Delft University of Technology

Numerical analysis of effect of micro-cracking and selfhealing on the long-term creep of cementitious materials

Lyu, Wenjuan; Schlangen, Erik; van Breugel, Klaas

Publication date
2018

Document Version
Final published version

Published in
Proceedings of the Symposium on Concrete Modelling

Citation (APA)
Lyu, W., Schlangen, E., & van Breugel, K. (2018). Numerical analysis of effect of micro-cracking and selfhealing on the long-term creep of cementitious materials. In E. Schlangen, G. de Schutter, B. Šavija, H. Zhang, & C. Romero Rodriguez (Eds.), *Proceedings of the Symposium on Concrete Modelling: CONMOD2018 27-30 August 2018 – Delft, Netherlands* (Vol. PRO 127, pp. 169-178). (Rilem proceedings; No. PRO 127). Rilem.

Important note
To cite this publication, please use the final published version (if applicable).
Please check the document version above.

Copyright
Other than for strictly personal use, it is not permitted to download, forward or distribute the text or part of it, without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license such as Creative Commons.

Takedown policy
Please contact us and provide details if you believe this document breaches copyrights.
We will remove access to the work immediately and investigate your claim.

This work is downloaded from Delft University of Technology.
For technical reasons the number of authors shown on this cover page is limited to a maximum of 10.

Green Open Access added to TU Delft Institutional Repository

'You share, we take care!' – Taverne project

https://www.openaccess.nl/en/you-share-we-take-care

Otherwise as indicated in the copyright section: the publisher is the copyright holder of this work and the author uses the Dutch legislation to make this work public.

NUMERICAL ANALYSIS OF EFFECT OF MICRO-CRACKING AND SELF-HEALING ON THE LONG-TERM CREEP OF CEMENTITIOUS MATERIALS

W. Lyu [(1)], E. Schlangen [(1)] and K. van Breugel [(1)]

(1) Faculty of Civil Engineering and Geosciences, Delft University of Technology, the Netherlands

Abstract

In order to gain a better understanding of the interaction between creep and micro-cracking during long-term creep process, a theoretical study was performed. An existing lattice model was modified to take creep into account. Based on the model, the micro-cracking in the creep process was simulated on a three-phase concrete sample under sustained compressive load (30% of compressive strength). The effect of on-going hydration and self-healing were considered in this process and inserted in the modified lattice model. This paper contains preliminary results of numerical simulations of an on-going study. The results show that continuous micro-cracking contributes to an extra deformation and degradation of mechanical properties, even though the on-going hydration is involved. The effect of self-healing in the damage zone leads to a decrease in the extra deformation and also to the recovery of the compressive strength and elastic modulus.

1. INTRODUCTION

Creep behaviour is of vital importance when it comes to serviceability and durability of concrete structures. Prediction of long-term creep has been widely investigated and formulated into several empirical models which serve as references for the structural design. However, making reliable predictions is still a challenge. Take the Koror-Babeldaob bridge in Palau as an example; it collapsed in 1996 due to grossly excessive creep deflections which reached to 1.61m within only 18 years [1]. Apparently the long-term creep deformation was severely underestimated during the design phase. This has kept us thinking about the reasons for the underestimation of creep and what is really happening during the creep phase.

Apart from the relatively complicated mechanisms of creep, it is possible to look at this from the perspective of the interaction between creep and micro-cracking. It has been proved experimentally with the use of acoustic emission techniques that micro-cracks do appear in creeping samples, due to the restraint at the structural or material level, even at stress levels below 40% of the strength [2-3]. These micro-cracks could contribute to not only the material discontinuity, but also an extra deformation. If the micro-cracks continue to grow, then eventually failure would be inevitable. However, most structures persist in reality. With load levels below 70% strength, no severe failures were observed, but only some bond and mortar cracks have been found in laboratory work [4-5]. Besides, compressive strength and elastic modulus under sustained compressive loading may increase by a certain amount depending on experimental conditions (stress levels, ambient conditions, etc.). Coutinho mentioned that the specimens, loaded with 30% of 28-day compressive strength, gained a mean increase of 14% in strength after 6 years, compared with the load-free specimens [6]. Froudenthal and Roll [7] applied stresses between 17% and 63% of the 28-day strength of concrete. Increase in strength of loaded specimens were reported up to 30% [7]. Similar results were also found by Washa and Fluck [8]. However, continuous micro-cracking leads to degradation of the mechanical properties of the materials, which seems not consistent with the above observations. Obviously there are some other mechanisms which influence the interaction between creep and micro-cracking and prevent the larger creep deformation, even the failure, to occur. On-going hydration and self-healing are considered to be potential ones.

