PREDICTION OF EARLY-AGE CRACKING IN CONCRETE CONTAINMENT VESSELS OF NUCLEAR POWER PLANT

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ABSTRACT

A numerical model has been developed to predict early age cracking for massive concrete structures, and especially concrete containment vessels. It includes major phenomena: hydration, heat diffusion, autogeneous and thermal shrinkage, creep and cracking. Since, studied structures are massive and the fact that one focuses only at early-age, drying is not taken into account. Such modeling requires the identification of several material parameters. An important experimental campaign has been carried out on a concrete representative of internal containment of French nuclear power plant. Besides, a relevant experimental device has been developed to validate the proposed modeling. It is based on the ring test, in which the temperature is controlled by heated water. Through numerical simulations, it is shown that taking into account creep at early-age is essential if one wants to predict quantitatively the induced stresses if autogenous or thermal strains are restrained. Moreover, coupling creep with cracking must be taken into account for an accurate prediction of cracking.

INTRODUCTION

Modeling the behavior of concrete at early age is a major industrial problem in civil engineering. Since the hydration of the cement paste is highly exothermic, thermal strains will arise. If these strains are restrained (by the previous lift for instance), or if a strain gradient occurs between the skin and core of the structure, there is a considerable risk of cracking. Besides, the volumetric balance of cement hydration is negative leading to autogeneous shrinkage, which can lead also to cracking if theses strains are restraint. These cracking increases leakage, which can reduce the serviceability of the structures (like containment in nuclear powerplant, gas tank …). Besides, it creates weak areas which may again crack during an accidental loading. In order to be able to predict this cracking, we need to thoroughly investigate and understand the behavior of concrete at early age.

An important experimental campaign is presented in order to identify the early-age behavior of a concrete which is representative of a French nuclear powerplant. It includes heat diffusion, hydration, autogeneous shrinkage, thermal shrinkage, basic creep (and effect of hydration and temperature) in tension, cracking (and interaction with creep) and evolution of material parameters with respect to hydration. Material parameters are identified from these experiments by numerical simulations using Cast3m finite element code. The model is based on an isotropic damage formulation, which takes into account all aforementioned phenomena.

Finally, the construction of a typical French containment vessel of a nuclear power plant is simulated by finite element calculations (with also Cast3m finite element code). The simulation takes into account some parts of the construction phase. Simulations with an axisymetric geometry will be presented. Calculations with a 3D mesh and the take into account of passive reinforcement is currently undertaken. They show that, the accurate prediction of cracking needs to model of creep and coupling between creep and cracking.

SHORT PRESENTATION OF THE MODEL AND IDENTIFICATION

In this part, a brief description of the model is presented. The numerical algorithm and the complete description of the model can be found in [1]. The constitutive model has been implemented in Cast3m finite element code [2].

Hydration and heat diffusion

The hydration of cement paste is a thermo-activated process. Its evolution is modeled by the following relation [3]:

$$\dot{x} = \dot{A}(x)\exp\left(-E_a/RT\right) \tag{1}$$

in which $\dot{x}$ is the rate of degree of hydration , $\bar{A}(x)$ is the normalized affinity, E_a is the activation energy, R is the constant of perfect gas and T is the temperature in Kelvin. The normalized affinity is associated the micro-diffusion process of water which react with unhydrated cement [3].

The evolution of temperature is obtained from the energy balance equation, which includes the release of heat due to the hydration reaction:

$$C\dot{T} = \nabla(k\nabla T) + L\dot{x} \tag{2}$$

in which C is the volumetric heat capacity, k is the thermal conductivity and L is the latent heat of hydration. This parameter and the normalized affinity $\bar{A}(x)$ can be obtained experimentally by measuring the temperature during a quasi-adiabatic test [1,3].

