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Requirements for the Modeling of Medium-Term Behavior of Nuclear Containment Concrete for a “Loss of Coolant Accident” Analysis

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Abstract. The objective of this research is to understand the behavior of concrete subjected to temperatures up to 180°C and to gas absolute pressures up to 5 bars applied during the two weeks envisioned in the “loss of coolant accident” (LOCA) scenario. Previous studies about delayed mechanical behavior of concrete have pointed out an increase of delayed strains with the temperature rise: the basic creep can be multiplied by a factor 10 at 80°C, and coupling between creep and heating can lead to damage and to transient thermal creep. These phenomena could be predominant if the LOCA induced conditions are maintained several days and more probably several weeks. So, a model able to predict the cracking and the gas leakages has to be developed. It has to consider these phenomena and their coupling with other possible causes of concrete damage previous to the LOCA. In fact, if the LOCA occurs on structure already damaged by early age cracking or endogenous chemical reactions, such as AAR or ettringite, the leakage risk could be increased. The paper will focus on some important aspects of these phenomena (creep rate dependency on temperature, scale effects at early age, damage induced by swelling reactions), and on their coupling in a finite element model.

Introduction

The French Nuclear industry provides 79% of the electricity used in France, but it has to face with two main problems: first the aging of its nuclear power park which, for some nuclear power plants, arrive at their design lifetime; and secondly there is an increasing need of safety demonstration following the severe accidents of Chernobyl and Fukushima. So, the different nuclear agencies, and the French government work together tirelessly to control the nuclear risk. Among the new measures already begun, there are several research programs aiming at increasing the knowledge level to predict more and more accurately the behavior of a double wall concrete vessel in case of loss of coolant accident (LOCA). If such an accident would occur, the vapor would be stopped by the double concrete wall system, and redirected to filters which work under a 4 bars relative pressure. At this pressure, the vapor temperature inside the vessel can reach 180°C, and be maintained until two weeks. This vapor pressure and this temperature constitute the internal conditions in the scenario of LOCA. The current research programs MACENA and ENDE, funded by the French research agency (ANR) work on tools to predict accurately the double wall mechanical behavior in case of LOCA. The objective of the research project MACENA is to provide an accurate finite element model able to predict if a vapor leakage would be possible in such conditions. The fact that some nuclear power plants have more than 50 years old has to be considered in the models, particularly because the internal concrete wall is pre-stressed with steel wires. With time, their pre-stress are relaxed, and on the other hand, the concrete, constantly compressed by the wires, creeps in compression, leading to a concrete shrinkage which contributes also to the loss of pre-stressing. While the pre-stressing is able to balance the tensile stress induced by the internal pressure in case of LOCA, the leak risk is low, but, if due to the loss of pre-stressing, the concrete passes in tension, even locally, there is a risk of cracking, and then a risk of radioactive

vapor leakage. Of course, the concrete can itself resist to a tensile stress of a few MPa, depending on its own tensile strength; this strength constitutes then a supplement safety margin which can be considered for the leakage prediction in case of LOCA. But the current tensile strength of a given concrete 50 years old is not so easy to know for different reasons: first, the tensile strength of concrete is strain dependent; it decreases if the strain exceeds the tensile strain, leading to a progressive strain localization causing finally a localized crack. So, if earlier in the wall life, a large tensile strain has been reached, even during a very short period (for example at early age before the pre-stressing, or during a decennial pressurization test), the tensile strength is definitively reduced. Another problem resides in the heterogeneity of concrete, which leads to an intrinsic variability of the tensile strength impossible to neglect in case of large structures as shown during the CEOS.fr research program [1]. A last problem, already observed in North America, concerns the concrete chemistry: in fact the cement paste and the aggregates of concrete can evolve chemically since the vessel construction. Among the different possibilities, the alkali aggregate reaction, the delayed ettringite formation, the corrosion of steel bars due to ingress of carbonate or other chemical species, could occur. Finally, the prediction of the double wall containment vessel behavior under LOCA must be based on a numerical simulation considering the whole causes of pre-stressing loss and tensile strength reduction previous to the envisioned LOCA. The paper is a listing attempt of model characteristics needed in order to predict the cracking under LOCA conditions.