In order to simulate the above phenomenon, an existing lattice fracture model [9-10] was extended to take creep into consideration. For creep modelling, the activation energy concept [11-14] was employed. The interaction between creep and micro-cracking was firstly simulated at meso-scale where concrete is considered to be a three-phase material and to continuously hydrate. Then, on top of that, the self-healing phenomenon was simulated in order to explore the effect on the long-term creep.

2. MODIFIED LATTICE MODEL

Lattice models are widely used for modelling fracture processes of multiphase materials. The structure of the material is schematised as a lattice network of Timoshenko beam elements, which can transmit axial forces, shear forces, bending moments and torsional moments, as shown in Fig.1.

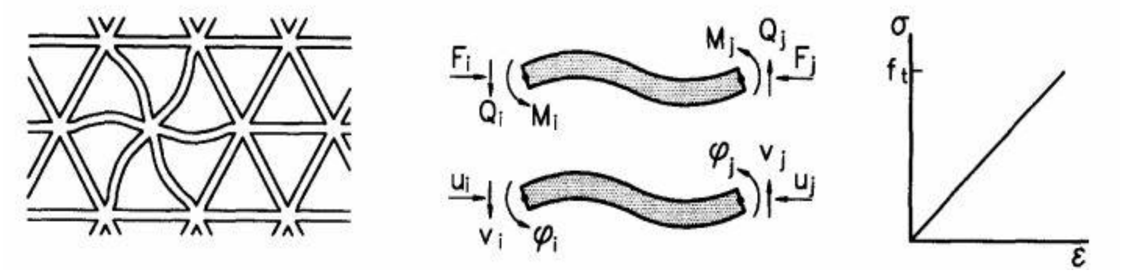
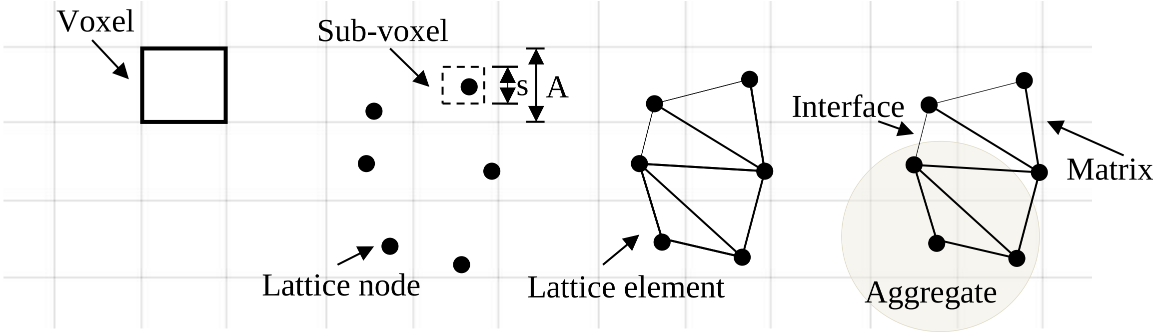


Fig.1 (a) Regular triangular lattice of beams, (b) external forces and deformations on a single beam element, and (c) stress-strain relation for an element [9]

In the 2D lattice approach, the meso-structure of concrete is considered as a composite including three phases: *aggregate* is modelled as disks surrounded by the *interface* and embedded in the bulk mortar *matrix*. The procedure for the discretization of the meso-structure is shown in Fig.2. The aggregate was generated randomly in the sample with dimension 100mm×100mm and mesh size 0.5mm. The aggregate distribution complies with the Fuller's curve. The maximum aggregate diameter is 16mm. Aggregate particles with diameters smaller than 2mm are excluded from the generated aggregate structures, since it is suggested that the smallest diameter should be two or three times larger than the mesh size. The minimum distance between the centre of two particles can guarantee the minimum distance of $1.1 * (d_A + d_B)/2$ suggested by Hsu [18]. The generated aggregate volume is 50% after overlay procedure (Fig.2d). The final meso-structure of concrete is shown in Fig.3.



