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Basic creep of concrete - Coupling between high stresses and elevated temperatures

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The prestressed concrete confinement vessel is the third and last barrier in French Nuclear Power Plants (NPP). In case of a severe accident (loss of cooling agent of the reactor for instance), pressure and temperature will increase in the nuclear vessel (+0,5 MPa and 180°C during 2 weeks). Due to elevated temperatures, the evolution of basic creep will be accelerated. In this case, due to internal pressure, some tensile stresses could appear in specific parts of the structure and induce cracking. The modelling of basic creep and its couplings with temperature is then very important for the safety of the structure (tightness of the concrete vessel). Here we present a model considering the following elements: a coupling between creep and damage is introduced, kinetics of basic creep is affected by temperature by the means of an Arrhenius thermo-activation, damage due to the increase of temperature (under stress or not) is taken into account. The model is compared with the available experimental results. This work is a part of the MACENA project.

Keywords: Concrete, basic creep, temperature, transient thermal strain, damage, coupling

Introduction

The prestressed concrete containment vessel constitutes the third and last barrier in French Nuclear Power Plants (NPP). It plays therefore a crucial role to limit the radionuclide dispersion in the environment in case of breakdown of the first two barriers (the fuel cladding and the primary cooling system). In case of a severe accident (loss of cooling agent of the reactor for instance), pressure and temperature will increase in the nuclear vessel (0.5 MPa and 180°C during 2 weeks). Due to elevated temperatures, the evolution of basic creep will be accelerated as the loss of prestressing. And, in this case, some tensile stresses could appear in specific parts of the structure with the formation of possible cracks that could affect the tightness of the structure.

So, the modelling of basic creep in the case of elevated temperature and high stresses is crucial in case of an accident. This modelling should take into account the couplings between creep, damage and temperature. After a presentation of the basic creep model, the coupling with damage at ambient temperature is considered. Then, the effect of temperature (below 100°C in this work) is introduced considering two cases: elevation of temperature before loading and after loading (transient thermal strain). For each component, the model is compared with experimental tests.

Basic Creep

In this paper, the compliance of the basic creep is expressed by the following formulation (equation (1)), which is similar to the relation proposed in the recent fib model code 2010 – MC2010 (Muller et al., 2013), (fib, 2012) and which is in accordance to several tests (Torrenti et Leroy, 2015):

$$J = 1/E(t_0) + \frac{1}{\beta_1 \cdot C} \log(1 + (t - t_0)/(\beta_2 \cdot \tau(t_0))) \quad (1)$$

where C is a constant for a given concrete (depending on the mechanical properties of concrete) while $\tau(t_0)$ depends on the age at loading. These two parameters could be obtained using the formulation of basic creep in MC2010 (equations (2) and (3)). β_1 and β_2 are added parameters that could be adjusted for a given concrete if experimental data are available. Note that the methodology that is presented below is general and could be used with another model for basic creep.

$$C = \frac{E_{28} f_{cm}^{0.7}}{1.8} \quad (2)$$

$$\tau(t_0) = [1/[0.035 + 30/t_0]]^2 \quad (3)$$

Coupling of basic creep with damage

Since Rüschi experiments (Rusch, 1960), one knows that when concrete is subjected to a high sustained compressive load (stress higher than 80% of the compressive strength), non linear creep is observed and failure occurs after a while. Several experimental evidences show that microcracking occurs during creep (even below 80% of the compressive strength): Smadi has shown that during a creep test microcracks are created and that the length of the microcracks evolves rapidly when the stress level is higher than 80% of the compressive strength (Smadi et Slate, 1989). Using a wedge splitting test, interaction between crack propagation and creep was demonstrated by Denarié (Denarié et al., 2006). And Rossi, using acoustic emission, has also highlighted microcracking during creep (Rossi et al., 94), (Rossi et al., 2012).