General principle of a model

As mentioned in the introduction, several phenomena influencing the cracking occurrence have to be considered to predict the risk of radioactive vapor leak in case of LOCA. They can be divided in three main sets: Loading effects prior to the LOCA, loading effects during the LOCA, and material characteristics, as illustrated in Fig.1.

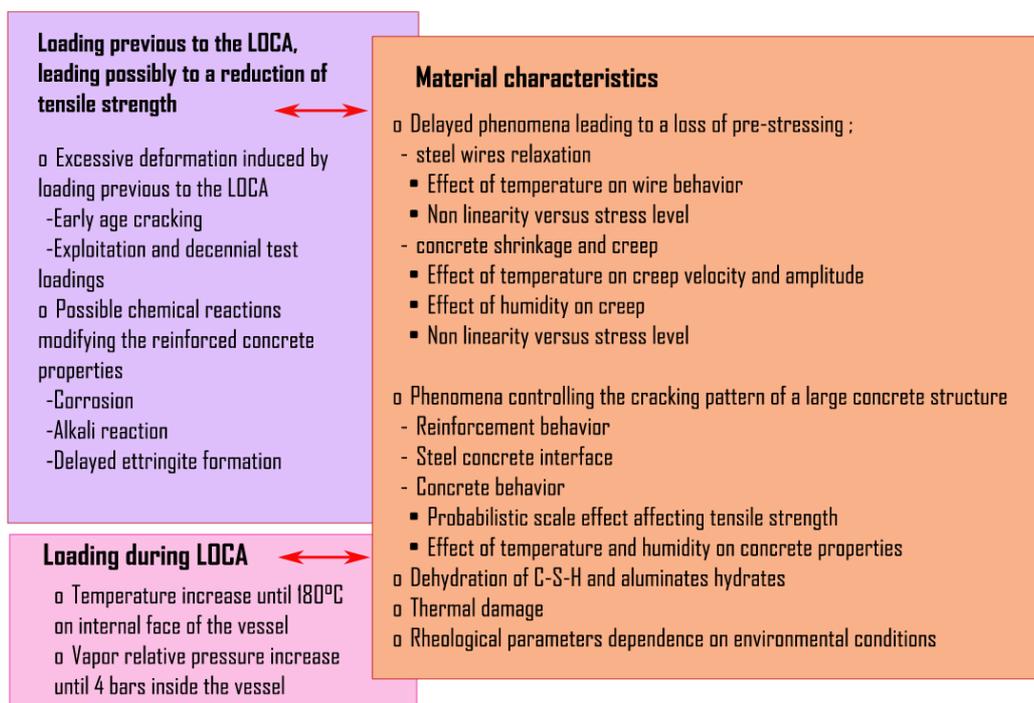


Figure 1: Phenomena to consider for a LOCA analysis

Even if each of these phenomena can occur independently, their consequences in terms of mechanical damage, inelastic strains, chemical evolution are most of the time irreversible. So, the material properties just before the LOCA depend on the solicitation history since the concrete pouring. Several computational strategies can be adopted to consider the damage accumulation; for example several models can be chained, a first one dedicated to the prediction of cracking at early age, a second one taking into account concrete creep and wires relaxation, and a last one able to

consider the effects of temperature and vapor pressure to assess the cracking occurrence during the LOCA. Therefore, chaining several models leads rapidly to complications in terms of continuities of material state between two consecutive modeling, particularly if the internal state variables are not exactly the same between two consecutive models (for example the damage variable can be a tensor in a model and a scalar in another one, the permanent strains can be split in a different number of tensors depending on the model used). To avoid these problems of links between elementary models, a better strategy consists to consider all the afore-mentioned phenomena relative to a given material in a single constitutive model. The main advantage is the continuity, along the numerical simulation, of the internal state variables, which considers then automatically the damage accumulation until the LOCA. The following sections focus on the constitutive model clarified in LMDC Toulouse (France) to consider the different phenomena involved in the concrete behavior since its pouring until the LOCA. Three main phenomena will be discussed: (1) the creep, (2) the way to consider the influence of some chemical reactions such as hydration or alkali aggregate reaction on the mechanical behavior law, (3) the probabilistic scale effect. The paper ends with considerations about coupling between these phenomena.

