On modelling the influence of creep on corrosion-induced cracking in reinforced concrete

I. Aldellaa[1*] , P. Havlásek[2] , M. Jirásek[2] and P. Grassl[1]

[1] University of Glasgow, Glasgow, UK

[*]ismail.aldellaa@glasgow.ac.uk, peter.grassl@glasgow.ac.uk

[2] Czech Technical University in Prague, Czechia

petr.havlasek@cvut.cz, milan.jirasek@fsv.cvut.cz

Abstract

Naturally occurring corrosion rates in reinforced concrete are so low that rust accumulates often over tens of years near the surface of the reinforcement bars before sufficient pressure in the surrounding concrete is generated to induce cracking in the concrete cover. To speed up the process in laboratory tests, corrosion setups with impressed currents are used in which the corrosion rate is controlled so that cracking of the concrete cover occurs within a few days. Extrapolating the results of these accelerated tests to those of naturally occurring corrosion requires an understanding of the influence of long-term creep deformations of concrete on the corrosion induced cracking process. In mathematical models in the literature, creep deformations are often ignored for accelerated but considered for natural corrosion rates in the form of a constant creep coefficient, which is used to reduce the Young modulus of concrete. In this work, two numerical models are proposed to investigate the effect of creep on corrosion-induced cracking. The first approach is based on an elastic axisymmetric thick-walled cylinder combined with a plastic limit on the circumferential stress. The second model uses a three-dimensional lattice (network) approach to discretise the thick-walled cylinder.

Key words: *Reinforced concrete; Corrosion-induced cracking; Creep; Thick-walled cylinder;*

1 Introduction

Corrosion induced cracking is the main deterioration process in reinforced concrete structures (Broomfield, 1997). Corrosion is commonly initiated once the passive layer around the reinforcement is lost either due to carbonation of the concrete or ingress of chlorides. Once corrosion has been initiated, expansive corrosion products accumulate adjacent to surface of steel bars. This results in radial pressure on the concrete, which can cause surface cracking and spalling of the concrete cover (Tuutti, 1982). It is important to develop predictive modelling techniques for corrosion induced cracking so that maintenance and repair of structures can be carried out cost-effectively. Naturally occurring corrosion rates in reinforced concrete structures are so low that corrosion products can accumulate for years before cracks are observed (Broomfield, 1997). Therefore, corrosion is often accelerated in laboratories by impressing a current (Andrade et al., 1993) so that cracking occurs after a few days. The results of these accelerated tests cannot be immediately extrapolated to applications with natural corrosion rates because factors such as the composition and migration of corrosion products into voids and cracks, as well as the deformation of the surrounding concrete are corrosion rate dependent. For the deformations in the surrounding concrete, a potential source of the corrosion rate dependence is linear creep (Alonso et al., 1998). The aim of the present study is to investigate the importance of modelling creep for predicting corrosion induced cracking. Only basic creep is considered, i.e. the creep due to drying and temperature changes is not taken into account.

2 Methodology

The influence of corrosion rate on the cracking process is studied by means of two mathematical models of the mechanical response of a thick-walled cylinder. The wall thickness of the cylinder represents the concrete cover of a reinforcement bar located close to the surface of a reinforced concrete specimen (Tepfers, 1979). The corrosion products are assumed to be uniformly distributed around the reinforcement bar. The first model combines plane stress elasticity assuming axisymmetry (Timoshenko and Goodier, 1987) with a plastic limit on the circumferential stress (Bažant, 1979). In this model, the reinforcement bar itself is not modelled. Instead, a radial outwards displacement is prescribed at the inner boundary of the cylinder to model the radial expansion due to the formation of the corrosion products. Creep is modelled by using for Young's modulus of concrete the approximate Age Adjusted Effective Modulus (AAEM), which is described in Example 4.5 in Bažant and Jirásek (2018). Dependence of tensile strength on concrete age is modelled using the fib Model Code 2010 expression. The second model uses a three-dimensional lattice approach presented earlier in Grassl and Davies (2011); Athanasiadis et al. (2018),

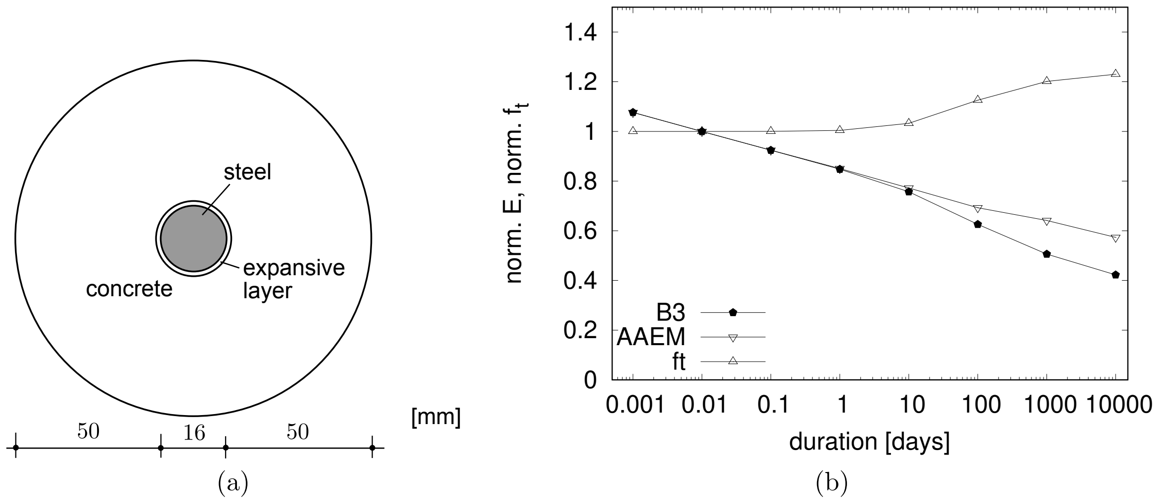


Figure 1: (a) Geometry of the thick-walled cylinder. The out-of-plane thickness is 10 mm. (b) Effective Young's modulus obtained from the lattice approach, AAEM used in the axisymmetric model and tensile strength as a function of time. The moduli and tensile strength are normalised by their short term values at 28 days.

