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# Modelling drying and loading effect in structural concrete repair

Laurent Molez & Yves Berthaud

Laboratoire de Mécanique et Technologie, ENS Cachan / CNRS / Université Paris 6, France

Benoît Bissonnette & Denis Beaupré

Centre de Recherche sur les Infrastructures en Béton, Université Laval, Canada

Drying shrinkage may be a significant cause of deterioration of thin concrete repairs. Shrinkage induced stresses can be partially relieved by tensile creep. Hydration effects and materials properties may have a significant influence on concrete repair behaviour. In this paper, a numerical tool that takes into account these different phenomena is presented. The aim of this numerical model is to obtain an analysis tool to complete experimental tests. Experimental results obtained on small lab specimens permit to calibrate numerical coefficients. Numerical results on larger specimens show a good agreement with experimental data.

## 1 INTRODUCTION

Second half of twentieth century is marked by an intense activity of construction of concrete infrastructures. These structures have a limited lifespan, and several of them require repairs today. Thus the field of concrete repairs knows, since ten years, a significant rise in the sector of construction. For owners, achieving durable repairs is of primary importance because the costs involved are generally very high. Data presented at table 1 give an idea of the extent of work in the field of repairs. Experience shows, however, that design of durable concrete repairs can be as complex as the design of new structures because each damaged structure imposes its own set of conditions (Emmons and Vaysburd 1994)

In this study, concrete repair is defined as a thin concrete layer ( $\simeq 50$  to  $150$  mm) cast on an existing structure to replace the deteriorated part close to the surface. These two concrete layers have differ-

Table 1: Value of construction work in some countries

|             |         | France <sup>1</sup> | UK <sup>2</sup> | Canada <sup>3</sup> | USA <sup>4</sup> |
|-------------|---------|---------------------|-----------------|---------------------|------------------|
| billion of  |         | €                   | £               | \$ CAD              | \$ US            |
| Building    | new     | 47,3                |                 |                     | 551              |
|             | repairs | 44                  |                 |                     | 294              |
| Nonbuilding | new     | 17                  |                 |                     | 103              |
|             | repairs | 9,5                 |                 |                     | 67               |
| All         | repairs |                     | 14,9            | 16                  |                  |

<sup>1</sup> Ministère de l'Équipement (2001)

<sup>2</sup> Cusson (2001)

<sup>3</sup> Emberson and Mays (1996)

<sup>4</sup> US department of commerce (2000)

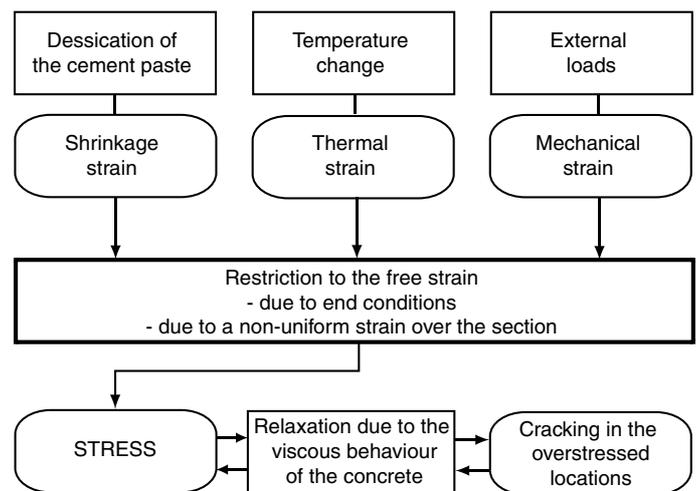


Figure 1: Schematic illustration of the stress build-up in repairs

ent mechanical and physical characteristics. The old one is quasi-stable with time. The new one change with time (hydration, drying, shrinkage, creep...). In the figure 1, Saucier et al. (1997) resume the effect of hygral, thermal and mechanical change. Shrinkage is identified to be the most severe parameter (Saucier et al. 1991; Bissonnette 1997; Laurence 2001). In the other hand, tensile creep can partly relax the induced strains (Bissonnette 1997). The cracking of repair materials can cause the most serious deterioration processes leading to repair failures, since the aggressive agents can then penetrate through these cracks.