The concrete creep modeling requirements

Multiaxiality and logarithm form of the long term creep. The internal wall of the structure is pre-stressed in two directions, with a compression stress close to 12 MPa and 8MPa in horizontal and vertical direction; so the creep model has to be able to manage the multi-axiality of the creep. Another particularity is the long duration of loading. Some nuclear power plants are around 50 years old, and their creep deformations are not yet stabilized, presenting all the same a slow decrease of the creep velocity with the time. The FIB recommendations, following the code model 2010 [2], proposes using a logarithm function of the time to model this type of non-asymptotic creep; it is convenient to compute concrete elements under quasi-constant loading, but not really adapted for a numerical implementation for which a differential formulation with internal variables is more suitable. Indeed, a differential formulation is able to consider transient changes of loading, temperature or humidity without any problem, while a creep function would be added for each change weighting the formulation with the complexity of the loading.

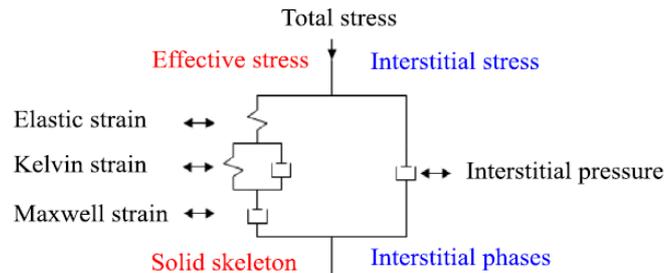


Figure 2: Poro-mechanic framework to model drying and creep coupling [3]

A differential creep model has been proposed by the LMDC [3] to consider both the multi-axiality and the logarithm form of the permanent creep (ε_{ij}^M in Eq.1) in a single differential formulation based on the principle of anisotropic consolidation.

$$\frac{\partial \varepsilon_{ij}^M}{\partial t} = \frac{\varepsilon_{ij}^E}{\tau^M C_c(\varepsilon_{ij}^M)} \quad (1)$$

In this model, the internal variables are the directional consolidation coefficients ($C_c(\varepsilon_{ij}^M)$ in Eq.1) which evolve with the creep strain main values, affecting the apparent viscosity (i.e. the characteristic time in Eq.1) of a Maxwell module (Fig. 2). The initial anisotropy of the creep is induced by the use of the elastic strain ε_{ij}^E in Eq.1, while the induced anisotropy is the consequence of the coefficients of consolidation ($C_c(\varepsilon_{ij}^M)$) evolution (see ref [3] for more details).

Effect of humidity and temperature on creep. Concerning the influence of temperature and humidity on creep velocity, it is necessary to consider them properly. In fact, as illustrated in [4] and reported in Fig.3, the relative humidity variations induces drying creep during drying periods, and swelling during wet periods; more, the creep velocity depends on the moisture content. The LMDC creep model considers the effect of humidity through the saturation degree which reduces the creep velocity, while the drying creep and the drying shrinkage are considered thanks to poro-mechanics considerations. Indeed, with a poro-mechanic formulation the effects of drying or wetting are the consequences of the interstitial pressure variations (Fig. 2).

