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A FINITE ELEMENT MODELLING OF THERMO-HYDRO-MECHANICAL BEHAVIOUR AND NUMERICAL SIMULATIONS OF PROGRESSING SPALLING FRONT

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Abstract. This paper presents a coupled thermo-hydro-mechanical (THM) model enriched with a buckling-type criterion for progressive spalling. In the first part of the paper, a general fully coupled multi-phase THM model describing the behaviour of concrete at moderate and high temperatures is presented. Then the spalling criterion and its numerical implementation in the framework of the finite element method are presented.

Finally, a simple 1D numerical example will illustrate the effectiveness of the implemented numerical approach.

1 INTRODUCTION

In the past few years, major tunnel fires (Channel 1996, Ekeberg 1996, Mont-Blanc and Tauern 1999, Kaprun 2000, Gleinalm 2001 and St Gotthard 2001) has caused fatalities, severe traffic restrictions as well as important economic losses. In extreme conditions such as those typical occurring during a fire (i.e. temperatures exceeding 1200^oC for considerable time spans), concrete experiences a drastic decrease of its performances due to degradation processes that are induced by several coupled thermo-hydro-chemo-mechanical (THCM) phenomena. Pore pressure build-up, restrained thermal dilatation, cement paste to aggregate incompatibility, thermal de-cohesion, dehydration ... are just some main physical phenomena affecting concrete performances and which may cause spalling. Progressive concrete spalling occurring during a fire is a physical process of the breakdown of surface layers which flake into small pebble-like pieces in response to THM stresses.

In this contribution, a THM finite element model is enriched with a buckling-type criterion for progressive spalling. The thermo-hygral part of the THM model is based on the three fluid approach for partially saturated media [5]. The approach is developed by writing the relevant balance equations for the constituents at the pore scale and by up-scaling these equations to the macroscopic scale, taking into account thermodynamic constraints. The mechanical part is derived within the framework of poro-mechanics coupled to damage and softening plasticity [1]. The final model, after introduction of the constitutive equations, consists of a mass balance equation for the dry air, a mass balance equation for the fluid phases (water and vapour), a mass balance equation for the solid phase, an energy balance and mechanical equilibrium equations for whole porous medium.

The spalling criterion is an iterative post-processing, within each time step, of stress, pore pressure, damage and current strength fields that are obtained from THM solution. In this criterion, effective (acting on the solid phase) pore pressures may give rise to micro-cracking that percolate to form a flake whose size is related to the maximum aggregate size. A buckling analysis is then performed on the delimited flake (with damaged stiffness) while subjected to compressive stresses. The efficiency of the implemented numerical model in capturing initiation and progression of a spalling front is finally illustrated by an example.

2 THERMO-HYGRAL MODEL

The thermo-hygral model is described by a set of balance equations completed by an appropriated set of constitutive relationships describing the behaviour of concrete at moderate and high temperatures. The main physical phenomena such as vapour diffusion, liquid water flow due to pressure gradients and capillary effects, dehydration [4], evaporation and condensation phenomena [9] are taken into account. The governing equations of the model are finally given in terms of the chosen state variables: the capillary pressure p_c, the gas pressure p_g and the temperature T. Hence, mass balance equations write, for solid matrix:

$$\frac{\partial m_s}{\partial t} = \dot{m}_{dehyd} \tag{1}$$

liquid water:

$$\frac{\partial m_l}{\partial t} + \nabla \cdot (m_l \boldsymbol{v}_{l-s}) = -\dot{m}_{vap} - \dot{m}_{dehyd} \tag{2}$$

vapour:

$$\frac{\partial m_v}{\partial t} + \nabla \cdot (m_v \boldsymbol{v}_{g-s}) + \nabla \cdot (m_v \boldsymbol{v}_{v-g}) = \dot{m}_{vap} \tag{3}$$

dry air:

$$\frac{\partial m_a}{\partial t} + \nabla \cdot (m_a \boldsymbol{v}_{g-s}) + \nabla \cdot (m_a \boldsymbol{v}_{a-g}) = 0 \tag{4}$$