We first present the numerical model developed in

this research study. Hydration process is not modelled, but its effects are taken into account in the evolution of physical and mechanical characteristics. Endogenous shrinkage is considered. The drying is modelled by a non-linear diffusion equation, and drying shrinkage is assumed to be proportional to relative humidity changes. Mechanical behaviour is introduced with respect of basic and drying creeps. A non-linear continuum damage model is applied to concrete rupture. In second time, numerical results are compared to experimental ones from previous study (Molez et al. 2001; Molez 2003).

## 2 NUMERICAL MODEL

### 2.1 Hydration effects

Hydration mechanisms are not modelled, but their effects have to be taken into account. Degree of hydration  $\xi$  can be evaluated from the experimental evolution of compressive strength  $f_c(t)$  (Ulm 1999):

$$\xi(t) = \xi_0 + (1 - \xi_0) \frac{f_c(t)}{f_c(\infty)} \quad (1)$$

where  $\xi_0$  is the percolation threshold as defined by Acker (1987) and  $f_c(\infty)$  is the compressive strength at an infinite time.

Thereafter, the evolution of strength will be expressed according to the following equation:

$$R(t) = R(\infty) \frac{t^{m_1}}{m_2 + t^{m_1}} \quad (2)$$

where  $R(\infty)$  is the strength at an infinite time, and  $m_1, m_2$  parameters determined from experimental results (figure 2).

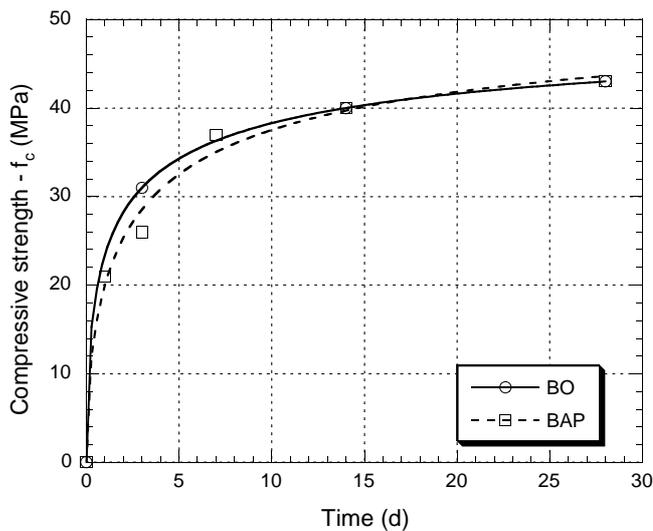


Figure 2: Experimental (dots) and calculated (lines) evolution of compressive strength for an ordinary concrete (BO) and a self-levelling concrete (BAP).

### 2.2 Thermal effects

We assumed that ambient temperature is constant. The thickness of new concrete layer is small then temperature growth due to chemical reactions is low. Consequently, in all this study, thermal effects are neglected.

### 2.3 Drying model

Mass conservation equation, expressed according to the mass water content  $w$ , is:

$$\frac{\partial w}{\partial t} = -\text{div}(J_v + J_l) + \frac{\partial w_{ad}}{\partial t} \quad (3)$$

where  $J_v$  is the flux of water in vapour form and  $J_l$  the flux of water in liquid form. The derivative term of  $w_{ad}$  represent the variation of water mass content due to self-desiccation.

Using Fick law and ideal gas law, vapour flux can be expressed according to the relative humidity  $h_r$ . Similarly, using Darcy law and Kevin law, the liquid flux can be written in terms of  $h_r$ . In additions, experimental results (Baroghel-Bouny 1994; Therrien 2001) show that desorption isotherms are linear (*i.e.* the slope of the curve  $w = w(h_r)$  is constant) for  $0.4 < h_r < 0.95$ . Then we obtain the classical diffusion equation:

$$\frac{\partial h_r}{\partial t} = \text{div}(D(h_r) \text{grad } h_r) + \frac{\partial h_{ad}}{\partial t} \quad (4)$$

Thereafter, we will neglect the variation of relative humidity  $\partial h_{ad}/\partial t$  due to hydration reactions. However associated shrinkage (part of endogenous shrinkage) is introduced further.