Many modelling approaches have been proposed to model this coupling between creep and damage of concrete. Bazant, assuming tertiary creep is only due to the growing of cracks with time, uses a fracture mechanics approach coupled to creep to model this behaviour (Bazant et Xiang, 1997). Coupling between creep and cracking can be modelled by combining a viscoelastic and a viscoplastic model (Berthollet et al., 2004). Several damage models were also used. (Li, 1994) proposed that the temporal variable can be explicitly introduced in the mechanical damage evolution law in terms of damage rate. (Challamel et al., 2005) have developed a softening visco-damage model that could be viewed as a generalisation of a time-independent damage model and describes phenomena like relaxation, creep and rate dependent loading. Recently, (Sellier et al., 2016) have proposed a creep model taking into account a material consolidation and a creep induced damage that affects the creep potential. (Mazzotti et Savoia, 2003) proposed to model non-linear creep strain by introducing a stress rate reduction factor as a function of the damage variable in the solidification model (Bazant et Prasannan, 1989). Moreover, an effective strain is then defined for creep damage,

replacing the equivalent strain, as defined by (Mazars, 1986), in damage evaluation for instantaneous loading case. The effective strain is defined as the sum of instantaneous damaged elastic strain with a fraction of creep strain. (Omar et al., 2004) and (Reviron, 2009) have also used this approach.

Among these approaches, our model is based on the one proposed by (Mazzotti et Savoia, 2003), since the use of damage allows a simple and natural coupling with creep and with other phenomenon through the use of the effective stress concept. For instance, it was used in the case of a coupling with leaching (Torrenti et al., 2008), (Torrenti et al., 2011). The damage model proposed by (Mazars, 1986) is used. In this model, a scalar mechanical damage variable D_c is associated to the mechanical degradation process of concrete induced by the development of microcracks. It is defined as the ratio between the microcracks area to the whole material area. An effective stress $\tilde{\sigma}$ is then defined from the apparent stress σ applied on the whole material section. The relationship between apparent stress σ , effective stress $\tilde{\sigma}$ and damage D_c reads:

$$\sigma = (1 - D_c)\tilde{\sigma} \quad (4)$$

Note that the use of the concept of effective stress implies that in a laboratory creep test where the apparent stress is constant, the effective stress which is applied to the material varies. Consequently to predict the delayed deformation with the relation used for basic creep here (equation (1)) the Boltzmann superposition principle should be used.

The Poisson ratio is assumed to be constant. The mechanical damage evolution is deduced from the equivalent tensile strain $\tilde{\varepsilon}$ defined in equation (5) and including the contribution of the elastic strain ε and a part β of the creep strain ε_c , with $\langle \varepsilon \rangle_+$ indicating

the positive part of the strains. The evolution law for the mechanical damage variable D_c is given in equation (6), where ε_D is the damage tensile strain threshold, A and B are constant material parameters which control the hardening/softening branch in the stress-strain curve.

$$\tilde{\varepsilon} = \sqrt{\langle \varepsilon + \beta \varepsilon_c \rangle_+ : \langle \varepsilon + \beta \varepsilon_c \rangle_+} \quad (5)$$

$$D_c = 1 - \frac{\varepsilon_D(1-A)}{\tilde{\varepsilon}} - \frac{A}{\exp(B(\varepsilon_D - \tilde{\varepsilon}))} \text{ if } \tilde{\varepsilon} > \varepsilon_D \quad (6)$$

The coupling between creep and damage is then taken into account twice: on the one hand, creep strains are considered to be driven by effective stresses - only the uncracked material creeps (Benboudjema et al., 2005) and on the other hand, damage is also affected by basic creep strain (equation (5)). Note that with this coupling, due to the choice of a non asymptotic damage, failure will finally occur due to tertiary creep.

The model is firstly compared with tests performed by (Ranaivomanana et al., 2013). In these tests, concrete samples which are protected against drying are loaded at 28 days at 30% and 50% of the compressive strength. Figure 1 shows that is it possible with a single set of parameters to fit the experimental results. The parameters C and $\tau(t_0)$ are obtained from the equations (2) and (3) proposed by the fib model Code 2010 (fib, 2012). To fit the experimental results, the parameters β_1 , β_2 and β are adjusted (the values are given in the legend of the figure 1).