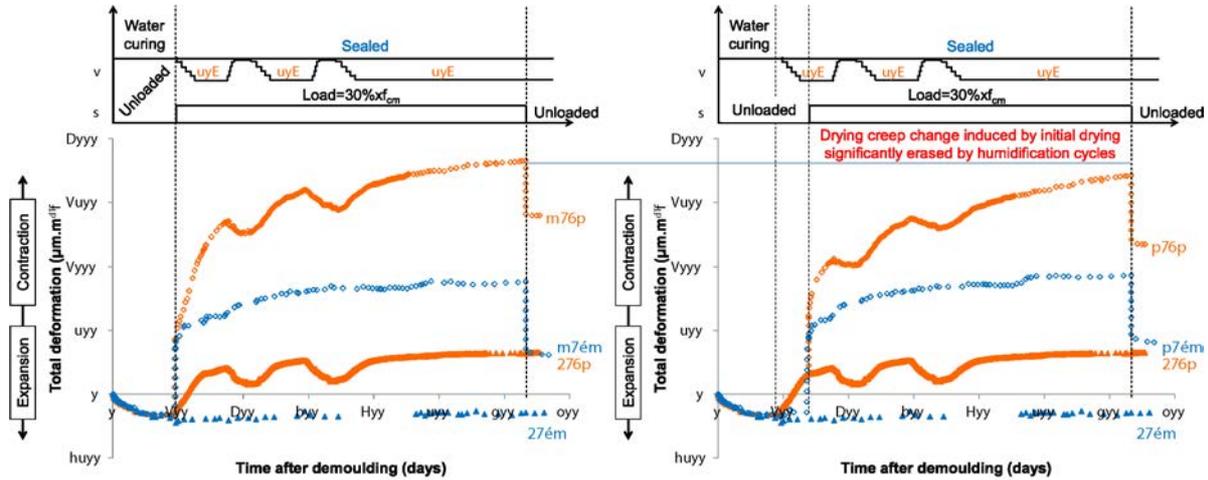


Figure 3: Effects of RH variations between 50% and 98% on the delayed strains of a concrete, $f_{cm} = 73\text{MPa}$, adapted from [4], SL=Simultaneously Loaded and dried, UL=UnLoaded, VD=Variable conditions of Drying, CS=Constantly Sealed

Concerning the temperature, the experimental program carried out by Ladaoui [5–7] shows clearly that creep amplitude and creep velocity are both amplified when the temperature rises. This aspect, illustrated in Fig.4 is perhaps among the most important to consider for the LOCA conditions. It is considered in the LMDC model through a dependence of the viscosity (i.e. characteristic time in Eq.1) to the temperature using an Arrhenius law, and through a modification of the creep potential which control the consolidation functions ($C_c(\varepsilon_{ij}^M)$) in Eq.1).

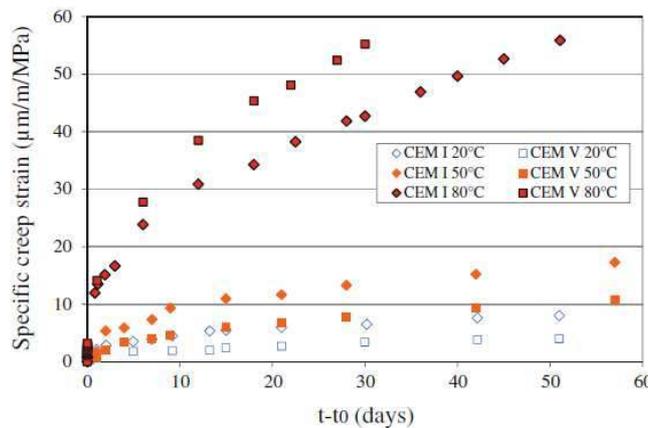


Figure 4: Influence of temperature on creep velocity and amplitude [5], for two types of HPC with CEMI or CEMV binders

Currently, complementary tests are performed by the “Centre de Recherche de l’Industrie du Béton” (CERIB) in the framework of the MACENA research project, in order to quantify creep at higher temperature (until 180°C), and the LMDC carries out tests in various RH and temperature conditions ($20\% \leq \text{RH} \leq 98\%$, $20^\circ\text{C} \leq T \leq 70^\circ\text{C}$).

Effects of chemical reactions on concrete mechanical behavior

The chemical reactions can be divided in two main types, the ones affecting chemically the solid skeleton of concrete such as hydration or leaching [8], and the ones constituting an internal loading through the pressure induced into the pores by the formation of new components such as gel of alkali aggregate reaction [9] or delayed ettringite [10].