The macroscopic diffusion coefficient depend on  $h_r$ . When  $h_r$  is important, humidity transfers takes place in water of capillary spaces. In opposition, when relative humidity is low, transfer is of vapour form and surface diffusion occurs in areas of hindered adsorption. According to these observations, we choose the following expression of  $D(h_r)$  (Bažant 1988) :

$$D(h_r) = D_0(t) \left( a + \frac{1-a}{1 + \left( \frac{1-h_r}{1-h_c} \right)^n} \right) \quad (5)$$

where  $a, n$  and  $h_c$  are adjustable parameters specific to material.  $h_c$  would be the humidity threshold where transfer change from first phenomenon to the second. Those parameters can be identified with experimental data for weight loss (figure 3).

Structure of the porous network evolves during hydration. Some results (Therrien 2001) show that diffusion coefficient is dependent on maturity of concrete. However, it is difficult to obtain an experimental relation  $D(\xi)$ . So, we fit the evolution of  $D$  to the inverse

of the evolution of strength.

$$D_0(t) = D_0(t_\infty) \frac{m_2 + t^{m_1}}{t^{m_1}} \quad (6)$$

Boundary conditions of convective type are imposed at the surface  $\Gamma$  in contact with air at relative humidity  $h_r^a$ . Convective flux is then written:

$$J_\Gamma = \beta(h_r^\Gamma - h_r^a) \quad (7)$$

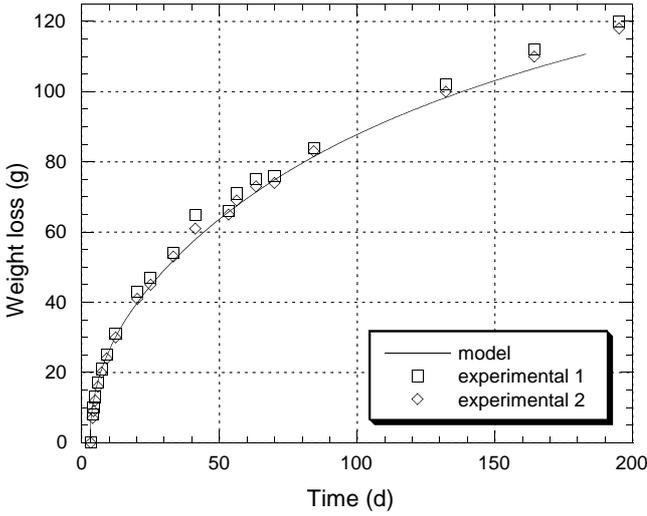


Figure 3: Comparison of experimental and calculated weight loss.

## 2.4 Shrinkage

Shrinkage of concrete is due to chemical reactions and drying of porous media. Thus, an endogenous shrinkage and a drying shrinkage can be identified.

In numerical simulations, experimental results of endogenous shrinkage are directly used. At each step, a homogeneous deformation is imposed in repair concrete layer.

Drying shrinkage is obtained from variation of relative humidity through a coefficient of hydrous dilatation:

$$\underline{\dot{\varepsilon}}_{ds} = \alpha_h(t) \dot{h}_r \underline{1} \quad (8)$$

This relation does not reflect micro-mechanisms of shrinkage (capillary depression, Gibbs-Bangham theory and disjoining pressure theory), but a theoretical study (Lassabatere 1994) has shown that it gives a not so bad approximation.

According to concrete structuration,  $\alpha_h(t)$  should depend on the maturity of material. Some experimental results (Therrien 2001) show this dependence. However, it is difficult to obtain an experimental evolution law. Thus,  $\alpha_h$  is considered constant and determined for each concrete (figure 4).

