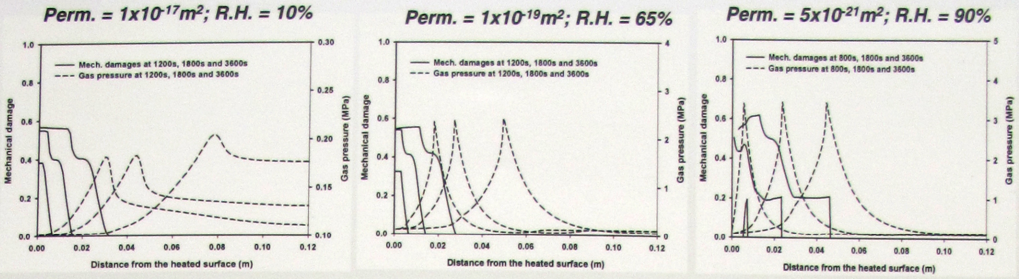

Fig. 2: (a) (b) (c)

When permeability is high and/or relative humidity is low, pore pressures have negligible contribution to the occurrence of damage (Fig. 2(a)). As permeability decreases and/or relative humidity increases, pore pressures become more and more significant (Fig. 2(b)) until pore pressures exceed the tensile strength of the concrete and peak pore pressures coincide with the location of the mechanical damage front (Fig. 2(c)).

2D problem – concrete column exposed to fire on all sides

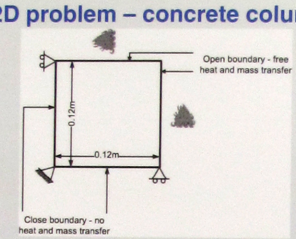

Fig. 3 Schematic diagram of 2D problem

In all cases, thermally induced stresses are found to build-up much faster than the pore pressures and can exceed the tensile strength of the concrete in a short time, resulting in mechanical damage representative of typical corner spalling patterns. In most cases, pore pressure has negligible effect on damage (Figs. 4 & 5). In concrete with very low permeabiltiy and high relative humidity, pore pressure is found to cause secondary damage close to the fire exposed corner (Fig. 6).

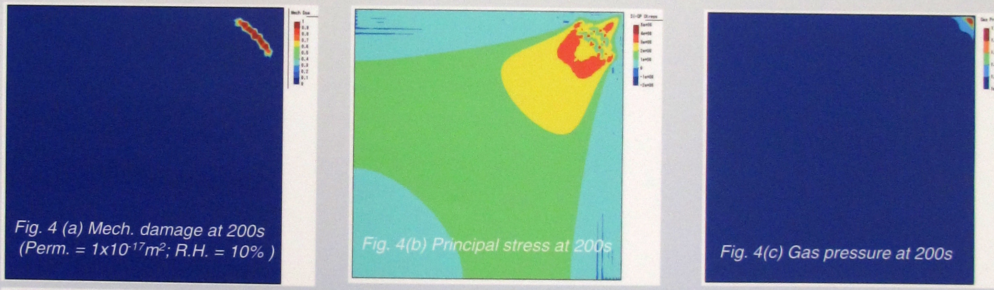

Fig. 4 (a) Mech. damage at 200s (Perm. = 1x10-17m2; R.H. = 10%) Fig. 4(b) Principal stress at 200s Fig. 4(c) Gas pressure at 200s

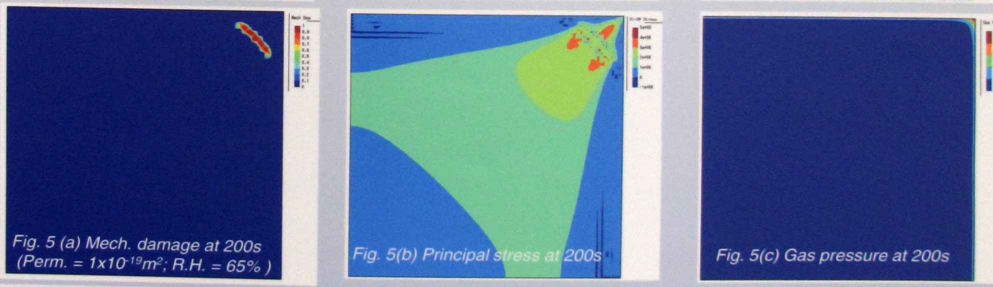

Fig. 5 (a) Mech. damage at 200s (Perm. = 1x10-19m2; R.H. = 65%) Fig. 5(b) Principal stress at 200s Fig. 5(c) Gas pressure at 200s

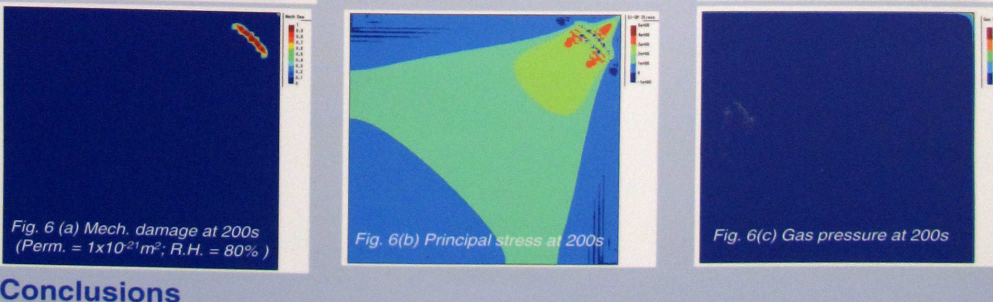

Fig. 6 (a) Mech. damage at 200s (Perm. = 1x10-21m2; R.H. = 80%) Fig. 6(b) Principal stress at 200s Fig. 6(c) Gas pressure at 200s

Conclusions

- For the one-dimensional problem, for concrete with high initial permeability and/or low relative humidity, pore pressures are shown not to be the primary cause of damage; for concrete with low initial permeability and/or high relative humidity, pore pressures may be a primary cause of spalling.
- For the two-dimensional problem, thermally induced stresses seem to be the primary cause of damage in the concrete and may therefore be inferred to have a predominant role in the occurrence of spalling. Pore pressures seem to have a negligible (or at most secondary) effect.
- Clearly, both thermally induced stresses and pore pressures are affected by the geometry and constraint conditions of the problem. This will be more thoroughly investigated.