Chemical reactions affecting the solid skeleton: as explained in [8], both the precipitation or the dissolution of hydrates can be considered with a differential form of the behavior law, but the term corresponding to the stiffness variation ($\partial S_{ijkl} / \partial t$ in Eq.2) must be considered only for leaching or dehydration (i.e. if the Young modulus (E) variation is negative in Eq.2). It corresponds to the loss of elastic energy associated to the dissolution of a loaded hydrate.

$$\frac{\partial \tilde{\sigma}'_{ij}}{\partial t} = S_{ijkl} \frac{\partial \varepsilon_{kl}^E}{\partial t} + H \left(-\frac{\partial E}{\partial t} \right) \frac{\partial S_{ijkl}}{\partial t} \varepsilon_{kl}^E \quad (2)$$

In Eq.2, $\tilde{\sigma}'_{ij}$ is the effective stress (the stress in the solid skeleton of concrete), ε_{kl}^E the elastic strain and H the Heaviside function. The evolution of mechanical parameters such as Young's modulus, Poisson ratio or strengths can be considered thanks to a relationship between the hydration degree and the corresponding parameters. A useful form for this type of relationship is the De-Shutter one (Eq.3) [11].

$$\frac{E}{E(\xi^{ref})} = \left(\frac{\xi - \xi^{ref}}{1 - \xi^{ref}} \right)^n \quad (3)$$

Eq. 3 is presented here for the Young's modulus, but similar relations exist for all the mechanical parameters. In these relations, ξ^{ref} is the solidification threshold, constant whatever the parameter for a given concrete, and n the non-linearity exponent, different for each parameter but quasi-independent of the concrete formulation.

Chemical reaction with pore pressures: Alkali reaction and delayed ettringite formation belong to this second family of chemical reaction affecting the concrete behavior. The coupling between these reactions and the other aspects of the concrete behavior can be advantageously formulated in the framework of the poro-mechanics, in order to benefit from other features of the model; like creep or hydration-dehydration effects which are then "encapsulated" in the solid skeleton behavior law, while the AAR or DEF are added as internal swelling pressure acting in the concrete pores. A typical form for the poro-mechanics formulation is given by Eq.4.

$$\frac{\partial \tilde{\sigma}'_{ij}}{\partial t} = \frac{\partial \tilde{\sigma}'_{ij}}{\partial t} - B \sum_{i=1}^N \frac{\partial (S_i P_i)}{\partial t} \quad (4)$$

with B the Biot coefficient of the porous media, N the number of phases in the porosity, S_i the saturation degree of the porosity with the phase i , P_i the internal pressure induced by a neo-formed phase (AAR gel or DEF), the water and the gas pressure. In [12,13], the form adopted to assess the pressure induced by AAR gel and DEF is Eq.5:

$$\frac{\partial P_i}{\partial t} = M_i \left(\phi^i \frac{\partial A^i}{\partial t} - \left(\frac{\phi_0^i}{P_{lim}^i} \frac{\partial P_i}{\partial t} + B \cdot \frac{\partial S_i \cdot tr(\varepsilon - \varepsilon^{pl,i})}{\partial t} + \frac{\partial S_i \cdot tr(\varepsilon^{pl,i})}{\partial t} \right) \right) \quad (5)$$

In Eq.5, M_i is the Biot modulus for the phase i , ϕ^i the final amount of the chemical reaction product, ϕ_0^i is the volume not efficient for the pressure (gel in pore connected to reactive sites, or gel with insufficient molar volume [14]), A^i is the reaction advancement ranging from 0 at the beginning of the reaction until 1 when the reaction is ended. P_{lim}^i is the limit pressure before cracking in free swelling conditions. $\varepsilon^{pl,i}$ is the plastic strain corresponding to the reaction products

solidified in cracks caused by an excessive pressure. This plastic strain is computed thanks to a plastic criterion written in terms of effective stress concentration in the vicinity of the reactive sites:

$$f_g^{i,l} = k^i P^i + \min(\tilde{\sigma}^l, R_t^i) - R_t^i \quad (6)$$

In (6), k^i is the stress concentration coefficient, $R_t^i(\varepsilon^{pl,i})$ the effective tensile strength of the solid skeleton. The function ‘min’ is used to consider only admissible effective stresses in the skeleton since another criterion is used to limit this last.

