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ABSTRACT

In this study, a multiphysics model is presented that predicts creep in three months old concrete cylinders subjected to drying. The model includes concrete hydration, and a moisture transport model with relative humidity as the driving potential. These parameters are important to include in order to simulate creep. The model was implemented in the finite element software COMSOL Multiphysics. The calculated axial deformation of the cylinder was compared with measurements performed on an experimental set-up. The model was found to be able to predict the axial deformations with reasonable accuracy. This study is a part of the VeRCoRs 2018 benchmark provided by the Electricité de France, EDF.

INTRODUCTION

This study presents mechanical analyses of a concrete cylinder subjected to a creep test. It is a part of the VeRCoRs benchmark 2018 arranged by Electricité de France, EDF. The results from the analyses have been compared with actual measurements performed on a concrete cylinder subjected to a certain experimental set up. In this study, the focus has been to use a model available for professional designers, Eurocode 2, and not to develop a model that only researchers is able to use and to show the magnitude of error that may be expected by using such a model in a laboratory test set up.

A number of different studies have been initiated by the Swedish power industry with an objective to develop advanced calculation tools to analyse mechanics and transport mechanisms in nuclear power and hydropower concrete structures [1, 2].

HYDRATION MODEL

Material properties of concrete change significantly during the first month. In order to correctly describe the behaviour of young concrete it is therefore vital to use a model that describes such material changes. As most of the material properties are related to the hydration degree of cement this is used as a method to address the changes with time.

The model of hydration, used in this study, was developed by Byfors [3] and it describes the hydration of concrete through time, $\alpha(t)$, Eq. 1

$$\alpha(t) = e^{A\log(\frac{t}{3600})^B} \tag{1}$$

where A and B are curve fitting parameters, in this study A=-7 and B=-2.7 was used. These parameters were determined by using the provided temperature development from VeRCoR at adiabatic conditions from the actual used concrete together with the maximum heat release from hydration.

Hydration in an early age concrete is described by adopting a model presented by Norling Mjörnell [4]. The mathematical formulation of hydration rate of concrete $\frac{\partial \alpha(t)}{\partial t}$ is shown in Eq. (2)

$$\frac{\partial \alpha(t)}{\partial t} = \beta_{WC}\beta_T\beta_\varphi \left(\frac{\partial \alpha(t_e)}{\partial t}\right)_{ref} \tag{2}$$

where $\beta_{WC}, \beta_T, \beta_\varphi$, are parameters dependent on the water to cement ratio, the temperature and the relative humidity, RH, respectively and $\left(\frac{\partial \alpha(t_e)}{\partial t}\right)_{ref}$ is the hydration rate in a reference climate 20 °C and at fully saturated conditions.

The expression used to calculate the water to cement ratio parameter is shown in Eq. (3)

$$\beta_{WC} = \left(\frac{\alpha_{max} - \alpha}{\alpha_{max}}\right)^{A_{betaWC}} \tag{3}$$

where α_{max}, here 0.98, is equal to the maximum possible hydration degree, and A_{betaWC}, here 1.9, which is a parameter used to fit the current hydration development to a reference hydration development on a concrete with a reference water to cement ratio. This takes into account that the amount of unreacted cement is reduced with time.

The temperature dependency on hydration rate is based on the Arrhenius equation for thermal activation and is described by the maturity function shown in Eq. (4)

$$\beta_T = e^{\left(\frac{1}{T_{ref}} - \frac{1}{T}\right)\theta} \tag{4}$$

where T_{ref} is the reference temperature, in our case 293.15 [K], T is the actual temperature in [K], and θ is the temperature dependency of the activation temperature. This temperature dependency is described by Eq. (5)

$$\theta = \theta_{ref} \left(\frac{30}{T + 10 - 273.15}\right)^{\kappa_3} \tag{5}$$

where θ_{ref}, here 4700 and κ_3, here 0.54 are empirical constants derived from experimental adaptations.