Autogeneous and thermal shrinkage

Due to Le Chatelier contraction, porosity filled with air and water arises during hydration of concrete. This leads capillary pressures to develop inside the material and induce autogeneous shrinkage strains $\boldsymbol{\varepsilon}_{au}$ given by:

$$\boldsymbol{\varepsilon}_{ij}^{au} = -k\bar{x}\,d_{ij} \quad \text{with} \quad \bar{x} = \left\langle \frac{x - x_0}{x_\infty - x_0} \right\rangle_+ \tag{3}$$

where x_∞ is the final hydration degree, and x_0 the mechanical percolation threshold: it corresponds to the hydration degree below the concrete has negligible mechanical properties (Young modulus, strength …). It is closely related to the setting time. It is kept constant and equal to 0.1, which corresponds to the usual value reported in the bibliography analysis of de Schutter and Taerwe [4]. However, it depends, in fact, on the aggregate content, type of cement and water to cement ratio [5]. k is a constant material parameter and $\mathbf{1}$ is the unit tensor. $\langle\cdot\rangle_+$ is the positive part operator.

In a similar way, the thermal strain rate tensor $\dot{\boldsymbol{\varepsilon}}_{th}$ is related to the temperature variation, due to the release of heat by the hydration, and to the dilation coefficient a:

$$\dot{\boldsymbol{\varepsilon}}_{th} = a\dot{T}\mathbf{1} \tag{4}$$

Creep

Models for basic creep are, usually, based on rheological elements (spring and dashpots): Kelvin-Voigt and Maxwell chains are combined in serial or/and parallel. Hauggaard et *al.* [6] and de Schutter [7] used only one Kelvin-Voigt unit for the modelling of early-age basic creep. Here, we used 3 Kelvin-Voigt chains (see Figure 1). The use of such elements gives straightforward formula for the computations of strain evolution, in contrary to Maxwell chains for instance, which need the use of an algorithm (such as the so called exponential algorithm proposed by Bazant and Wu [8]). The incremental constitutive relation for an aging spring was shown in [9] to be the only possible one which does not violate thermodynamic restrictions. It will be adopted here.

For each Kelvin-Voigt unit, the differential equation can be written as:

$$t_{bc}^{i}\dot{\tilde{s}}_{bc}^{i} + \left(t_{bc}^{i}\frac{\dot{k}_{bc}^{i}(x,T)}{k_{bc}^{i}(x,T)} + 1 \right)\tilde{s}_{bc}^{i} = \frac{\dot{\tilde{s}}}{k_{bc}^{i}(x,T)} \tag{5}$$

where t_{bc}^{i} is the characteristic time (constant), $k_{bc}^{i}(x)$ is the spring stiffness (increasing with the hydration degree), $\tilde{s}$ is the effective stress (see equation 7).

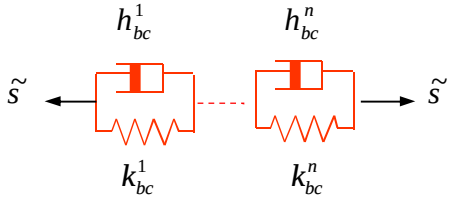

Fig.1: Aging Kelvin-Voigt elements for the prediction of basic creep strains.

The stiffness parameter for each unit is calculated with the following equation (based on [7] and assuming that creep increases with temperature by an Arrhenius law):

$$k_{bc}^{i}(x) = k_{bc\_\infty}^{i} \frac{0.473}{2.081 - 1.608\bar{x}} \bar{x}^{0.62} e^{\frac{E_{ac}}{R}\left(\frac{1}{T} - \frac{1}{T_0}\right)} \tag{6}$$

where $k_{bc\_\infty}^{i}$ is the final stiffness, E_{ac} is the creep activation energy and T_0 = 293 K.