Coupling between creep and chemical reactions: finally, the coupling between chemical reactions and other phenomena is automatically considered since the effective stress used in Eq.6 takes into account Eq. 2 and Eq. 3 in case of hydration or leaching, and creep computed with Eq. 1 is based on the elastic strain which depends also on Eq. 2. The combination between the different strains is a classical cumulative form:

$$\frac{\partial \varepsilon_{ij}}{\partial t} = \frac{\partial \varepsilon_{ij}^E}{\partial t} + \frac{\partial \varepsilon_{ij}^K}{\partial t} + \frac{\partial \varepsilon_{ij}^M}{\partial t} + \sum_i \frac{\partial \varepsilon_{ij}^{pl,i}}{\partial t} + \delta_{ij} \alpha \frac{\partial T}{\partial t} \quad (7)$$

With superscript E for the elasticity level (Fig.1), K for the Kelvin level, M for the Consolidating Maxwell level, α the coefficient of thermal expansion and $\varepsilon_{ij}^{pl,i}$ the permanent strains associated to each plastic criterion.

Probabilistic scale effect

Experiments on large reinforced structured carried out during the CEO.fr project [1,15] have clearly shown the important effect of the concrete heterogeneity on the cracking pattern. In a large structure, the first cracks appear under stresses lesser than the tensile strength measured with usual laboratory tests (such as split test or direct tension test). This is due to the heterogeneity character of the concrete at meso-scale (scale of aggregate), which leads to a random field of tensile strength, and consequently to the existence of weakest links of which the strength decreases when the size of the solicited volume increases. This effect is illustrated in Fig.5.

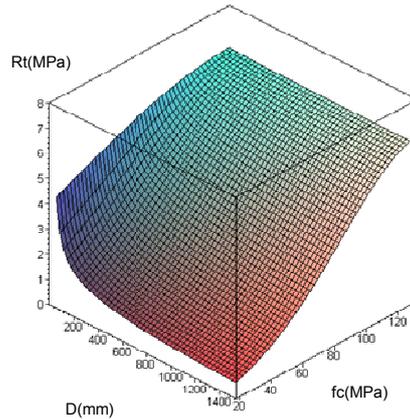


Figure 5: Scale effect on tensile strength R_t , versus characteristic size of the specimen (D) and compressive strength f_c , adapted from [16] and [17].

To consider this effect, the Weibull formulation can be used (Eq. 8); it needs the assessment of the loaded volume V_{eq} which corresponds to the volume of an “equivalent” structure loaded homogeneously; more V_{eq} , lesser R_t . In Eq.8, $R_{t,ref}$ is the tensile strength measured with a specimen of which the loaded volume is V_{ref} .

$$\frac{R_t}{R_{t,ref}} = \left(\frac{V_{ref}}{V_{eq}} \right)^{1/m} \quad (8)$$

Following the research project CEOS.fr, a new method has been proposed in [16] to actualize the tensile strength at each step of a nonlinear analysis. The proposed method, called WL2, allows considering the strength field heterogeneity without resorting to a random field sampling. Thanks to the WL2 method, the tensile strength used in plastic and damage formulation (Eq.9) takes into account automatically the size of the volume loaded. Indeed, the tensile damage is not assessed with $R_{t,ref}$, but with R_t given by Eq.8.

$$\sigma_{ij} = (1 - D^t)_{ijkl} \tilde{\sigma}_{ij} \quad (9)$$

Informations concerning the damage law are available in [18,19].

Conclusion

The safety demonstration corresponding to the LOCA needs to consider all the phenomena causing either a loss of pre-stressing or a reduction of tensile strength. The best way to merge them is to use a numerical model in which all the phenomena are coupled. The method adopted to clarify the LMDC concrete model consists to build it in the framework of poro-mechanics. The swelling reaction, vapor pressure and water pressure are then considered as internal loadings acting on the solid skeleton. The probabilistic character of the tensile strength is considered through a Weibull formulation (WL2 method); the creep, the plastic strain and the damage depend then automatically on this reduced tensile strength and on the pore pressure. The elastic and the creep strains of the behavior law are written in a differential form. The differential form of the elastics part can be full, or not, depending if the concrete hydrates or dehydrates. The creep velocity derives from the elastic strain to consider implicitly these last chemical effects. The creep strains, corresponding to the non-linear Maxwell module of the rheological scheme, are obtained thanks to a modification of the characteristic time of creep, which is affected by an anisotropic consolidation coefficient. Once the global architecture of the model implemented, the functions are fitted on several experimental campaigns designed to assess effects of temperature and humidity on the evolution laws associated to this model.

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