where m_x is the mass per unit volume of porous medium of each constituent ($x = s, l, v, a$):

$$m_s = (1-\phi)\,\rho_s\ ,\ m_l = \rho_l S_l \phi\ ,\ m_v = \rho_v\,(1-S_l)\,\phi\ ,\ m_a = \rho_a\,(1-S_l)\,\phi \tag{5}$$

in which ρ_x is the corresponding density, ϕ is the porosity, S_l is the degree of saturation, $\dot{m}_{vap}$ is the evaporation mass rate and $\dot{m}_{dehyd}$ is the dehydration mass rate.

Besides, the energy balance equation of the whole medium is:

$$\begin{aligned} \rho C_p \frac{\partial T}{\partial t} - K\left(C_l \frac{\rho_l k_{rl}}{\mu_l}\,(\nabla p_g - \nabla p_c) + C_g \frac{\rho_g k_{rg}}{\mu_g} \nabla p_g\right) \cdot \nabla T - \nabla \cdot (\lambda \nabla T) \\ = -H_{vap}\dot{m}_{vap} + H_{dehyd}\dot{m}_{dehyd} \end{aligned} \tag{6}$$

where C_p is heat capacity, $\boldsymbol{q}$ is the heat flux, H_{vap} is the enthalpy of vaporization and H_{dehyd} is the enthalpy of dehydration.

3 MECHANICAL MODEL

The mechanical behaviour of the matrix is described by an elasto-plastic approach coupled to damage. The constitutive law reads:

$$\sigma = (1 - D_{tc})(1 - D_m)\tilde{\sigma} + b p_s \delta \tag{7}$$

where σ is the apparent stress tensor, $\tilde{\sigma}$ is the effective stress tensor [7], $b = 1 - (1 - b_0)[1 - (1 - D_{tc})(1 - D_m)]$ is the Biot's coefficient of damaged porous medium [6], p_s is the pore pressure acting on the solid phase and $\boldsymbol{\delta}$ is the second order unit tensor.

This equation takes into account the thermo-chemical process due to degradation and the mechanical damage. Two variables of thermo-chemical damage D_{tc} and mechanical damage D_m are therefore introduced.

Furthermore, the effective strain tensor $\tilde{\varepsilon}$ is given by the decomposition of total strain tensor ε to the elastic strain tensor ε_e, the plastic strain tensor ε_p describing crack opening, the transient creep component which is the additional strain observed when heating occurs with a concomitant sustained applied load ε_{tc} [10] [11] and the free thermal strain tensor ε_{th}.

Thus the effective stress tensor is given by:

$$\tilde{\sigma} = \boldsymbol{E} : (\varepsilon - \varepsilon_p - \varepsilon_{th} - \varepsilon_{tc}) \tag{8}$$

The final mechanical constitutive equation then writes:

$$\sigma = (1 - D_{tc})(1 - D_m)\boldsymbol{E} : (\varepsilon - \varepsilon_p - \varepsilon_{th} - \varepsilon_{tc}) + bp_s\delta \tag{9}$$

4 SPALLING CRITERIA AND SIMULATION OF SPALLING FRONT

4.1 Spalling criteria

The spalling phenomenon is assumed to be the result of a combination of two main processes: the first one is the thermo-hygral process related to the build-up of pore pressures acting on the solid phase; the second one is the thermo-mechanical process which is associated to the thermal dilatation gradient.

The first process is related to the mass transfer of liquid phases (liquid water, vapour and dry air) [8]. When temperature increases, strong vapour gradients are generated causing moisture to migrate both towards the heated surface and inwards, towards the colder layers: this latter results in vapour condensation. This phenomenon, often referred to as "moisture clog", forms a quasi-saturated layer that acts as an impermeable wall for gases, resulting in gas pressure built-up (Fig:1-b). This pressure may give rise to micro-cracks that propagate forming a flake whose size is related to the maximum aggregate size.