Figure 1. Comparison of the model with Ranaivomanana's basic creep tests (Ranaivomanana et al., 2013). The mechanical strain is the sum of the elastic and of the delayed strains. Values of the parameters of the model: $t_0 = 28$ days, $E(t_0) = 41.5$ GPa, $f_{cm} = 71$ MPa, $\tau(t_0) = 0.8$ days, $\varepsilon_D = 124$ $\mu\text{m/m}$, $C = 228$ GPa, $\beta_1 = 10$, $\beta_2 = 1$, $\beta = 0.1$, $A = 0.85$, $B = 1000$

The model is also compared with tests performed by (Rossi et al., 2012). In these tests, concrete samples are loaded at 34%, 55% and 78% of the compressive strength. Figure 2 shows that is again possible with our model to fit the experimental results at 34% and 55% with a common set of parameters and predict the behaviour at 78%. The model is also compared to a basic creep test where the stress is increased with time: the stress to strength ratio is equal to 54% during 353 days, to 58% during 30 days, to 73% during 7 days and then to 80% till the end of the test (figure 3). Except at the end of the test, where tertiary creep occurs, there is a good agreement between the model and the experimental results. The difference could be due to a nonlinear evolution of damage that is not taken into account by our model (for instance the parameter β could evolve with the damage). But this phenomenon should have also affected the previous creep test especially when the stress level was equal to 78% (cf.

figure 2). This could be also due to an underestimation of the ratio of the applied stress to the compressive strength (because of the natural variability of the concrete strength and/or to an underestimation of the applied stress). In this case damage will be higher and it is possible to obtain tertiary creep (Torrenti et al., 2008).

Figure 2. Comparison of the model with Rossi's basic creep tests (Rossi et al., 2012). Values of the parameters of the model: $t_0=64$ days, $E(t_0) = 30$ GPa, $f_{cm} = 43$ MPa, $\tau(t_0)=3.9$ days, $\varepsilon_D = 122$ $\mu\text{m/m}$, $C=231.9$ GPa, $\beta_1=1$, $\beta_2=1$, $\beta=0.08$, $A=0.85$, $B=1000$

Figure 3. Comparison of the model with a test including an increasing stress (Rossi et al., 2012). The values of the parameters of the model are identical to the one used in Figure 2.

Coupling of basic creep with temperature

Coupling at constant temperature

We consider the firstly the coupling between basic creep and a constant temperature (concrete is heated before loading). An elevated temperature (below 100°C here) has several consequences on basic creep. The first consequence is a damage induced by the temperature increase. Here the relation proposed by (Vidal et al., 2015) is used:

$$D_T = 1 - \exp \left[- \left(\frac{T - T_{ref}}{\Delta T_k} \right) \right] \quad (7)$$

where T_{ref} and ΔT_k are parameters of the evolution of damage. Due to the damage induced by temperature D_T , equation 4 becomes:

$$\sigma = (1 - D_c)(1 - D_T)\tilde{\sigma} \quad (8)$$

The second consequence of an elevated temperature is an effect on the kinetics of basic creep. This effect could be taken into account by means of an equivalent time

(or a time–temperature superposition which is used for polymers or bituminous materials). This idea was used by (Bazant et al., 2004) for instance. Here, another way to model this effect is used: as proposed by (Benboudjema et Torrenti, 2008) or (Sellier et al., 2016), the coefficient C (equation (1)) is affected by a thermo-activation corresponding to the activation energy Q of water viscosity:

$$C_T = C \exp \left(Q \left(\frac{1}{T} - \frac{1}{293} \right) \right) \quad (9)$$

The model is compared with tests performed by (Vidal et al., 2015) where basic creep tests on a high performance concrete at 20°C, 50°C and 80°C were performed with a stress corresponding to 30% of the compressive strength. Figure 4 presents the comparison between the model and the experimental results. Note that the three tests were used in order to adjust the parameters of the model. So the good agreement shows here the capability of the model to reproduce the behaviour of concrete during a basic creep test with elevated temperatures.

Figure 4. Comparison of the model with Vidal's basic creep tests (Vidal et al., 2015). Values of the parameters of the model: $t_0=300$ days, $E(t_0) = 45$ GPa, $f_{cm} = 86$

MPa, $\tau(t_0)=4.4$ days, $\varepsilon_D = 130 \mu\text{m/m}$, $C=565$ GPa, $\beta_1=0.08$, $\beta_2 = 0.65$, $\beta=0.08$, $A=0.95$,
 $B=1000$, $T_{ref}= 323$ K, $\Delta T_k =383$ K, $Q=2500$ K

The model is also compared to Okada's tests where the temperatures were between 20°C and 80°C. The parameters of the creep model are determined using the test at 20°C. For the other parameters the set of parameters used for Vidal's test is used. Again a good agreement is obtained (figure 5).