Finally, β_φ, is a parameter determined by the proportion of capillary pores filled with water, as it is mainly the liquid water in the pores that contributes to the formation of hydration products. The capillary pore volume P_{cap_p} is determined by using Eq. (6)

$$P_{cap_p} = \frac{\frac{W_0}{C} - .39 \cdot \alpha(t)}{0.32 + \frac{W_0}{C}} \tag{6}$$

where $\frac{W_0}{C}$, is the water to cement ratio in [kg/kg]. And parameter β_φ is then described by Eq. (7)

$$\beta_\varphi = \frac{\frac{W_e(\varphi)}{C} - P_{cap_p} \cdot \alpha(t)}{\frac{W_0}{C} - .19\alpha(t) - P_{cap_p} \cdot \alpha(t)} \tag{7}$$

where, $W_e(\varphi)$, is the moisture content at a certain RH.

HEAT TRANSFER MODEL

The temperature condition inside the concrete cylinder was determined by solving the conventional energy-balance Eq. (8)

$$\rho \cdot C_p \cdot \frac{\partial T}{\partial t} = \nabla(k\nabla T) + Q \tag{8}$$

where ρ represents the density 2350 [kg/m³], C_p the specific heat capacity 880 [J/(kgK)], T the temperature in [K] and k the heat conductivity 1.8 [W/(mK)]. The heat released from the cement hydration reaction Q, was also included as a function of the hydration rate see Eq. (9)

$$Q = \frac{d\alpha(t)}{dt} \cdot q_u \cdot C \qquad (9)$$

where q_u represents the maximum heat released by hydration and C represents the cement content in the concrete mixture, 320 [kg/m³]. The initial concrete temperature of the concrete cylinder was assumed to be 293 [K]. The cement used in the actual concrete mixture, CEM I 52,5 N CE CP2 NF Gaurain, has a maximum heat release of 376 [kJ/kg], and this was used in the model.

MOISTURE TRANSPORT MODEL

Moisture transport may be modelled by using a number of different transport potentials, such as air vapour content, air vapour pressure or capillary pressure. This model used relative humidity as a driving potential and was previously developed in the Nugenia-Acceppt project. Results from using this model were verified qualitatively with measurements from Swedish nuclear reactor Ringhals 4 performed in another study [5]. The moisture transport, J, was modelled by using the relative humidity as the driving potential, see Eq. (10)

$$J = -\delta_\varphi \frac{\partial \varphi}{\partial x} \qquad (10)$$

where φ [-], is the ratio between actual and saturation vapour content, which is the RH in the pores of the material and δ_φ [m²kg/(sm³)] is the moisture dependent transport coefficient with RH as the transport potential.

The moisture transport in the proposed model [6], is based on the mass conservation equation, Fick's second law, Eq. (11)

$$\frac{\partial W_e}{\partial t} = \frac{\partial W_e}{\partial \varphi} \frac{\partial \varphi}{\partial t} = \nabla(\delta_\varphi \nabla \varphi) + Q_2 \qquad (11)$$

where $\frac{\partial W_e}{\partial \varphi}$ represents the moisture capacity derived from the sorption isotherm, δ_φ represents the moisture transport coefficient with relative humidity as a driving potential, φ is the relative humidity, and Q_2 represents the self-desiccation of concrete. Self-desiccation was evaluated by using Eq. (12)

$$Q_2 = \frac{\partial \alpha(t)}{\partial t} \cdot C \cdot 0.25 \qquad (12)$$

where $\frac{\partial \alpha(t)}{\partial t}$ represents the hydration rate, C, represents the cement content [kg/m³] in the concrete mixture and 0.25, which represents an assumed maximum possible amount of water chemically bounded by the cement.

THERMAL EXPANSION, SHRINKAGE AND CREEP MODEL

The thermal expansion, ε_{th}, was included by using, Eq. (13)

$$\varepsilon_{th} = \alpha \cdot (T - T_{ref}) \qquad (13)$$

where α, is the thermal coefficient $(1,1 \cdot 10^{-5})$ [1/K], T represents the temperature [K] and T_{ref} represents the reference temperature 293 [K].

