SPALLING RISK ASSESSMENT OF CONCRETE SUBJECTED TO DIFFERENT FIRE SCENARIOS

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Abstract
Spalling of concrete subjected to high temperature can cause loss of the cross-sectional area and exposure of steel bars to fire. Since spalling is induced by combined thermal strains (thermal-mechanical processes) and accumulated pore pressures (thermal-hydro processes), so-called coupled models are required to take into account these two mechanisms.

In this paper, the effect of underlying model assumptions on the numerical results is investigated by means of a 2D axisymmetrical model, keeping material and geometry parameters constant. Based on different fire scenarios, both coupled analysis (thermal-hydro-mechanical) and uncoupled analysis (thermal-mechanical) are performed. While the results of the coupled analysis and uncoupled analysis give similar stresses’ distributions, relations between fire scenarios and the risk of spalling are revealed.

Keywords: concrete spalling, high temperature, coupled analysis, numerical simulations

<table>
<thead>
<tr>
<th>List of Symbols</th>
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<tbody>
<tr>
<td>$c_p$</td>
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<tr>
<td>$c_g + c_w$</td>
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<tr>
<td>$D_e$</td>
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<tr>
<td>$D_{eff}$</td>
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<tr>
<td>$E$</td>
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<tr>
<td>$f_t$</td>
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<tr>
<td>$g$</td>
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<td>$h$</td>
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1. INTRODUCTION

Concrete structures exposed to evaluated temperatures will experience severe chemical and mechanical processes, which may result in sudden loss of near-surface concrete layers, referred as spalling. Two mechanisms are attributed to cause spalling: thermal stresses and pore pressure caused by water vapors.

The controversy about the influence of these two mechanisms is still ongoing, with different simulations and experiments giving different conclusions [1-3]. In general, this influence varies with concrete type, section shape and size, fire loading, constraint.

In this paper, a 2D axisymmetrical model with constant concrete properties (OPC) and size of the model and varying fire loading is used to assess the risk of spalling. Both coupled and uncoupled analysis will be conducted for every considered case. Studies about the relationships among fire loading, stress (first principal) distribution, initiation of spalling are presented, providing insights into the risk and origin of spalling.
2. ANALYSIS METHOD

2.1 Thermo-hydro-chemical model

The coupled model adopted in this paper is the thermo-hydro-chemical model proposed in [4]. This model treats concrete as a multi-phase medium. The capillary pressure \( p^c \) [Pa], gas pressure \( p^g \) [Pa] and temperature \( T \) [\(^\circ\)C] are treated as unknowns. Three field equations are formulated using mass and energy balance.

1. Mass-balance equation of water phase (vapor and water):

\[
\frac{\partial S_w}{\partial t} + n(1-S_w) \frac{\partial \rho^w}{\partial t} + nS_w \frac{\partial \rho_w}{\partial t} = (1-n) \beta_s \left[ \rho^w + (\rho^w - \rho^{gw}) S_w \right] \frac{\partial T}{\partial t} \\
- \text{div} \left\{ \rho^{gw} \frac{k^g}{\eta^g} \text{grad} \, p^g \right\} - \text{div} \left\{ \rho^w \frac{k^w}{\eta^w} \text{grad} \, p^w \right\} - \text{div} \left[ \rho^s M_a M_w D_{\text{eff}} \text{grad} \left( \frac{p^{gw}}{p^g} \right) \right] \\
+ \frac{(1-n)}{\rho^s} \left[ \rho^{gw}(1-S_w) + \rho^w S_w \right] \frac{\partial \rho^s}{\partial t} + \frac{\rho^{gw}(1-S_w) + \rho^w S_w}{\rho^s} \frac{\partial m_{\text{dehydr}}}{\partial t} = \dot{m}_{\text{dehydr}} = 0
\] (1)

2. Mass-balance equation of dry-air phase:

\[
- n \rho^a \frac{\partial S_a}{\partial t} + n(1-S_a) \frac{\partial \rho^a}{\partial t} = (1-n)(1-S_w) \beta_s \frac{\partial T}{\partial t} - \text{div} \left[ \rho^a \frac{k^a}{\eta^a} \text{grad} \, p^a \right] \\
- \text{div} \left[ \rho^s M_a M_w D_{\text{eff}} \text{grad} \left( \frac{\rho^a}{p^g} \right) \right] (1-n) \rho^a (1-S_w) \frac{\partial \rho^s}{\partial t} + \rho^a (1-S_w) \frac{\partial m_{\text{dehydr}}}{\partial t} = 0
\] (2)

3. Energy-balance equation:

\[
\rho^c \left( \frac{\partial T}{\partial t} \right)_{\text{eff}} - \text{div} \left( \lambda_{\text{eff}} \text{grad} T \right) \\
+ \dot{m}_{\text{dehydr}} \frac{\partial T}{\partial t} + \dot{m}_{\text{vap}} \left( \frac{\rho^g \frac{k^g}{\eta^g} \text{grad} \, p^g + \rho^w \frac{k^w}{\eta^w} \text{grad} \, p^w }{\rho^s} \right) \text{grad} T = 0
\] (3)

In which,

\[
\dot{m}_{\text{vap}} = - n \rho^w S_w \frac{\partial S_w}{\partial t} + n \rho^w S_w \frac{\partial \rho^w}{\partial t} + \rho^w (1-S_w) \beta_s \frac{\partial T}{\partial t} + \text{div} \left( \rho^w \frac{k^w}{\eta^w} \text{grad} \, p^w \right) (1-n) \rho^w S_w \frac{\partial \rho^s}{\partial t} - \rho^w S_w \frac{\dot{m}_{\text{dehydr}}}{\rho^s} + \dot{m}_{\text{dehydr}}
\]

