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Numerical investigation of the size effects on the creep damage coupling

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Abstract

The service-life of concrete structures depends on the delayed strains that appear due to creep phenomenon. Few are the studies that treated the effect of the dimensions of concrete specimens on the amplitude and the kinetics of creep and the results show many contradictions. Thus, to design reliable civil engineering structures, the knowledge of the behaviour of concrete under a sustained load including size effect is necessary and performing calculations are needed. In this paper, the physical mechanisms behind the size effect on creep rate are evaluated at the mesoscopic scale. The material volume is modeled, by a Digital Concrete model which takes into account the microstructure heterogeneities and the "real" aggregate size of concrete. Calculations are performed in 2D by considering a viscoelastic damage behaviour law for the matrix and an elastic behavior for aggregates. The numerical results show that size effect is well reproduced by the meso-scale approach. The stresses under a sustained load are induced by strain incompatibilities between the components at the mesoscale. Accordingly, the evolution of the microcracked zone with the size of the bending specimens can be related to the creep rate.

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1. Introduction

In order to design reliable concrete structures, prediction of long term behaviour of concrete is important by considering a coupling between creep and damage. In common practice, it is usually assumed that linear viscoelasticity takes place for low load levels and that in the same loading range, the instantaneous mechanical behaviour of concrete remains elastic. For high load levels, micro-cracks can nucleate, grow and interact with the time dependent response of the bulk material. So, a deviation from linearity of the response of concrete to creep is expected and a deviation from linearity of the instantaneous mechanical response occurs as well. In addition, many studies showed that the principal mechanism of tensile creep is due to microcracks development which contribute to make the concrete weaker (Cook & Haque, 1974; Rossi & al., 2012; Saliba & al., 2013). This mechanism can increase the influence of the size of structural element on the concrete behavior (Bazant, 1993). However, few studies investigated the size effect on creep and not so much data has been accumulated in the literature. Furthermore, the results showed many contradiction. No significant size effects related to basic creep in compression was observed in (L'Hermite & Mamillan, 1969) and (Rossi & al., 2012). While (Hansen & mattock, 1966) and (Imamoto & al., 2005) showed that the amount of creep decreases as the size of specimen increases. A recent study conducted by (Omar et al., 2009) showed a very important volume effect related to flexural creep, the amplitude and the kinetics of creep increase with the dimensions of concrete specimens.

The objective of this study is to perform a thorough investigation on this subject using finite elements calculations. For this, the behaviour of concrete is modeled at the mesoscopic scale by coupling a linear viscoelastic model, defined by Kelvin-Voigt chains, and a damage model, based on the microplane theory (Fichant et al., 1997). The mesoscale modelling presents many advantages in the understanding of the fracture process and the corresponding effect of concrete heterogeneities and has shown a particular interest for the evaluation of material characteristics affected by the material characteristics of the components. More particularly, the multi-scales approach was found very useful to study the size effect on the strength of plain concrete structures (Grassl et al., 2012). The model is implemented in the finite element code Cast3m. The size effect on creep was discussed through the comparison between experimental results performed by (Omar et al., 2009) and the computed values obtained by the nonlinear viscoelastic model (Saliba et al., 2012). Three dimensions of prismatic specimens of a concrete representative a French nuclear containment were studied with a height of 100, 200 and 400 mm respectively.

In the first section, the non linear viscoelastic model is presented. Then, the influence of size effect on the mechanical properties is investigated by comparing the load-deflection curves obtained with the numerical simulation and the experimental measurements. Finally, the size effect on creep is studied.

Nomenclature

$\underline{\underline{\tilde{\sigma}}}(\underline{y})$ effective stress

$\underset{\sim}{C}^{0}(\underline{y})$ initial stiffness of the material phases

$\underset{\sim}{C}^{-1}(\underline{y},\underline{\underline{\varepsilon}}(\underline{y}))$ stiffness of the damaged material

$\underline{\underline{\sigma}}(\underline{y})$ local stress fields

$\underline{\underline{\varepsilon}}(\underline{y})$ local strain fields

d damage variable

ε_{d0} strain threshold

G_f fracture energy

$\varepsilon_{\upsilon}^{n}$ viscoelastic strain vector at time-step number n

k^{υ} stiffness of the Kelvin voigt unit.

η^{υ} viscosity of the Kelvin voigt unit.