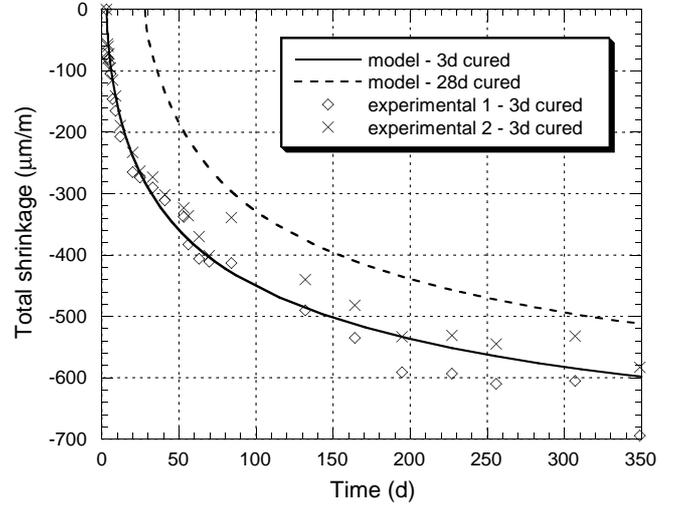


Figure 4: Evolution of total shrinkage. Comparison of experiments and numerical simulation.

## 2.5 Creep

Creep of concrete can be separated in two parts: basic creep and drying creep. The origins of compressive or tensile creep are discussed in Bažant (1988), Bissonnette (1997), or Molez (2003).

### Basic creep:

Basic creep can be written according to viscoelasticity theory. A compliance function  $J$  is defined by:

$$\varepsilon(t) = J(t_0, t) \sigma_0 \quad (9)$$

where  $t_0$  is the age at loading  $\sigma_0$ , and  $t - t_0$  the load duration.

For a stresses history, creep strain can be written:

$$\underline{\underline{\varepsilon}}(t) = \underline{\underline{\varepsilon}}(t_0) + \int_{t_0}^t \underline{\underline{B}} J(\tau, t_0) \underline{\underline{\dot{\sigma}}}(\tau) d\tau \quad (10)$$

where  $B$  is the fourth order tensor of Poisson's terms.

Adopting a Dirichlet series expression for compliance function (Bažant 1988):

$$J(t_0, t) = \frac{1}{C_0(t_0)} + \sum_{\mu=1}^n \frac{1}{C_\mu(t_0)} \left( 1 - \exp\left(-\frac{t-t_0}{\tau_\mu}\right) \right) \quad (11)$$

makes it possible to free from storage of stresses history, and strain can be calculated from the preceding step. Previous expression can be explained in terms Kelvin chain (figure 5) with ageing modulus  $E_\mu = C_\mu - \tau_\mu \dot{C}_\mu$  and constant dashpot viscosity  $\eta_\mu = \tau_\mu C_\mu$ .

Strain evolution is calculated step by step. For step  $[t_n, t_{n+1}]$ , one can write:

$$\underline{\underline{\Delta\varepsilon}} = \underline{\underline{\varepsilon}}(t_{n+1}) - \underline{\underline{\varepsilon}}(t_n)$$

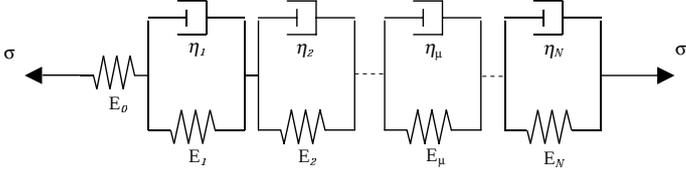


Figure 5: Kelvin chain equivalent to the proposed model

If  $C_\mu$  and  $\dot{\sigma} = \Delta\sigma/\delta t$  are constant during this step, integral can be easily calculated (see Molez (2003) for detailed calculus):