Cracking

The mechanical behaviour of concrete is modelled by an elastic-damage model coupled with creep, which includes the evolution of the elastic stiffness with respect to the hydration degree (taking from [4]) and with respect to damage [10]. The relationship between apparent stresses $\boldsymbol{\sigma}$, effective stresses $\tilde{\boldsymbol{\sigma}}$, damage D, elastic stiffness tensor $\mathbf{E}$, elastic strains $\boldsymbol{\varepsilon}_{el}$, basic creep strains $\boldsymbol{\varepsilon}_{bc}$ (defined in the next part), total strains $\boldsymbol{\varepsilon}$, and previously defined strains reads:

$$\boldsymbol{\sigma} = (1-D)\tilde{\boldsymbol{\sigma}} \text{ and } \tilde{\boldsymbol{\sigma}} = \mathbf{E}(x)\boldsymbol{\varepsilon}_{el} = \mathbf{E}(x)\left(\boldsymbol{\varepsilon} - \boldsymbol{\varepsilon}_{bc} - \boldsymbol{\varepsilon}_{au} - \boldsymbol{\varepsilon}_{th}\right) \tag{7}$$

The Poisson ratio is assumed to be constant and the Young modulus E increases due to hydration as follows [4]:

$$E(x) = E_{\infty}\bar{x}^{b} \text{ with } \bar{x} = \left\langle \frac{x - x_0}{x_{\infty} - x_0} \right\rangle_{+} \tag{8}$$

in which E_{∞} is the final Young modulus (i.e. when $x = x_{\infty}$) and b is a constant equal to 0.62 according to [4].

D is linked to the elastic equivalent tensile strain $\hat{e}$ and is coupled with creep by a constant coefficient b:

$$\hat{e} = \sqrt{\left\langle \mathrm{e}_{el} + b\mathrm{e}_{bc} \right\rangle_{+} : \left\langle \mathrm{e}_{el} + b\mathrm{e}_{bc} \right\rangle_{+}} \tag{9}$$

The damage evolution reads:

$$\dot{D} = 0 \text{ if } \hat{e} \le k_0(x) \text{ and } D = 1 - \frac{k_0}{\hat{e}}\left[(1+A_t)\exp(-B_t\hat{e}) - A_t\exp(-2B_t\hat{e})\right] \text{ if } \hat{e} \ge k_0(\xi) \tag{10}$$

where $k_0(x)$ is the tensile strain threshold, A_t and B_t are constant material parameters which controls the softening branch in the stress-strain curve in tension.

The evolution of the tensile strain threshold depends upon the Young modulus (Eq. 8) and the tensile strength ones:

$$k_0(x) = \frac{f_t(x)}{E(x)} = \frac{f_{t\infty}}{E_{\infty}}\bar{x}^{g-b} \tag{11}$$

Strain softening induces inherent mesh dependency and produces failure without energy dissipation [11]. In order to avoid such shortcomings, a characteristic length l_c is introduced. This length is related to the mesh size [12] in order to dissipate the same amount of energy after mesh refinement, when strains localize in one row of finite elements. For the adopted model, the dissipated energy density g_{ft} at failure in tension is related to the fracture energy G_{ft}:

$$g_{ft}(x) = \frac{f_t(x)(1 + A_t/2)}{B_t} = \frac{G_{ft}(x)}{l_c} \tag{12}$$

Identification

The prediction of early-age stresses in concrete structures requires the identification of lots of material parameters data (see previous equations), which depend (for some of them) on the concrete mix design. Experiments have been performed in order to identify most of needed parameters on a concrete representative of a French nuclear power plant. As example, the basic creep is displayed in Figure 2.

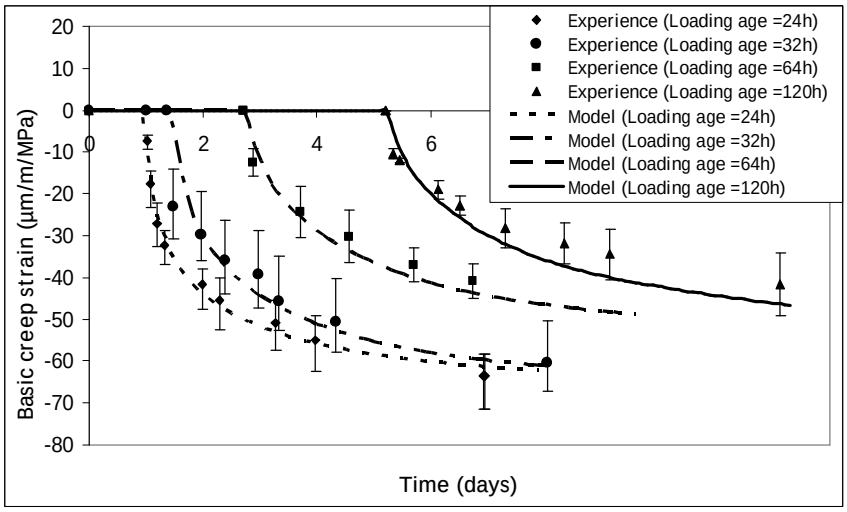

Fig.2: Compressive basic creep strain: numerical simulations versus experimental data.