2. The non-linear viscoelastic model

The chosen damage model is the isotropic model developed by Fichant et al. (1997). It allows to represent the unilateral effect and to obtain objective results independently of the length of the finite elements by controlling the fracture energy. This model is a simplified version of the microplan model and is based on the relation between the total stress and the effective stress $\tilde{\underline{\underline{\sigma}}}(y)$ of the material defined by:

$$\tilde{\underline{\underline{\sigma}}}(\underline{y}) = \underset{\sim}{C}^0(\underline{y}) : \underline{\underline{\varepsilon}}^e(\underline{y}) \quad or \quad \tilde{\underline{\underline{\sigma}}}(\underline{y}) = \underset{\sim}{C}^0(\underline{y}) : \underset{\sim}{C}^{-1}(\underline{y}, \underline{\underline{\varepsilon}}(\underline{y})) : \underline{\underline{\sigma}}(\underline{y}) \tag{1}$$

where $\underset{\sim}{C}^0(\underline{y})$ is the initial stiffness of the material phases considered isotropic and linear elastic, $\underset{\sim}{C}^{-1}(\underline{y}, \underline{\underline{\varepsilon}}(\underline{y}))$ the stiffness of the damaged material, $\underline{\underline{\sigma}}(\underline{y})$ the local stress fields in each point $\underline{y}$ and $\underline{\underline{\varepsilon}}(\underline{y})$ the local strain fields. For the isotropic version of the model, the relation between the effective stress and the total stress is :

$$\underline{\underline{\sigma}} = (1-d)\tilde{\underline{\underline{\sigma}}} \tag{2}$$

where d is the scalar value of the isotropic damage that depends only on the equivalent strain calculated according to the elastic strain tensor $\underline{\underline{\varepsilon}}^e \left(= \underline{\underline{\varepsilon}}(\underline{y}) - \underline{\underline{\varepsilon}}^v(\underline{y})\right)$:

$$\varepsilon_{eq} = \sqrt{\underline{\underline{\varepsilon}}^e : \underline{\underline{\varepsilon}}^e} \tag{3}$$

The evolution of the damage variable, due to external mechanical loads, is an exponential form:

$$d = 1 - \frac{\varepsilon_{d0}}{\varepsilon_{eq}} \exp\left[B_t\left(\varepsilon_{d0} - \varepsilon_{eq}\right)\right] \tag{4}$$

where B_t represents a damage parameter to control the slope of the strain softening constitutive relation in function of the width h of the element and ε_{d0} the strain threshold. Damage increases when the equivalent strain ε_{eq} is higher than the threshold strain ε_{d0} linked to the fracture energy G_f as follow:

$$\frac{G_f}{h} = \frac{f_t \varepsilon_{d0}}{2} + \frac{f_t}{B_t} \tag{5}$$

Where h is the element size and f_t the tensile strength.

The viscoelastic strain is defined by several Kelvin-Voigt chains. With those elements, the stress history does not have to be stored for the calculation of creep strain (Benboudjema, 2008). For a Kelvin-Voigt unit i, the basic strain evolution is given by:

$$\eta^v \dot{\underline{\underline{\varepsilon}}}^v(t) + k^v \underline{\underline{\varepsilon}}^v(t) = \tilde{\underline{\underline{\sigma}}}(t) \tag{6}$$

where $\dot{\underline{\underline{\varepsilon}}}^\upsilon(t)$ represents the derivative of the elementary basic creep strains, k^υ the stiffness and η^υ the viscosity of the Kelvin voigt unit.

The total viscoelastic strain is deduced from the sum of all the elementary viscoelastic strains.

$$\underline{\underline{\mathrm{E}}}(t) = \sum_{i=1}^{i=n+1} \underline{\underline{\varepsilon}}^v(t) \tag{7}$$

The Digital Concrete Model has been developed with the aim to have a 'realistic' representation of cement-based materials by taking into account the random size distribution of heterogeneities (Mounajed, 2002; Grondin et al., 2007). A specific algorithm has been developed to make a spatial and random distribution of these phases on the basis of a finite element grid. First of all, all grid elements have mortar properties. Then, aggregates are placed in the grid from the biggest to the smallest, according to the aggregate size distribution, such that no overlapping is obtained with other particles already placed. The properties of the grid elements located in an aggregate area are those of aggregate.