(a) Voxel generation (b) Node placement (c) Lattice generation (d) Overlay procedure
Fig.2 Schematics of the generation of meso-structure of concrete

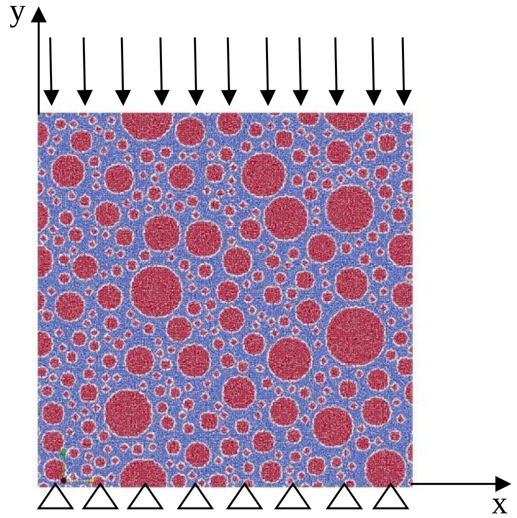


Fig.3 Meso-structure of concrete and boundary conditions

In this study, the original lattice model [9-10], which is mainly used for fracture simulations, was modified by taking creep of individual beams into consideration. The creep rate is calculated by activation energy concept (Eq.1). Under the condition of low stresses and logarithmic evolution of activation energy, Eq.1 can be further simplified into Eq.2 [14]. Creep strains (Eq.3) are obtained by solving Eq.2 based on Euler's method.

$$\dot{\varepsilon}^{cr} = C \cdot e^{-\frac{Q}{RT}} \cdot \sinh(b \cdot \sigma) \quad (1)$$

$$\dot{\varepsilon}^{cr} = a \cdot t^{-m} \cdot \sigma \quad (2)$$

$$\varepsilon_{i+1}^{cr} = a \cdot (t_i + \Delta t)^{-m} \cdot \sigma_i \cdot \Delta t + \varepsilon_i^{cr} \quad (3)$$

where C is constant and a is an empirical ageing factor; Q is activation energy; b is related to activation volume; σ is local stress in a beam.

In the first step ($i = 0$; $t_0 = 0$; $\varepsilon_0^{cr} = 0$), only an external load is considered at the top of the sample and stresses are distributed among the beams. In the following steps creep strains of the beams, which are supposed to creep at $i + 1$ step, are calculated based on local stresses and creep strains at i step (Eq.3) and are converted into local axial forces f_{i+1}^{cr} (Eq.4). It should be noted that only mortar and bond beams are creeping, whereas aggregate beams are assumed to perform linear elastically. The local axial forces are applied to the mortar and bond beams, as shown in Fig.4, together with the constant external force applied to the whole sample (Fig.3). Due to the heterogeneity of the materials, local stress concentration will occur. Once the stress in a beam exceeds its strength, it will be removed from the lattice network and its axial force will be released. Other beams, initially connected to the broken beams, are less restrained. However, due to the existence of the external load, it is plausible that stresses in the surviving beams will be redistributed. This is realized by keeping the external load at the top of the sample and executing one more step without changing the time step (i.e., $f_{i+1}^{cr} = 0$ in Fig.4). Then the creep deformation calculated by these stresses in next step will be larger. This will further influence the development of micro-cracking. Finally, the apparent deformation taking into account the interaction between creep and micro-cracking are obtained. The constitutive equation can be written as Eq.5.

$$f_{i+1}^{cr} = \varepsilon_{i+1}^{cr} \cdot E \cdot A \tag{4}$$

$$\sigma = E(\varepsilon - \varepsilon^{cr}) \tag{5}$$

where E is the elastic modulus [MPa] and A the cross section [mm^2] of the beams.