The first spalling criterion is then stated by comparing the pore pressure and the tensile strength:

$$F_{cri1} = f_t(T) - bp_s < 0 \tag{10}$$

where F_{cri1} is the value of the first spalling criterion, f_t is the tensile strength which depends on the temperature, b is the Biot's coefficient and p_s is the pore pressure acting to the solid phase:

$$p_s = p_g - \chi p_c = p_g - S_l p_c \tag{11}$$

in which χ is the Bishop's coefficient.

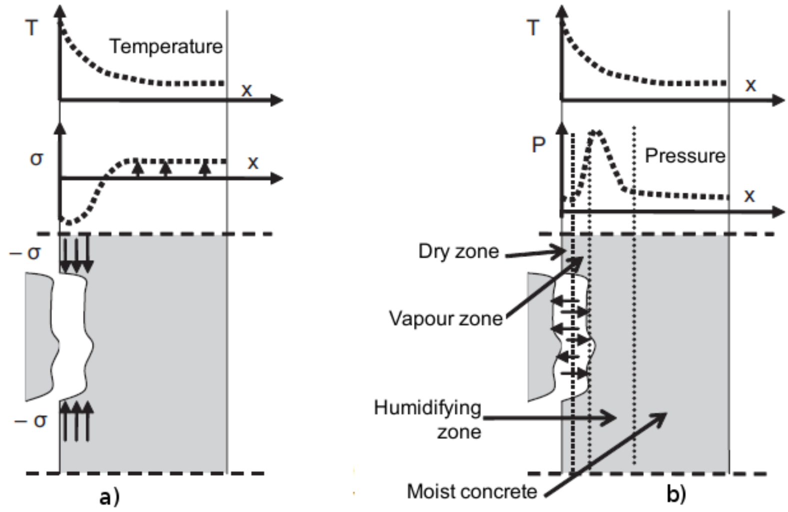

Figure 1: Spalling mechanism: a) Thermal dilatation [3] b) Pore pressure [2]

The thermo-mechanical process is directly associated to the temperature field. As temperature increases, the temperature gradients generate a thermal dilatation which engenders compressive stresses in the direction parallel to the heated face (Fig:1-a). An additional external compressive load parallel to the heated face can intensify this effect [8, 12].

If the compressive stresses induced by the thermal gradients are strong enough (and the first spalling criterion is satisfied), the external layer buckles.

The second spalling criterion writes:

$$\begin{aligned} F_{cri2} &= \sigma_{cr} - < \sigma > \\ &= \frac{\pi^2 EI}{Ah} - < \sigma > \\ &= \frac{\pi^2 e^2}{12h^2}(1 - < D >)E_0 - < \sigma > \end{aligned} \tag{12}$$

where F_{cri2} is the value of the second spalling criterion, σ_{cr} is the Euler's criterion stress, σ is the compressive stresses (in equation 7) in the direction parallel to the heated face, A is the area of spalling zone, h is the length of spalling zone, e is the depth of the spalling zone, E is the stiffness of material, $< \cdot >$ is the average operation and D is the damage of material.

4.2 NUMERICAL SIMULATION OF SPALLING

The spalling criterion is an iterative post-processing of stress, pore pressure, damage and current strength fields that are obtained from the THM solution.

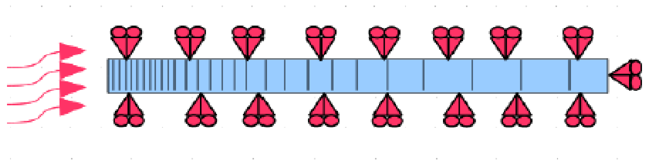

Figure 2: Studied configuration

The simulation of a progressing spalling front within one time step is then verified by using the two spalling criteria presented in the previous section. If the criteria are both verified and concrete spalls, the associated FE mesh is deactivated (no remeshing is required) and boundary conditions are transferred to the interface between the spalled zone and the intact layer of elements.

The THM model and the spalling criteria have been introduced into CESAR, a finite element code developed by Laboratoire Des Ponts et Chaussées (LCPC).