3. Application on concrete at the mesoscale

The considered mesoscale for modelling the behaviour of concrete is the scale at which the material can be observed as a set of coarse aggregates embedded in a mortar matrix. Here, coarse aggregates are inclusions of a size greater than 5 mm following the experimental aggregate size distribution while mortar matrix is a mixture of finer aggregates and the cement paste. The aggregates volume represents 41 % of the total volume of concrete. The stability of results depending on the size of the specimen and the maximal diameter of the inclusion was performed in a recent study (Grondin et al., 2007) and was respected here with dimensions equal to four times the highest inclusion diameter (L/Dmax>4) and finite element size equal to 0.8 time the smallest inclusion diameter. Note here that, the random aggregates distribution have a non-negligible effect on the stress concentration that can influence the cracking process and the path of the macro-crack (Saliba et al., 2012).

Three different sizes of geometrically similar notched beams were used. The cross section of the specimens is rectangular, and the span to depth ratio is l/d = 3:1 for all the specimens. The cross sectional height is equal to 100 mm for D1, 200 mm for D2 and 400 mm for D3 with a length of 350, 700 and 1400 mm respectively. The thickness is kept constant at 100 mm for all the specimens. The beams are notched at midspan with a notch length of 0.15 D and a thickness of 3 mm.

3.1. Structural response on a three-point bending test

A regular mesoscopic mesh related to the middle part of the concrete specimen is generated and two homogeneous concrete blocks are attached to the left and right end of the beam with progressively larger mesh to avoid stress concentration. The loading is applied as an incremental vertical displacement of a rigid plate (linear elastic law) fixed at the top middle of the beam. The numerical simulations were conducted under plane stress condition. For the homogeneous part, the parameters are determined by the mechanical concrete properties of concrete specimens. A fracture test is performed to determine the maximal flexural strength and to validate the choice of the mechanical properties defined for mortar and aggregates. The numerical results are compared to the experimental results analysed in a previous study by (Omar et al., 2009). They reproduced well the experimental load-deflection curves (figure 1).

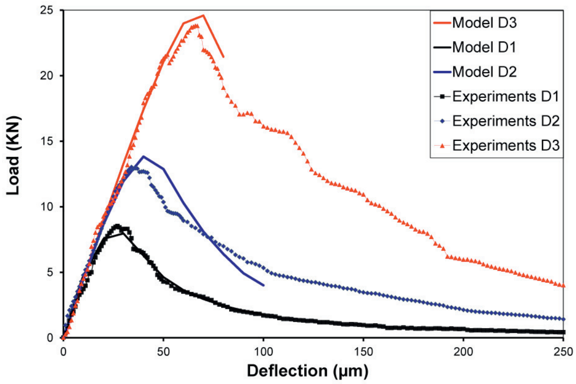

Figure 1: Comparison of numerical and experimental load versus deflection curves for the three sizes beams D1, D2 and D3.

The digital concrete model permits also to simulate the cracking process. The damage is localized at the front of the notch at the beginning of the test. Then cracks begin to join up together and propagate in the mortar matrix exhibiting different realistic features as crack bridging and branching.

3.2. Basic creep results

The proposed model was used for the computations of creep damage in bending. It is considered that the matrix governs the viscoelastic behaviour of concrete and creep strain for aggregates is equal to zero. Four Kelvin-Voigt chains have been retained corresponding respectively to the characteristic times of 0.1 day, 1 day, 10 days and 100 days. The Kelvin-Voigt parameters of the viscoelastic model are calibrated to calculate the total strain evolution of concrete. Creep compliance is assumed equal in compression and in tension.

Three-point bending creep tests are realized on notched D1 beams loaded at 36%, 60% and 80% of the maximum strength. Deflection-time curves are plotted in figure 2(a). The numerical simulations reproduce well the experimental creep tests. The displacement rate is very fast in the first few days of loading (primary creep) and then stabilizes (secondary creep). The kinetics and amplitude of basic creep displacement increases with the rate of loading which exhibits good agreement with the experimental data. Specimens loaded at 36% show no damage. However, the specimen loaded at 60% and 80% show little damage localized at the mortar-aggregates interface with a more important damage intensity for the beam loaded at 80%. This damage is due to the load application at the beginning and increase with the rate of creep leading to a progressive degradation of the material stiffness.