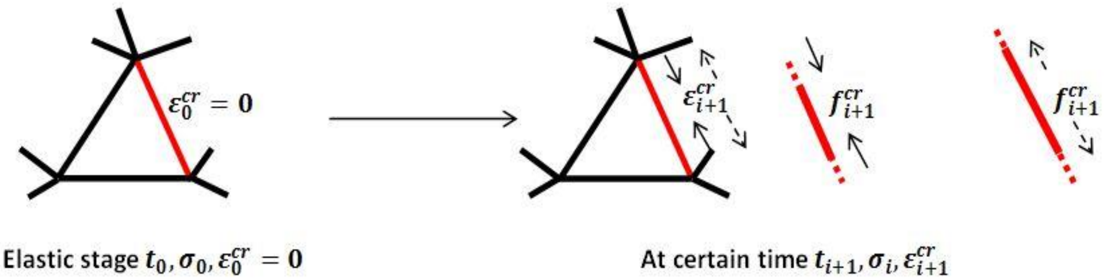


Fig.4 Creep deformation and local axial force of an individual mortar or bond beam (Arrow on the right side means creep can be tensile or compressive creep, depending on the sign of stress in the beam)

3. SIMULATION RESULTS

The initial local mechanical properties for mortar, bond and aggregate beams are $E_{agg} = 50$ GPa, $E_{mor} = E_{bond} = 25$ GPa; $f_{t,agg} = 24$MPa, $f_{t,mor} = 9$MPa, $f_{t,bond} = 3$MPa; $f_{c,agg} = -240$MPa, $f_{c,mor} = -90$MPa, $f_{c,bond} = -30$MPa; Poisson's ratio is 0.24. The boundary conditions for both compressive strength and creep simulations are free boundaries, i.e. translation Y is fixed for the nodes at the bottom and translation X and rotation XY are allowed for nodes on the top and at the bottom, as shown in Fig.3. In order to involve shear effects during compression, when the stress in a beam exceeds its strength for the first time, the shear and bending stiffness of the beam are set to 0. When the stress exceeds the strength for the second time, the axial stiffness is set to 0 [19]. The compressive strength and elastic modulus were simulated and the results are 36.26 MPa and 32.84 GPa. Then, with constant stress level of 30% of compressive strength, a compressive creep test was simulated. It should be noted that only basic creep (i.e. 100% humidity) at room temperature is considered in this study.

3.1 Effect of on-going hydration

As mentioned in the beginning, it has been reported that compressive strength and elastic modulus continuously increase under sustained loads. As suggested in [20], continuous hydration of the concrete must be considered in the simulations. However, there is no consensus on how much the strength and elastic modulus increase under certain load level within a certain period. Furthermore, how the degree of hydration increased with time is also not quantified explicitly in the reported studies. Here, for the sake of simplicity, the evolution of the compressive strength and elastic modulus are assumed as a function of time instead of degree of hydration. The relevant data from Brooks' test [17] were referred to. In his test, the compressive strength and elastic modulus of the loaded specimens after 30 years are reported to increase substantially, by 67% and 83% respectively, compared with the strength and elastic modulus at age of loading (14 days). It is assumed that the global strength and elastic modulus after 30 years increase by the same amount as Brook's test. Besides, the increase in local strength and elastic modulus for mortar and bond beams after 30 years is also assumed to be proportional to the one in global strength and elastic modulus. In order to consider different hydration rates, several power and logarithmic functions are employed, as shown in Eq.6 and 7. An example of how the elastic modulus develops according to these functions within a period of 100 years is shown in Fig.5a.