Since lots of phenomena are involved at early-age, a experiment has been design to validate the models: a ring test which includes an increase of internal temperature has been setup. (see Figure 3) The principle of the ring test is to cast around a metallic ring a concrete specimen. Then, the concrete (autogeneous and thermal) shrinkage is restrained by the metallic ring. To take into account the thermal shrinkage (which does not occur because specimen dimensions are too small to create a temperature evolution representative of a massive structure), an evolution of this test has been proposed [1]. This evolution consists in the possibility to increase the temperature of the metallic ring to expand it by (controlled temperature) water circulation. As the thermal dilatation of the metal used (brass) is about 3 times higher than the concrete one, supplementary tensile stresses are generated. The internal brass strain is measured continuously. The device and some experimental vs numerical data are provided in Figure 3.

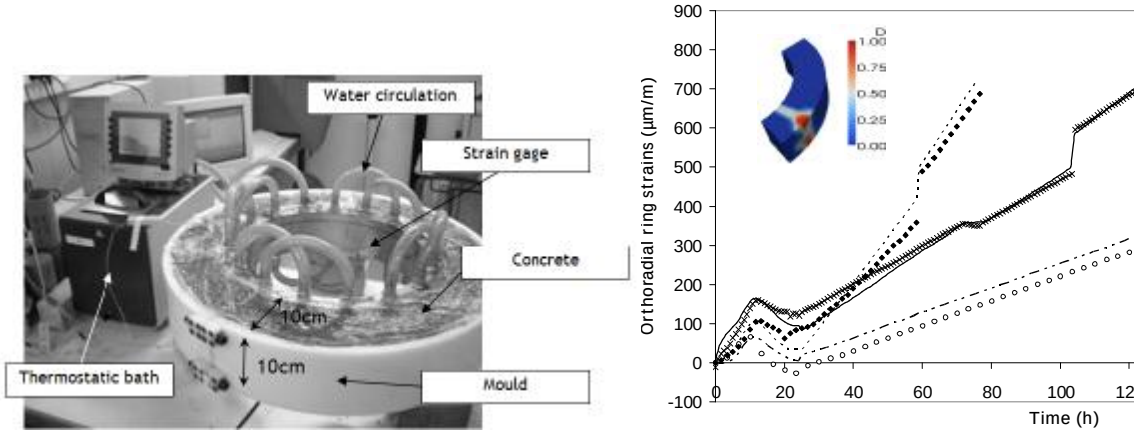

Fig.3: Thermal active ring test and some experimental vs numerical data (evolution internal orthoradial brass strain and predicted cracking by damage mechanic).

NUMERICAL SIMULATIONS

Using previous models and after identification of material parameters data, numerical simulations are performed in order to predict the behavior at early-age of a French nuclear power plant (inner concrete containment) during its construction. Indeed, cracking at early age may be harmful since it leads to preferential leakage areas. For this study, two geometries were studied. Respectively, they correspond to the first (just after the cast of the power plant slab) and the second lifts (the second lift can be assimilated to a current lift). Reinforcement has not been taken into account since the objectives is to unveil the role played by the creep and creep/damage coupling.

The first lift

A 2.4 meters high cylindrical containment part is calculated. The geometry and the boundary conditions are given in Figure 4. The calculations correspond to a period of 15 days (duration between lifts). Axisymetric conditions are used. Initial and ambient temperatures are taken equal to 20°C. Note that for the simulation, due to the size effect, the tensile strength has been reduced to 60% of the original (measured in 11x22cm specimen) one according to experimental findings [13].