The drying shrinkage was included by using Eq. (14)

$$\varepsilon_{sh}(t) = \frac{W_i - W(t)}{W_i - W_\infty} \cdot \varepsilon_{sh,\infty} \qquad (14)$$

where $\varepsilon_{sh}(t)$, represents the shrinkage strain at time t, W_i, is the initial moisture content, $W(t)$ is the moisture content at time t, W_∞ is the moisture content when in equilibrium with the current humidity exposure, and $\varepsilon_{sh,\infty}$ represents the final shrinkage strain which is estimated to 0.05%.

Creep was modelled by using the model described in Eurocode 2. In this model, the creep coefficient, $\varphi_c(t, t_0)$, is described by Eq. (15)

$$\varphi_c(t, t_0) = \varphi_0 \cdot \beta_c(t, t_0) \qquad (15)$$

where the φ_0 is the notional creep coefficient and $\beta_c(t, t_0)$ is a coefficient to describe the development of creep with time after loading. A thorough description is found in in Eurocode 2[7].

The creep strain, ε_{cr}, is included by using Eq. 16

$$\varepsilon_{cr} = \varphi_c(t, t_0) \cdot \frac{\sigma}{E} \tag{16}$$

where σ, represents the stresses in the concrete and E represents the modulus of elasticity which was assumed constant 31.8 [GPa].

The total strain is then described by Eq. 17

$$\varepsilon_{tot} = \varepsilon_{el} + \varepsilon_{th} + \varepsilon_{sh} + \varepsilon_{cr} \tag{17}$$

where ε_{el} is the elastic strain from the mechanical loads.

CASE STUDY

The above presented model was applied to various laboratory test set-ups on a number of concrete cylinders subjected to various boundary conditions with the finite element software COMSOL. The diameter of each cylinder was 0.08 m and the length was 1.0 m. In Figure 3 and Figure 2, the geometry and the finite element mesh are shown.
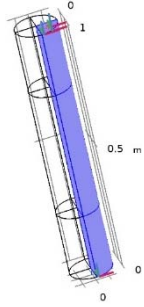

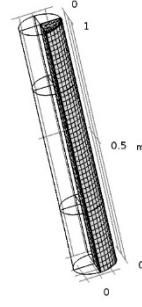*Figure 1 Geometry of the concrete cylinder, 1 m long and 0.16 m in diameter*

Figure 2 Illustration of the finite element mesh of the concrete cylinder

Only one forth of the cross section of the cylinder was modelled. The mesh consisted of around 2000 hexahedral elements and the degrees of freedom used were around 220 000.

The surrounding temperature was set as 293 K. A convective heat flux was used at the vertical concrete surfaces. The humidity during the drying shrinkage test was set to 50% RH 24 hours after casting. In the creep test, the surface was assumed to be totally sealed for 90 days, before loading the concrete cylinder. At the time of the exerted axial load the sealing was removed and the surface exposed to a relative humidity of 50 % RH. The simulations were performed by setting the climate to 30, 50 and 70 % RH.

The surface mass transfer resistance with RH as a driving potential, k_{RH}, was modelled by using Lewis relation [8], Eq. (18)

$$k_{RH} = \frac{h \cdot v_s}{\rho_{air} \cdot C_{p(air)}} \tag{18}$$

where, h, is the convection heat transfer coefficient [W/(m^{2}K^1)], v_s is the saturation vapour content [kg/m^3], ρ_{air}, is the air density [kg/m^3], and $C_{p(air)}$, is the heat capacity of air [J/(kgK)]. This model is an estimation of the surface mass transfer resistance.

The exerted axial load was modelled as a constant boundary load of 60.25 kN on the surface perpendicular to the length of the cylinder. The creep test was controlled by a hydraulic jack, and a pressure cell was used to monitor the applied pressure. Because of creep and shrinkage, the applied force continuously decreased from the initial force of 241 kN. When the force decreased 10 %, to 216 kN the force was adjusted and increased to 241 kN again.