Figure 5. Comparison of the model with Okada's basic creep tests (Okada et al., 1977). Values of the parameters of the model: $t_0=90$ days, $E(t_0) = 35$ GPa, $f_{cm} = 39.4$ MPa, $\tau(t_0)=7.4$ days, $\varepsilon_D = 99 \mu\text{m/m}$, $C=191$ GPa, $\beta_1=3$, $\beta_2 = 0.75$, $\beta=0.08$, $A=0.95$,
 $B=1000$, $T_{ref}= 323$ K, $\Delta T_k =383$ K, $Q=2500$ K

Transient thermal strains

Transient thermal strains are additional strains that appear when a loaded concrete specimen is heated. In sealed conditions, we assume that these strains are mainly due to an incompatibility in the thermal strains between the cement paste and the aggregates as proposed by (Mounajed et al., 2005) or (Bosnjak et Ozbolt, 2016). This incompatibility creates damage at a mesoscopic level, with consequences at the macroscopic scale.

Experimental results (Cagnon et al., 2014), (Ranaivomanana et al., 2013) show that, even for temperatures below 100°C, the contribution of transient thermal strains to delayed deformations could be not negligible and should be added to the model.

As proposed by (Pearce et al., 2004), we assume here that transient thermal strains are the consequence of damage on the elastic part and on creep due to the coupling introduced by the effective stress. So another damage variable D_{tts} is introduced. Consequently the definition of the effective stress is modified (equation 10). Using this relation, the thermal transient strain is only a variation of the viscoelastic response due to the evolution of damage.

$$\sigma = (1 - D_c)(1 - D_T)(1 - D_{tts}) \tilde{\sigma} \quad (10)$$

The evolution of damage is given by a classical relation (equation 11) where ε_{tts} corresponds to the thermal transient strain proposed by the model code MC2010 (fib, 2012) (equation 12), which is based on a relation proposed by (Nielsen et al., 2002).

$$D_{tts} = \frac{\varepsilon_{tts}}{\varepsilon_{tts} + \varepsilon_0} \quad (11)$$

where ε_0 is a parameter of the model. The evolution of D_{tts} is irreversible.

$$\varepsilon_{tts} = 4 \cdot 10^{-4} (T - 20)^2 \frac{\sigma}{E} \quad (12)$$

where σ is the applied stress during the temperature increase, T (°C) is the final temperature.

The global model is compared with the results of Fahmi's test (Fahmi et al., 1972). In this basic creep test, the temperature evolves from 23°C to 47°C then to 60°C. Figure 6 presents the comparison between experimental results and modelling. If we take into account the fact that, as indicated in Fahmi's paper, when the temperature is

increased there is a variation of the Young modulus that has been neglected in the measurements, we obtain a good agreement with our model. The complete curve, including the instantaneous effect of damage is also represented figure 6. The model, only by means of an additional damage, predicts an important additional strain.

Figure 6. Comparison of the model with Fahmi's test (Fahmi et al., 1972).

Values of the parameters of the model: $t_0 = 21$ days, $E(t_0) = 30$ GPa, $f_{cm} = 20$ MPa, $\tau(t_0) = 0.5$ days, $\varepsilon_D = 73$ $\mu\text{m/m}$, $C = 136$ GPa, $\beta_1 = 0.8$, $\beta_2 = 1$, $\beta = 0.08$, $A = 0.95$, $B = 1000$, $T_{ref} = 323$ K, $\Delta T_k = 383$ K, $Q = 2500$ K, $\varepsilon_0 = 300$ $\mu\text{m/m}$

Conclusions

Basic creep is an important part of the delayed deformations of prestressed concrete. In the case of a severe accident in a nuclear power plant, basic creep will be affected by elevated temperatures and damage. The presented model allows taking into account in a fully coupled way these parameters. It was compared with available experimental results. The comparison shows that the model is able to reproduce the experimental behaviour.

Within the MACENA project, basic creep tests coupling elevated temperatures and a high stress level will be performed. The model will be compared to these tests.

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