$$\underline{\underline{\Delta\varepsilon}} = \left[ \frac{1}{C_0(t_n + \Delta t/2)} + \sum_{\mu=1}^n \frac{1 - \left(1 - \exp\left(-\frac{\Delta t}{\tau_\mu}\right)\right) \tau_\mu/\Delta t}{C_\mu(t_n + \Delta t/2)} \right] \underline{\underline{B}} \underline{\underline{\Delta\sigma}} + \sum_{\mu=1}^n \left(1 - \exp\left(-\frac{\Delta t}{\tau_\mu}\right)\right) \underline{\underline{\Delta\varepsilon}}_\mu^*(t_n) \quad (12)$$

with the recursive expression:

$$\underline{\underline{\Delta\varepsilon}}_\mu^*(t_n) = \frac{1 - \exp\left(-\frac{\Delta t}{\tau_\mu}\right) \tau_\mu/\Delta t}{C_\mu(t_n - \Delta t/2)} \underline{\underline{B}} \underline{\underline{\Delta\sigma}} + \underline{\underline{\Delta\varepsilon}}_\mu^*(t_{n-1}) \exp\left(-\frac{\Delta t}{\tau_\mu}\right) \quad (13)$$

Thus the increment of deformation is calculable according to the increment of load and the history of loading defined in previous step. The increment of basic creep is obtained by subtracting the increment of instantaneous strain from previous equation. We obtain:

$$\underline{\underline{\Delta\varepsilon}}_{bc} = \left[ \sum_{\mu=1}^n \frac{1 - \left(1 - \exp\left(-\frac{\Delta t}{\tau_\mu}\right)\right) \tau_\mu/\Delta t}{C_\mu(t_n + \Delta t/2)} \right] \underline{\underline{B}} \underline{\underline{\Delta\sigma}} + \underline{\underline{\Delta\varepsilon}}^{hist} \quad (14)$$

Characteristic relaxation times  $\tau_\mu$  are fixed a priori according to a logarithmic series (Bažant 1988; Granger 1997):

$$\tau_\mu = \tau_1 10^{\mu-1} \quad (15)$$

and  $C_\mu$  parameters are obtained by the method of least squares. An example of results is given in figure 6.

### Drying creep:

Creep experimental tests show that an extra creep can be measured when test specimen is allowed to dry. This phenomenon is called drying creep. Different interpretations are proposed. Bažant and Chern (1985) suggest a mechanism of stress-induced shrinkage. On the contrary, drying creep can be interpreted as a drying-induced creep (Bažant 1988). These different mechanisms can be written mathematically as

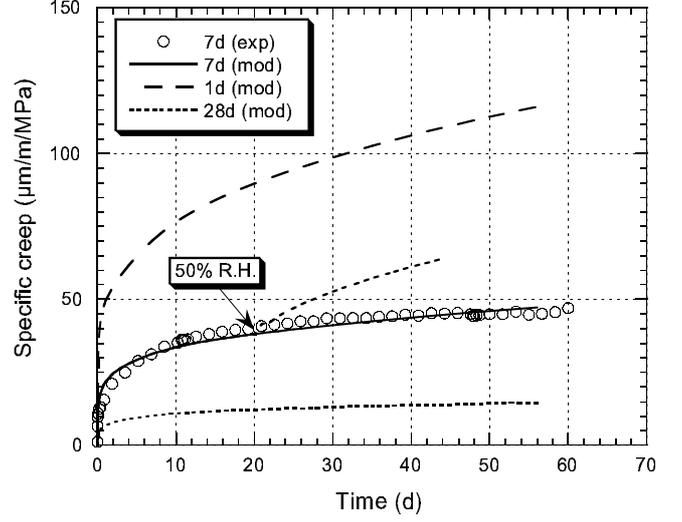


Figure 6: Experimental (dots) and calculated (lines) basic creep of an ordinary concrete

a single equation:

$$\underline{\underline{\dot{\varepsilon}}}_{dc} = \kappa_{fs} \underline{\underline{B}} \underline{\underline{\sigma}} |\dot{h}_r| \quad (16)$$

Coefficient  $\kappa_{fs}$  is determined from basic and drying creep test. We can notice that the sign of  $(\dot{\varepsilon}_{dc})_{ij}$  depends only on the sign of  $(\sigma)_{ij}$ . So in uniaxial traction, we notice an increase of drying creep whether it is in moistening or drying conditions.