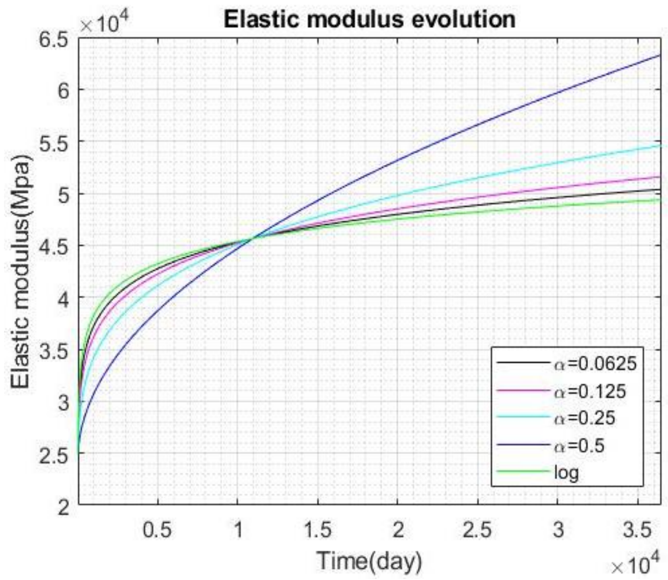
The modelling procedure for the effect of on-going hydration is similar to what has been introduced before. The additional thing is that strength and elastic modulus of local mortar and bond beams have to be updated at each time step, following Eq.6 or 7. After the creep strains of local beams have been calculated (Eq.3), elastic modulus (and shear modulus) of local beams has to be updated firstly in order to calculate local axial forces (in Eq.4: $E = E_{i+1}$) and the element stiffness. Then, after the application of local axial forces and external force, the obtained stresses of local beams are compared with their updated strength to determine broken beams. If there are no broken beams, the calculation will go to the next time step; once any beams are broken and removed from the system, only an external load will be applied at the top of the sample and one more step will be executed without updating time steps, elastic modulus and strength. The simulated results on the interaction between creep and micro-cracking with different hydration rates are shown in Fig.5b. Simulations without micro-cracking (pure creep) were also performed. Only the one with strength and elastic modulus following the logarithmic function is presented in Fig.5b.

$$f_c(\mathrm{t})\ or E(t) = A\ln(t) + B \tag{6}$$

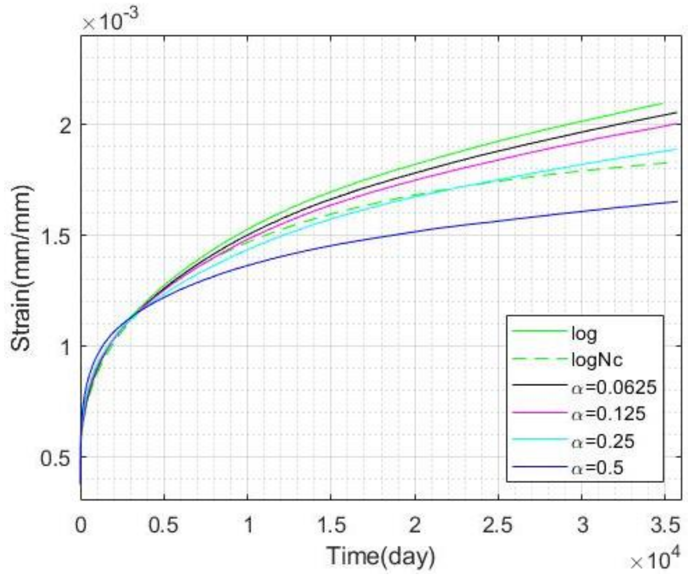
or

$$f_c(\mathrm{t})\ or E(t) = \ At^{\alpha} + B \tag{7}$$

where $f_c(\mathrm{t})$ and $E(t)$ are compressive strength and elastic modulus of mortar or bond beams; A and B are constants; α is set as 0.0625, 0.125, 0.25 and 0.5 in order to consider different hydration rates. The local tensile strength is 0.1 times the local compressive strength.



(a)



(b)

Fig.5 (a) Evolution of local elastic modulus; (b) Interaction between creep and micro-cracking considering different hydration rates (Time means loading duration; 'log' means elastic modulus and strength follow the logarithmic function (Eq.6); Nc means no micro-cracking)

As shown in Fig.5b, the evolution of strength and elastic modulus of local beams influences the creep rate. The smaller the strength and elastic modulus are, the higher the creep is. Despite different hydration rates, an extra deformation does appear in the simulations for interaction between creep and micro-cracking, compared with the results of pure creep. This is contributed by micro-cracking. Although material keeps hardening, locally micro-cracks still occur, which enlarges creep in return and thus creates more micro-cracks in the next step; finally an extra overall deformation occurs. At 100 years, micro-cracking results in 12%-15% extra deformation for different hydration rates considered in this paper, as shown in Fig.6. With continuous micro-cracking, the global compressive strength and elastic modulus after 30 years are also lower than the assumed values, i.e., they will never gain the 67% and 83% increase in strength and elastic modulus after 30 years. The simulated compressive strength and elastic modulus at 30 years decreases by 13% and 6% respectively, compared the simulated ones without micro-cracking at 30 years (following the logarithmic function Eq.6). The situation will be more severe after 100 years or under higher stress levels.