2.2 Effective stress theory

The effective stress theory [5] is employed in order to link the thermo-hydro-chemical model to the mechanical model, finally yielding the thermal-hydro-mechanical model.

\[
\text{div} \, \sigma + \rho \mathbf{g} = 0
\]

\[
\sigma_{\text{eff}} = \sigma + \mathbf{I} \left( p^g - \chi_S \rho^w \mathbf{p}^c - \rho_{\text{atm}} \right) - \mathbf{D_e} (\varepsilon - \varepsilon_T)
\]
3. NUMERICAL STUDY

3.1 Axisymmetrical spalling model—geometric properties and fire loadings

A concrete member for the numerical investigation of spalling is given by a 2D axisymmetrical model with boundary restraints as shown in Figure 1. The displacement of the concrete member in the vertical direction is restrained at point B. The bottom surface is subjected to fire loading, where the fire load changes spatially and temporally. While the spatial distribution follows a Gaussian function, see Figure 2(a), the evolution of the temperature at the rotation axis, Ts, is shown in Figure 2(b).

The cases considered in this paper and the corresponding fire load are listed in Table 1.

![Figure 1: Axisymmetrical spalling model](a)
![Figure 2: Fire loading considered in numerical study](b)

Table 1: Considered cases of fire loading

<table>
<thead>
<tr>
<th>Parameter A[m⁻²]</th>
<th>Case</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>-115.13</td>
<td>-18.42</td>
<td>-7.19</td>
</tr>
<tr>
<td>Case</td>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
</tbody>
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3.2 Material parameters

In this paper, OPC (C-25) is adopted in the numerical study the material parameters of which are listed in Table 2. All material parameters are temperature or gas/capillary pressure dependent, when the values in Table 2 are at initial state. The relationships of elastic modulus and tensile strength with temperature are taken from [6], while the evolution of the remaining parameters is taken from [7].

Table 2: Material parameters

<table>
<thead>
<tr>
<th>$E$ [MPa]</th>
<th>$f_t$ [MPa]</th>
<th>$k$ [m$^2$]</th>
<th>$S_w$ [-]</th>
<th>$\beta_5$ [1/K]</th>
<th>$\lambda$ [J/(s m K)]</th>
<th>$c_p$ [J/(kg K)]</th>
<th>$n$ [-]</th>
<th>$\rho_s$ [kg/m$^3$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$3.15\times10^4$</td>
<td>1.67</td>
<td>$10^{-17}$</td>
<td>0.4</td>
<td>$3.6\times10^{-5}$</td>
<td>1.9</td>
<td>900</td>
<td>0.1</td>
<td>2400</td>
</tr>
</tbody>
</table>

3.3 Numerical results

Large scale fire tests with similar dimensions to those of the numerical example revealed that spalling mostly occurs 3 mins after heating[8]. Accordingly, Figures 3 to 5 show the distribution of the first principal stress after 180s of fire loading. Figures 5 to 8 show the distribution of the first principal stress after 300s of fire loading.

The coupled and uncoupled analysis gave not only similar distributions but also similar values for the first principal stress, which is explained by the rather short simulation time of 180s, with the gas permeations not yet fully developed. A 1D simulation using the same parameters reveals that the maximum gas pressure increases from 0.4268MPa at 180s to 0.8939MPa at 300s (Figure 9).

Initiation of spalling (coupled analysis) is illustrated in Figure 10. The curves in Figure 10 show the developments of the depth of maximum first principal stress on the whole domain. Theoretically, since the distributions of first principal stress and tensile strength along the depth are different, first spalling (there is a point on the whole domain with its first principal stress greater than its tensile strength) happens not always on the point with maximum first principal stress. However, in this paper, in all cases the first spalling happen on the points with maximum first principal stress. Actually the points with conspicuous decrease of tensile strength are mostly under compression.

In Figure 10, the dashed lines indicate that the maximum first principal stress is below the actual temperature-dependent tensile strength on the same point. Accordingly, spalling is initiated after about 130s of fire loading in all cases.

Figure 3: First principal stress [Pa] at 180s for Case 1:
(a)coupled analysis and (b)uncoupled analysis
Figure 4: First principal stress [Pa] at 180s for Case 2: (a) coupled analysis and (b) uncoupled analysis

Figure 5: First principal stress [Pa] at 180s for Case 3: (a) coupled analysis and (b) uncoupled analysis

Figure 6: First principal stress [Pa] at 300s of Case 1: (a) coupled analysis and (b) uncoupled analysis

Figure 7: First principal stress [Pa] at 300s of Case 2: (a) coupled analysis and (b) uncoupled analysis
CONCLUSIONS

In this paper, a numerical study on a simplified 2D axisymmetrical spalling model considering different fire scenarios are presented.

Based on obtained results, the following conclusions can be drawn:

1. Coupled and uncoupled analysis produce similar results, while the uncoupled analysis has great advantages as regards to calculation time.
2. Gas pressure has little influences on spalling in the considered cases, which is explained by the high permeability of concrete and the rapid initiation of spalling (due to steep fire loading adopted in this paper).

3. The initiation of spalling (location) under different fire loading (distribution) has smooth development, which in all cases the spalling is initiated after 130s of fire loading.

5. OUTLOOK

Spalling of concrete refers to multi-fields coupled analysis. Though effective stress theory links the mass transport (thermo-hydro-chemical) fields to the mechanical field, the effects from mechanical field to mass transport fields (thermo-hydro-chemical-mechanical-damage) have not been taken into account yet. The construction of relevant model is ongoing, which will combine strong discontinuities approach with the present coupled model.

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REFERENCES