Then, total creep can be obtained by adding basic and drying creep (figure 7).

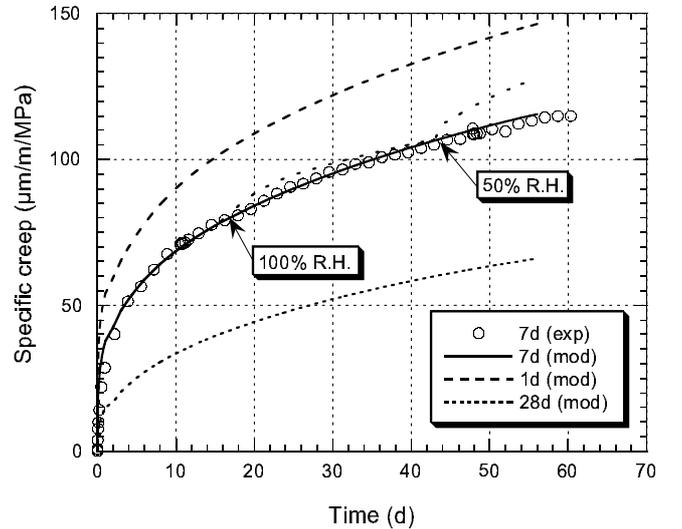


Figure 7: Experimental (dots) and calculated (lines) total creep (basic + drying creep) of an ordinary concrete

### 2.6 Mechanical damage

Total strains  $\varepsilon_{total}$  are supposed to be the sum of instantaneous strains  $\varepsilon_i$ , shrinkage strains  $\varepsilon_s$  and creep strains  $\varepsilon_c$ :

$$\varepsilon_{total} = \varepsilon_i + \varepsilon_s + \varepsilon_c \quad (17)$$

The stress-strain relation of damaged material is written:

$$\underline{\underline{\sigma}} = \underline{\underline{C}}^d (\underline{\underline{\varepsilon}}_{total} - \underline{\underline{\varepsilon}}_s - \underline{\underline{\varepsilon}}_c) = \underline{\underline{C}}^d \underline{\underline{\varepsilon}}_i \quad (18)$$

In the present analysis, we use an isotropic scalar damage model (Mazars 1984). In this model, the mechanical effect of progressive micro-cracking due to external loads is described by a single internal variable which degrades the Young's modulus of the material. The constitutive relations are:

$$\sigma_{ij} = (1 - d)\Lambda_{ijkl}(\varepsilon_i)_{kl} \quad (19)$$

where  $\sigma_{ij}$  and  $(\varepsilon_i)_{kl}$  are the components of the stress and strain tensors respectively ( $i, j, k, l \in [1, 3]$ ),  $\Lambda_{ijkl}$  are the initial stiffness moduli, and  $d$  is the damage variable. The material is initially isotropic, with  $E$  and  $\nu$  the initial Young's modulus and Poisson's ratio respectively. Damage is a function of the positive strains which means that it is mainly due to micro cracks opening in tension mode. In order to avoid ill-posedness due to strain softening, the mechanical model has to be enriched with an internal length (Pijaudier-Cabot and Bažant 1987).

### 3 NUMERICAL EXAMPLES

In this section, we present some results of numerical simulations of concrete repairs. Test configuration is the same one as that used in previous experimental study (Molez et al. 2001; Molez 2003).

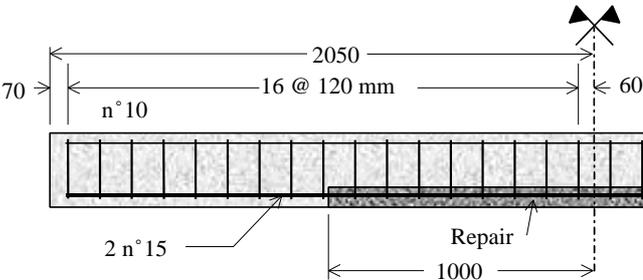


Figure 8: Test specimens

Figure 8 shows the geometry of the investigated concrete repair. A 2D analysis of one half of the beam, using four-noded plane stress elements, was performed (figure 9).