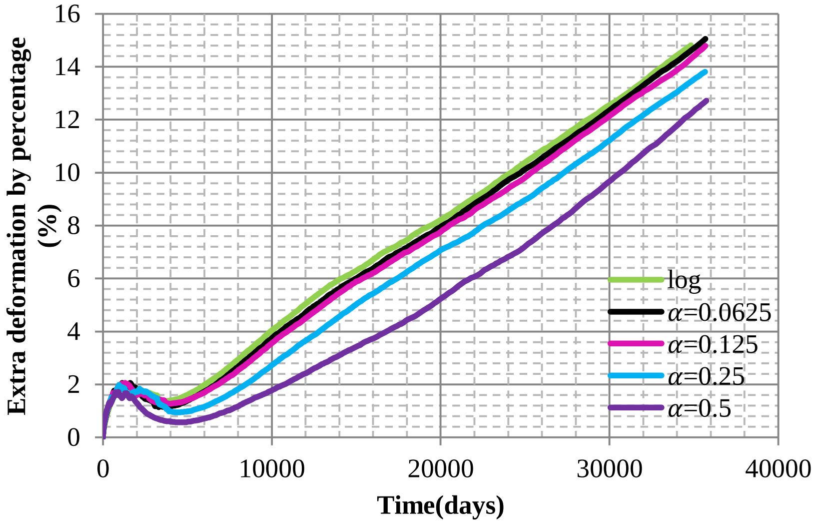


Fig.6 Extra deformation due to micro-cracking in the long term [extra deformation by percentage = (deformation with micro-cracking – deformation without micro-cracking) / deformation without micro-cracking]

3.2 Effect of self-healing

The deviation from the pure creep and decrease of global strength and elastic modulus make it clear that other mechanisms need to be considered. The mechanisms are supposed to prevent larger deformation and to recover strength and elastic modulus during the long-term creep process. Self-healing could be a promising one, as have been mentioned by several researchers [2-3,21]. The increase of compressive strength and elastic modulus in the experiments mentioned before could be a consequence of the equilibrium between micro-cracking and self-healing. That is to say, once micro-cracking occurs locally, self-healing is able to make up for the loss in strength and elastic modulus due to these micro-cracks with widths of a few micrometres. In this case, the mechanical properties could possibly gain the 67% and 83% increase after 30 years, as assumed before. Based on this hypotheses, the self-healing effect during creep process was modelled in the modified lattice model. The modelling procedure is still similar to what has been introduced before. The only difference is that the broken beams are firstly removed from the system at time step *i* and then will be restored in a *stress free* condition at the next step. The local mechanical properties of these restored beams follow Eq.6 or 7. The complete modelling procedure (including micro-cracking, on-going hydration and self-healing) is present in the Appendix. One result is shown in Fig.7.