The creep displacement obtained for specimens of three sizes loaded at 80% of their maximal strength is presented in figure 2(b). The numerical results show that the basic creep displacement decreases with the increase of specimen size. This result is opposite to the measurements obtained by (Omar et al., 2009). Note here that a small size effect was observed under the same rate of loading for the three specimen sizes considering the variability due to the random distribution of aggregates. This may be due to weak coupling between creep and damage in the considered model and the simplification related to the presence of the interface transition zone and the additional self-drying shrinkage (Rossi et al., 2012).

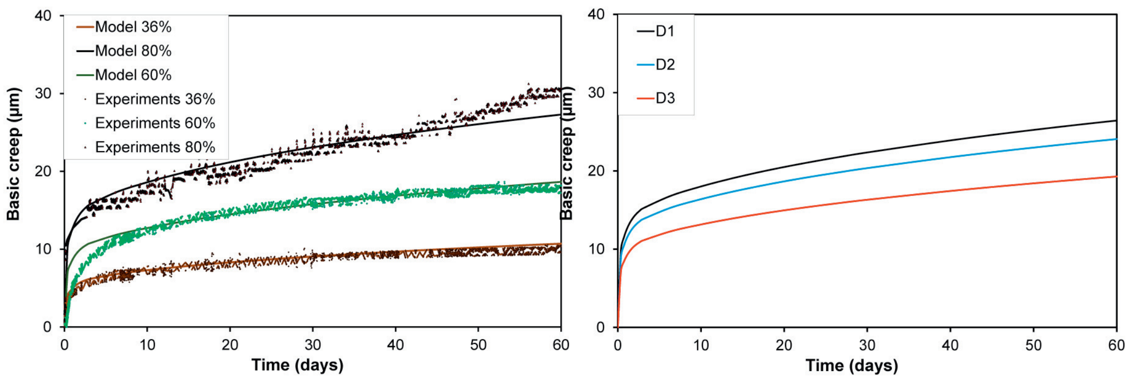

Figure 2: a) Comparison of numerical and experimental basic creep displacement of notched beams D1 for 36, 60 and 80% of the maximal strength b) Basic creep displacement of D1, D2 and D3 beams loaded at 80% of peak load

In order to have more information about the physical mechanisms involved, the damage localization maps after two months of sustained loading are presented in figure 3. The damage zone is localized at the notch and is more important in D1 beams in comparison with D2 and D3 beams which could explains the size effect observed in the fracture test as well as in creep test. This may be also due to a more important stress gradient in small specimens compared to the large one.

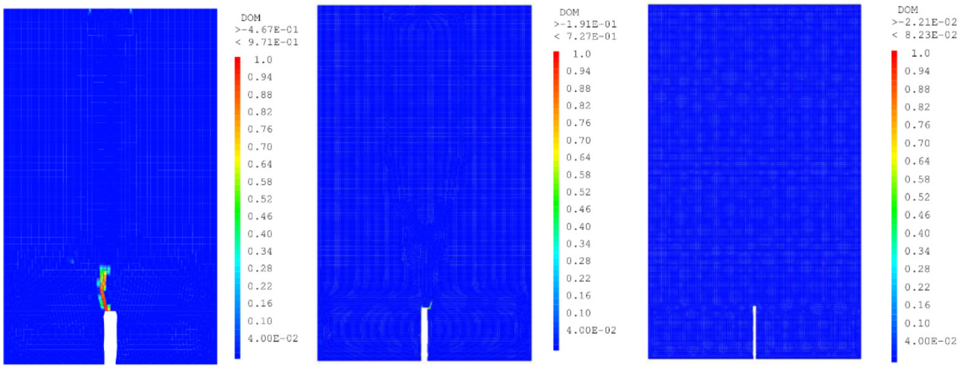

Figure 3: Localization of damage in D1, D2 and D3 concrete beams after two month of loading at 80% of the maximal strength.

4. CONCLUSIONS

A mesoscopic non-linear viscoelastic model was performed to assess the size effect on creep of concrete. The influence of the microstructure is modelled by taking into account the effective interactions between the concrete matrix and inclusions. The mesoscale modelling reproduced well the size effect on the load deflection curves of bending beams. The numerical results showed that the member sizes affected the rate of creep. It has been found that the flexural creep decreased with increasing the size of the specimen. This behavior may be due to the evolution of the damage zone with the specimen's size and to stress gradient. Additional studies will be realized in order to take into account the presence of the interface transition zone and the interaction between creep and additional self-drying shrinkage.

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