Examples of calculated humidity distribution, corresponding deformation and induced damage are shown in figures 12, 13 and 14.

Numerical results can be compared to experimental ones. During experimental tests, crack width and deflection has been measured for different configurations: drying only, drying and loading at 33% of ultimate load, and flexural testing. Those results are compare in figures 10 and 11.

These numerical results show a good agreement with experimental ones.

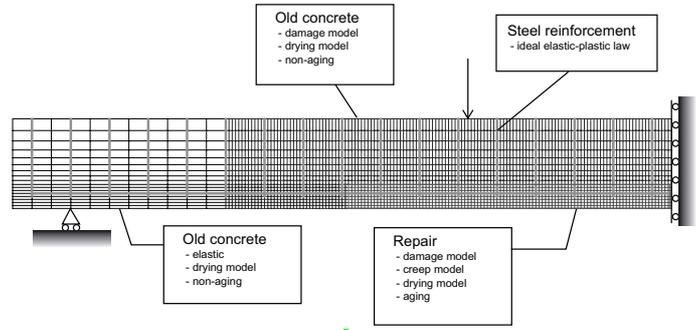


Figure 9: FE mesh

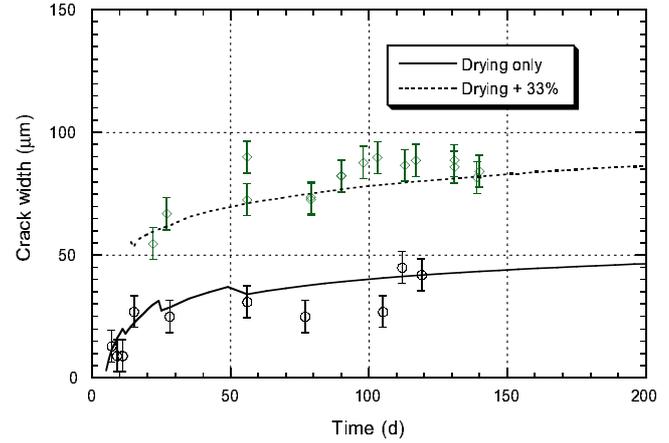


Figure 10: Comparison of experimental (dots) and calculated (lines) average crack width for a repaired beam submitted to drying and loading.

### 4 CONCLUSIONS

To be able to make a complex analysis (to complete experimental study) of the behaviour of structural concrete repairs, the main phenomena acting in those structures have been integrated in a finite elements code.

So, we can take into account the evolution of mechanical properties during hydration process and induced volume change (endogenous shrinkage). The drying of the material is modelled by a non linear law. Furthermore, the diffusion law is coupled with the evolution of hydration process by a diffusion coefficient which depends on the maturity of the material. Drying shrinkage is connected with the variation of humidity by a proportionality law that is experimentally verified for relative humidity included between 0.5 and 0.95. Viscoelastic behaviour is modelled by a Kelvin chain. The effects of hydration are taken into account with variable coefficients of the Kelvin chain. The influence of drying on creep is introduced by means of an extra term proportional to variation of relative humidity and imposed stress. A damage model is used to reproduce the mechanical effect of progressive micro-cracking of concrete.

The identification phase shows that the numerical tool well reproduces the behaviour of small lab specimens, and also bigger structures.