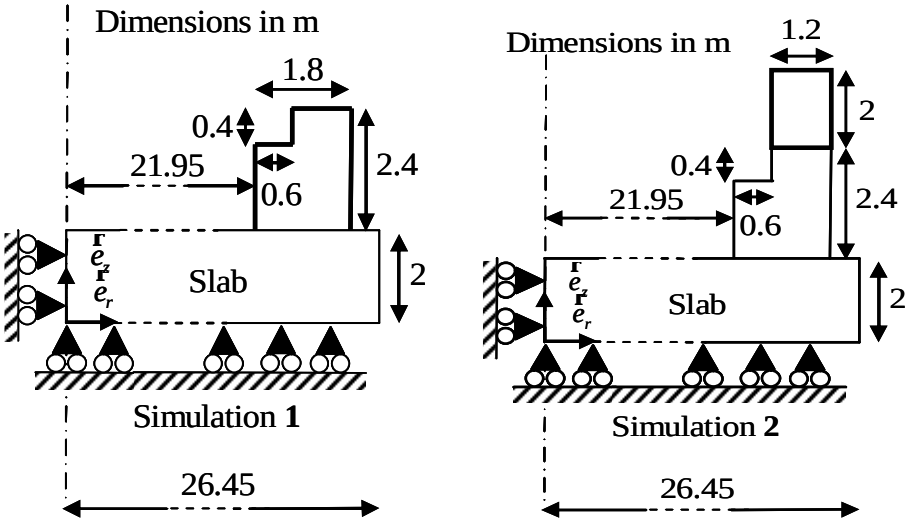

Fig.4: Geometry and boundary conditions for the first and second lift simulation.

The damage fields in the structure, after 15 days, are displayed on Figure 5, where 3 assumptions where tested:

1. creep effect is not taken into account,
2. tensile creep is taken into account without coupling between creep and damage,
3. tensile creep is taken into account with coupling between creep and damage (as it has been identified from experiment).

During this stage (first lift), numerical simulation shows damage due to different phenomena:

- Firstly, because of the high stiffness of the slab, a high shear stress state appears just at the interface between the slab and the wall (because of autogenous and thermal restraint). This leads to a cross over cracking at the interface between the slab and the first lift. This cracking is limited due to the presence of reinforcement which is not taken into account here. The same simulation with reinforcement (modelled with bar elements) would not change the results because bar elements are not able to sustain shear stress. Thus, a three dimensional modelling or specific elements (like beam element) are needed.
- Secondly, damage occurs in the core of the containment where the temperature variation is the most important. This is due to the restraint induced by the lower part of the containment, which has been previously cast (the slab in this case). When the coupling between creep and damage is not taken into account (but basic creep and transient creep are considered), no damage is predicted. Nevertheless, with a coupling coefficient equal to 0.4, the simulation shows an increase of the damage field with regards to the previous case (with creep). Moreover, the damage field represents a non crossing crack. This results highlight that, in the case of a massive structure submitted to restrained shrinkage, the skin cracking pattern is not sufficient to correctly estimate the degradation of a massive structure. The damage of the core of this structure could have a non-negligible impact on the permeability of the nuclear power plant. One can remark that the maximal damage is not obtained close to the geometrical singularity of the first lift.
- Thermal gradients (between the core and the skin) is not sufficient to create cracking (as found in [14])

The second lift

A 2 meters high cylindrical containment part is calculated. The geometry and the boundary conditions are given in Figure 4. The calculations correspond to a period of 15 days (duration between lifts). Again, axisymetric conditions

are used; initial and ambient temperatures are taken equal to 20°C. Note that the initial conditions of theses calculations are not the end of the first lift simulation because axisymetric damage is not realistic and in this case the shrinkage will not be restrained.
The damage fields in the structure, after 15 days, are displayed on Figure 5 with the three same assumptions:

1. creep effect is not taking into account,
2. tensile creep is taken into account without coupling between creep and damage ,
3. tensile creep is taken into account with coupling between creep and damage.