RESULTS AND DISCUSSION

Results from calculations performed by using the presented model, are shown in Figure 3 to Figure 5. In Figure 3, the results from the simulated axial deformation is presented together with the measurements performed on the concrete cylinder during drying. Figure 4 shows the actual basic creep of the concrete cylinder, in addition to the results from the applied creep model.
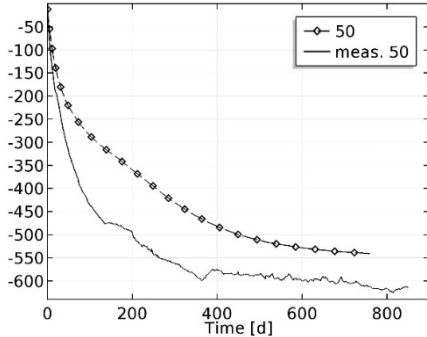

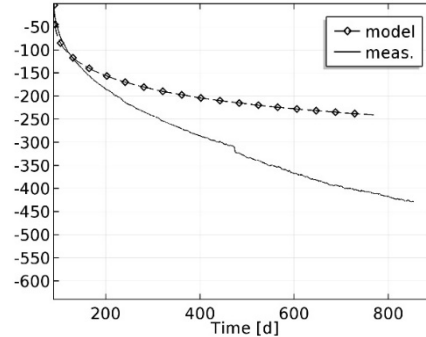Figure 3 Drying shrinkage axial strains (10^{-6} m/m)

Figure 4 Basic creep axial strains (10^{-6} m/m)

During the first 150 days, the actual, measured, shrinkage is larger than the simulated. After 200 days, the measured shrinkage is about 500 micro strains compared to 375 micro strains obtained by the simulation, see Figure 3. This difference may be an effect of underestimated drying caused by an underestimation of the moisture transport property of the early age concrete. Another possible reason for this difference may stem from underestimation of the maximum shrinkage coefficient. In addition, the difference could partly be explained by the fact that the modulus of elasticity is assumed to be constant during the simulation. This overestimates the modulus of elasticity during early ages. The actual shrinkage in the range between 400-800 days is of a similar magnitude compared with the results from the model. The calculated basic creep of the concrete cylinder, see Figure 4, is not as large as the actual basic creep. During the first few days the simulated creep is larger than the calculated creep but afterwards the actual axial deformations are larger. This indicates that the Eurocode underestimates the actual basic creep of concrete on a long-term basis. The fact that Eurocode underestimates creep has been shown by other authors, i.a. Lundqvist [9] and Raphael et al. [10].

Calculated drying creep for three different exposure humidities, 30, 50 and 70% RH, are shown in Figure 5 including measurements performed on one concrete cylinder exposed to 50% RH.
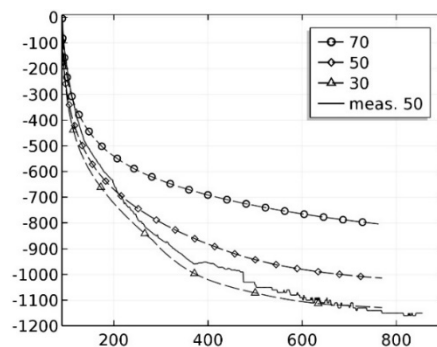

Figure 5 Drying creep axial strains (10^{-6} m/m)

The calculated drying creep clearly shows that low humidity increases the deformations with time, see Figure 5. Furthermore, it is shown that the applied model from Eurocode underestimates the actual creep. The underestimation is around 10 % after some 750 days. After that amount of time deformations caused by shrinkage are reduced to a large extent and the major contribution should originate from creep alone.

CONCLUSIONS

A method to model axial deformation in COMSOL was developed. The Eurocode model to estimate creep is underestimating the actual creep compared to the measurements. This means that practitioners using the established Eurocode model underestimates creep in this type of application which may have an impact on the design of new structures.

ACKNOWLEDGEMENT

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