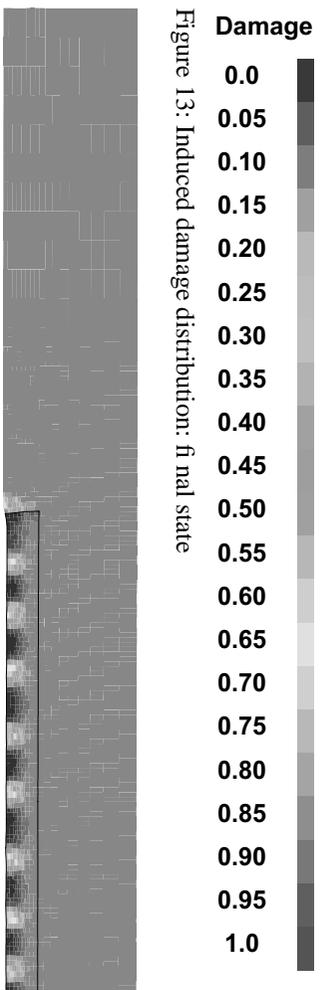
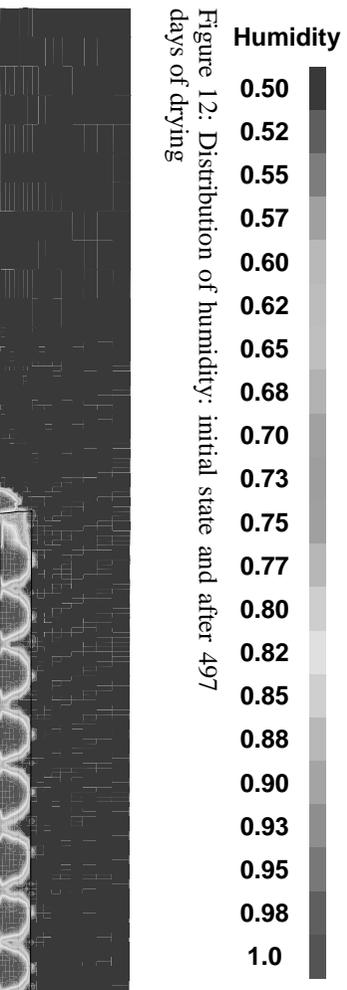
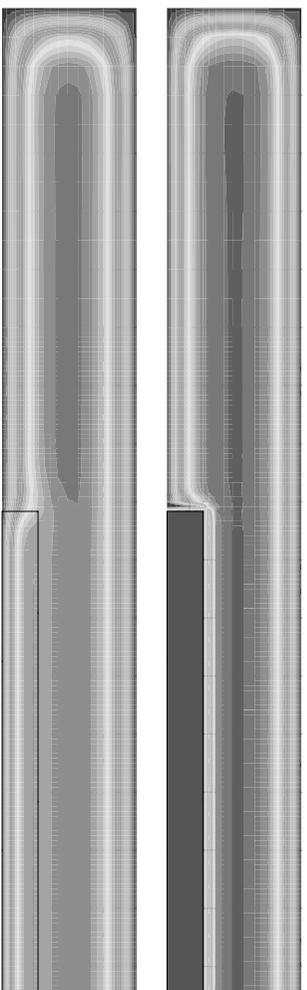
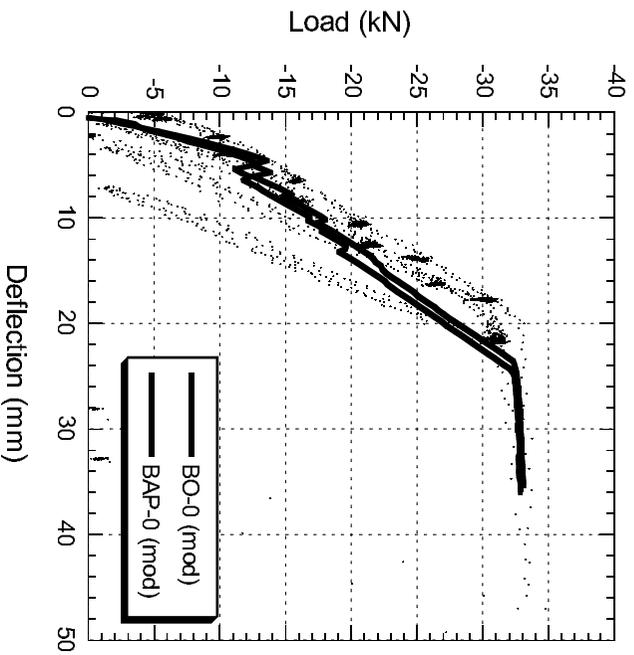


Figure 14: Induced deformation distribution: final state.

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