5 NUMERICAL SIMULATION

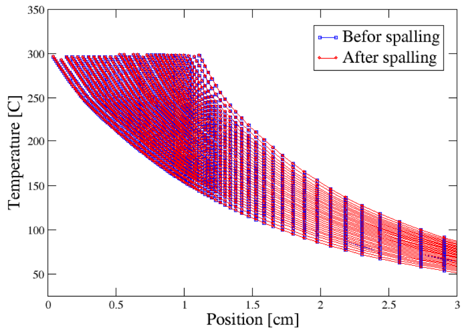

Figure 3: Temperature evolutions in different time steps

In this section, the presented THM modelling and the spalling phenomenon are illustrated by a simple numerical 1D example. The concrete specimen ($2mm \times 10cm$) is exposed to an ISO Fire and a Neumann type boundary condition on p_c and p_g on the left side of the specimen (Fig 2) is applied. In order to promote the spalling phenomenon, in this (purely numerical) example the spalling criteria related to the gas pressure is considered as satisfied (i.e. the tensile strength is artificially set to zero $f_t = 0$). In figures 3-4 the evolutions of capillary pressure, gas pressure and temperature are given. We observe that the specimen spalls many times from $t = 485s$ to $t = 760s$. The depth of the spalling zone is $12mm$ and the spalling velocity variate from $1.8mm/min$ to $5mm/min$. The figure 5 represent the evolution of capillary pressure in the first $2mm$ of the specimen. At the first spalling, the heated surface layer of 4 elements is deactivated. Then the boundary condition is transferred successfully to the the surface between external spalled layer and inner layer. This boundary condition causes the increase of capillary pressure (Fig 4-5) and the decrease of gas pressure (Fig 4)

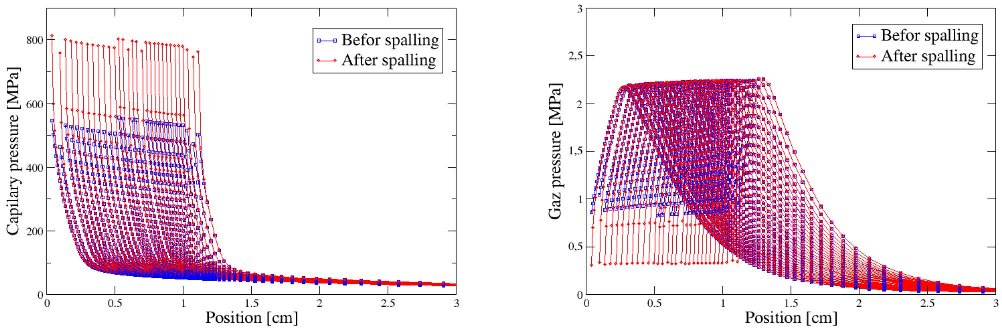

Figure 4: Capilary pressure evolutions in different time steps

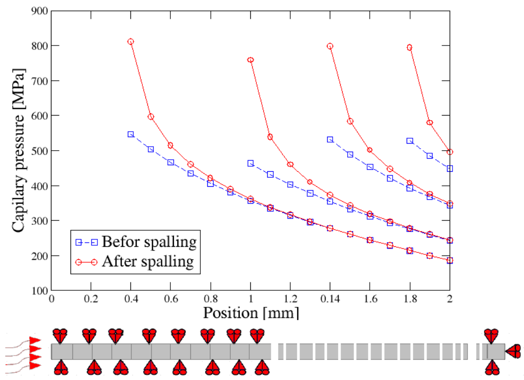

Figure 5: Capilary pressure evolutions in different time steps of $2mm$ external layer

6 CONCLUSION

In this paper, a fully coupled THM model, enriched with a buckling-type criterion for progressive spalling, has been presented. Spalling is taken into account by a combination of two criteria based on pore pressure and thermal expansion. The feasibility of the proposed approach is illustrated by means of a simple, 1D example illustrating the propagation of a spalling front. The presented approach constitutes a general framework for describing the behaviour of concrete when extreme loading conditions (such as those typical of a fire in a tunnel) occur.

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