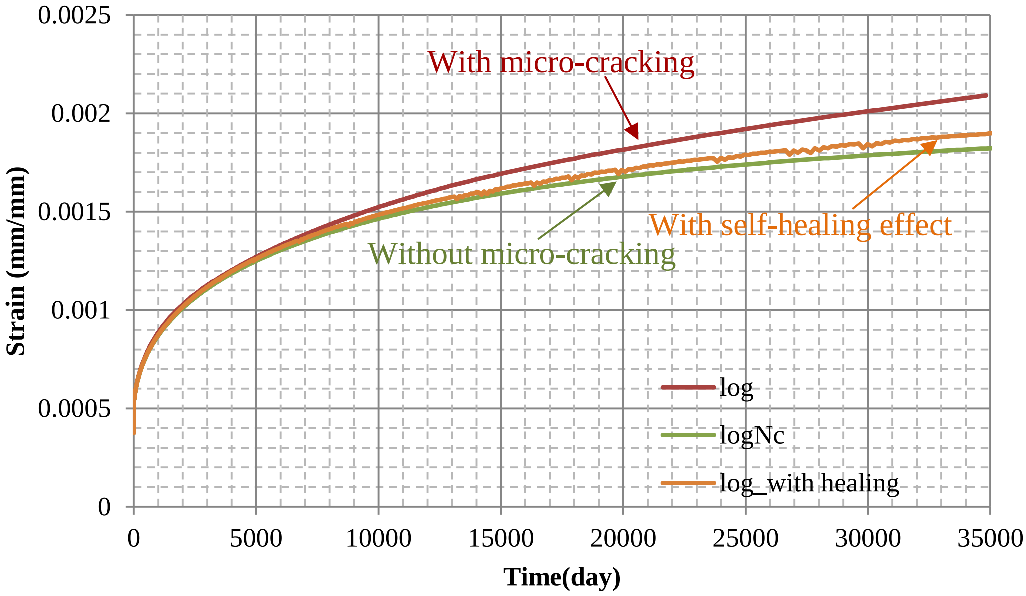


Fig.7 Effect of self-healing during the long term creep process (local mechanical properties follow Eq.6)

As shown in Fig.7, if the self-healing effect is considered, the long-term global strain (orange curve) gets closer to the one without micro-cracking (green curve). There is a small deviation between the two curves. This is because self-healing of broken beams leads some other beams to break locally at each time step. Once there are broken beams, they are restored in a stress free condition. After the application of load (external and local load), these restored beams start to carry load and to creep again. In this process, stress concentration still occurs locally and so does micro-cracking. On the whole, the results suggest the above hypotheses is reasonable, i.e., under long-term sustained load local stress concentrations leads to micro-cracking which can be healed (or: restored) subsequently due to autogenous self-healing. In this case, continuous micro-cracking is avoided and the extra deformation due to micro-cracking decreases dramatically. Besides, self-healing effect can make up for the loss in strength and elastic modulus due to micro-cracking. The simulated 30-year strength and elastic modulus with self-healing effect are only 1.2% and 0.7% lower respectively than the ones without micro-cracking at 30 years (with on-going hydration). Micro-cracks tend to be 'stabilized' mainly in bond area with stress level prior to 40% of compressive strength, as observed by some researchers [4-5].

4. CONCLUSIONS

In this paper a lattice model with extended features is presented, which takes creep into account. The model is able to consider different mechanisms during the creep process: on-going hydration, micro-cracking and self-healing. With respect to the influence of micro-cracking and self-healing on the long-term creep of concrete, it can be concluded that:

– Under long-term sustained load (low stress levels), concrete continues to harden, which is in accordance with experimental observations. However, due to heterogeneity, local stress concentrations and micro-cracking occur. This, in return, enlarges the creep deformation. Despite continuous hydration of the material, this interaction will eventually lead to an extra overall deformation and degradation of mechanical properties of concrete materials.

- The outcome of self-healing modelling shows that the continuous micro-cracks are closed and the extra deformation is reduced through autogenous self-healing of the micro-cracks. Also, the loss in strength and elastic modulus due to micro-cracking can be recovered by self-healing. To some extent, it proves the general observation that micro-cracks stay stable in the bond area under relatively low stress levels.
- One of the final aims of this research is to predict long-term creep without simple fitting but with considering different possible mechanisms during creep process. In order to make the prediction reliable, comparison with long-term experimental creep data is necessary in the following studies.

APPENDIX

Set $i = 0$; $t_0 = 0$; $\varepsilon_0^{cr} = 0$;
Apply external load and stresses of local beams σ_0 are obtained;
1: calculate creep strain of local mortar and bond beams;

$$\varepsilon_{i+1}^{cr} = a \cdot (t_i + \Delta t)^{-m} \cdot \sigma_i \cdot \Delta t + \varepsilon_i^{cr}$$

Update elastic modulus and strength of local beams;
Calculate local axial forces of local beams;

$$f_{i+1}^{cr} = \varepsilon_{i+1}^{cr} \cdot E_{i+1} \cdot A$$

Broken elements from i step are restored with mechanical properties following Eq.6 or 7;
Apply external load together with local axial forces and local stresses of local beams are obtained;

$$\sigma_{i+1} = E_{i+1}(\varepsilon_{i+1} - \varepsilon_{i+1}^{cr})$$

If local stresses exceed strengths of beams, these beams are removed from the system, go to 2; if not, go to 3;
2: Only external load is kept on the top of the sample and one more step is executed; despite any occurrence of micro-cracks, go to 3;
3: if $t < t_{critical}$; set $i \coloneqq i + 1$, go to 1;
else finish;

ACKNOWLEDGEMENTS

The authors would like to acknowledge the financial support of China Scholarship Council.