In this simulation, damage occurs only in the core of the containment where the temperature variation is the most important. The results are similar to the one obtained for the first lift. This is due to the restraint induced by the lower lift, which has been previously cast. When tensile creep is taken into account without coupling between creep and damage, no damage is predicted. When coupling is taken into account, Figure 5 shows that a damage is predicted but this damage is lower than for an elastic damage simulation.
The simulations of the first and the current lifts underline the crucial role played by tensile creep on the prediction of cracking for such a massive structure. Moreover they highlight the mismatch on the prediction which can be obtained if the tensile creep (and especially its coupling with damage) is not correctly estimated.

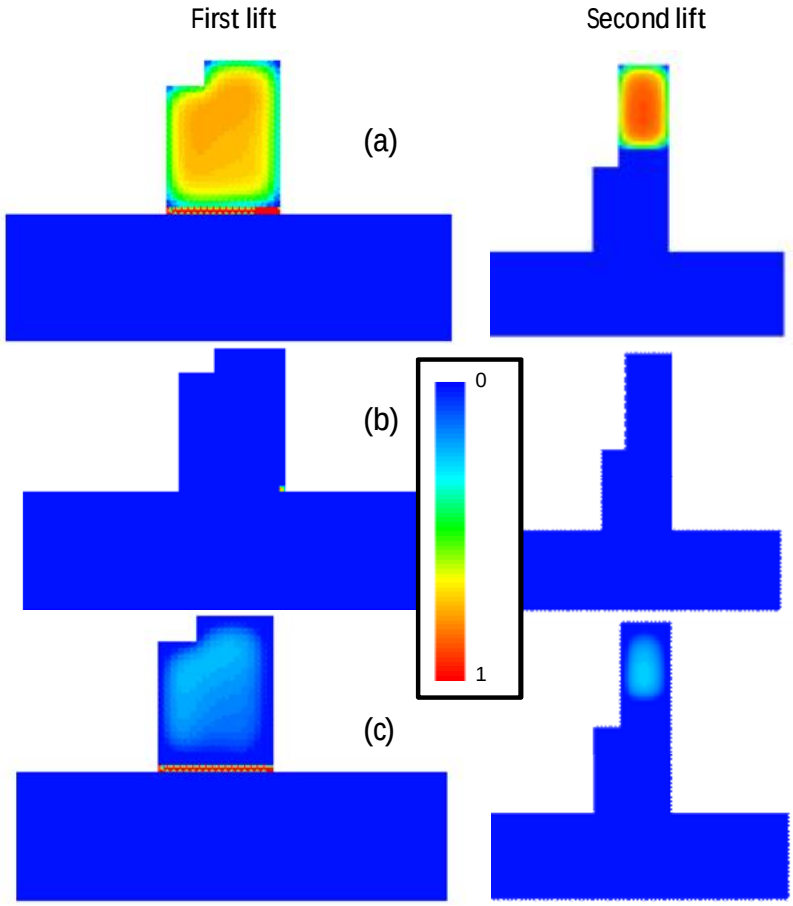

Fig.5: Damage field in the first and second lift of the containment (see Figure 4) after 15 days :
(a) = Damage model without creep taken into account
(b) = Damage model with creep taken into account and without coupling between creep and damage
(c) = Damage model with creep taken into account and with coupling between creep and damage

CONCLUSION

An active device to study the early age behavior and cracking of massive structure has been developed. In this test many coupled phenomena occur simultaneously (mechanical characteristics evolution due to the hydration, shrinkage, creep,…) which is representative of real concrete massive structures. Therefore, this test may be used to validate models or to identify some coupling parameters. Simulations on a representative massive structure (inner concrete containment of a typical French nuclear power plant) have highlighted the crucial role played by tensile creep on the prediction of cracking for such a massive structure, and especially the misleading results which can be predicted if no coupling between creep and damage is taken into account.

However, some deeper investigations are needed. Effect of temperature on creep in tension has not been studied yet in the literature. Besides, difference of creep in tension and compression must be taken into account. The prediction of behaviour of the concrete containment needs the use of a 3D mesh, which integrates passive reinforcement and some particular areas (hatch ... etc). These aspects are currently undertaken.

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