REFERENCES

[1] Bažant, Z.P., Yu, Q. and Li, H. 'Excessive Long-Time Deflections of Prestressed Box Girders. I: Record-Span Bridge in Palau and Other Paradigms; II: Numerical Analysis and Lessons Learned', J. Struct. Eng. **138**(6) (2012) 676-696.

[2] Rossi, P., Tailhan, J.L., Le Maou, F., Gaillet, L. and Martin, E. 'Basic creep behaviour of concretes investigation of the physical mechanisms by using acoustic emission', Cem Concr Res. **43**(2012) 61-73.
[3] Rossi, P., et al..'Investigation of the basic creep of concrete by acoustic emission', Mater. Struct **27** (1994) 510-514.
[4] Carpinteri, A., Ingraffea, A.R., 'Fracture mechanics of concrete: Material characterization and testing', Volume 3 of Engineering application of fracture mechanics (The Hague, The Netherlands, 1984).
[5] Chen, W.F., 'Plasticity in reinforced concrete', McGraw-Hill edition (New York, Unite States, 1982).
[6] Coutinho, A.S., 'A contribution to the mechanism of concrete creep', Matériaux et Construction**10**(1)(1977) 3-16.
[7] Freudenthal, A.M., Roll, F., 'Creep and creep recovery of concrete under high compressive stress', ACI Proceedings **55**(1958) 1111-1142.
[8] Washa, G.W., Fluck, P.G., 'Effect of sustained loading on compressive strength and modulus of elasticity of concrete',ACI Proceedings **46**(1950) 693-700.
[9] Schlangen, E., 'Experimental and numerical analysis of fracture processes in concrete', PhD thesis, Delft University of Technology(Delft, The Netherlands, 1993).
[10] Qian, Z., 'Multiscale modelling of fracture processes in cementitious materials'. PhD thesis, Delft University of Technology(Delft, The Netherlands, 2012).
[11] Wittmann F., 'Kriechen bei gleichzeitigem schwinden des zementsteins', Rheol. Acta. **5**(3) (1966) 198-204.
[12] Wittmann, F., 'Kriech messungen an Zementstein', Rheol. Acta. **6**(4) (1967) 303-306.
[13] Wittmann, F. and Klug, P. 'Zum zeitlichen Verlauf des Kriechens von Zementstein und Beton', Rheol. Acta. **7**(1) (1968) 93-95.
[14] Wittmann,F.'Bestimmung Physikalischer Eigenschaften des Zementsteins', Heft 232(Berlin,1974).
[15] van Breugel, K. 'Relaxation of young concrete', Report-5-80-D8, Delft University of Technology (Delft, The Netherlands, 1980).
[16] Brooks, J.J. and Neville, A.M., 'Estimating long-term creep and shrinkage from the short-term tests', Magazine of Concrete Research **27**(90) (1975)3-12.
[17] Brooks, J.J., '30-year creep and shrinkage of concrete', Magazine of Concrete Research **57**(9) (1975)545-556.
[18] Hsu T.T.C., 'Mathematical Analysis of Shrinkage Stresses in a Model of Hardened Concrete', Journal of ACI **60**(3) (1963)371-390.
[19] Abreu M.M., Lemos J.V.,Carmeliet J. and Schlangen E., 'Modelling compressive cracking in concrete by a modified lattice model', FraMCoS-6: Fracture Mechanics of Concrete and Concrete Structures, At Catania, Italy, 2007.
[20] Sawko, F., Saha, G.P., 'Fatigue of concrete and its effect upon prestressed concrete beams', Magazine of Concrete Research **20**(62)(1968) 21-30.
[21] Hughes, B.P., ASH, J.E., 'Some factors influencing the long term strength of concrete', Matériaux et Construction **3**(14)(1970) 81-84.