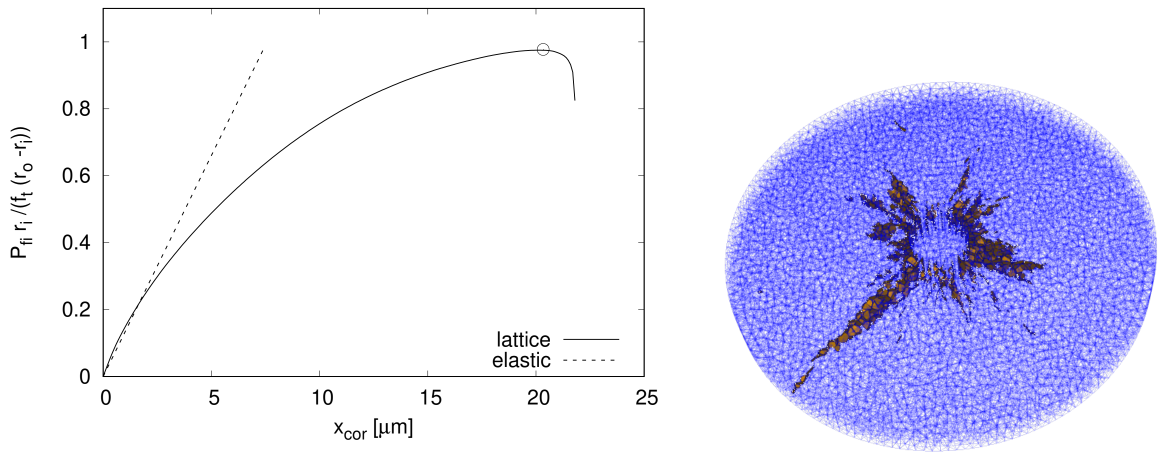
which is based on the concept of rigid body spring networks (Yip et al., 2005). Autocorrelated random fields for tensile and compressive strengths are used to represent the meso-structure of concrete. Creep is modelled using the microprestress-solidification theory (MPS) implemented in OOFEM (Jirásek and Havlásek, 2014), which for basic creep provides a material response which is identical to the basic creep compliance function of the B3 model (Bažant and Baweja, 1995). Again, fib Model Code 2010 is used to model the age dependent tensile strength.
The geometry of the thick-walled cylinder used in this study is shown in Figure 1a. The radius of the reinforcement bar is $r_{\mathrm{i}} = 8$ mm and the outer radius of the concrete cylinder is $r_{\mathrm{o}} = 58$ mm, which corresponds to a concrete cover of 50 mm. The out-of-plane thickness of the specimen is 10 mm. For the axisymmetric model, plane-stress conditions are assumed. The ratio of the corrosion penetration (loss of steel) layer dx_{cor} in μm over time dt in days is linked to the corrosion rate i_{cor} in μA/cm^2 as

$$dx_{\mathrm{cor}}/dt = 0.0315 i_{\mathrm{cor}} \quad (1)$$

where 0.0315 is a factor to convert μm/day into μA/cm^2 as stated in Molina et al. (1993). In the analysis, it is assumed that the corrosion penetration layer dx_{cor} is so thin that it is acceptable to calculate the radial expansion as $du_{\mathrm{cor}} = (\alpha - 1) dx_{\mathrm{cor}}$ where an expansion factor of $\alpha = 2$ is used, as in many studies before. Therefore, $du_{\mathrm{cor}} = dx_{\mathrm{cor}}$.

3 Analyses

Analyses with the elastic-axisymmetric and lattice models for different corrosion rates $i_{\mathrm{cor}} = 0.1$, 1, 10, 100, 1000 and 10000 μA/cm^2 are performed to determine the amount of corrosion penetration at which the strength of the thick-walled cylinder is reached. For all analyses, corrosion starts at 28 days. Here $i_{\mathrm{cor}} = 100$ μA/cm^2 is a typical corrosion rate of accelerated tests for which cracking is reached within a few days, whereas $i_{\mathrm{cor}} = 0.1$ μA/cm^2 is a low corrosion rate typical for naturally occurring corrosion with cracking occurring after several years. The parameters of the two models were calibrated so that a tensile strength of $f_{\mathrm{t}} = 3$ MPa and a Young's modulus of $E = 30$ GPa was obtained for short term loading at 28 days. For the axisymmetric model, the results are obtained in the form of the critical inner radial displacement (which is equal to the critical corrosion penetration) which results in failure of the cylinder. The lattice model, which is based on a three-dimensional discretisation of the thick-walled cylinder provides detailed information about crack patterns and force distributions at different stages of the analysis. Since the lattice model uses random fields to represent the meso-structure of concrete, six simulations for each corrosion rate are performed. In Figure 2, the results of one of these random simulations for $i_{\mathrm{cor}} = 100$ μA/cm^2 are shown in the form of a) normalised average pressure versus



(a) (b)

Figure 2: (a) Normalised average pressure versus corrosion penetration curve of one random analysis for $i_{\rm cor} = 100\ \mu{\rm A/cm}^2$ for the lattice model and the elastic response for the axisymmetric model. (b) Crack patterns for the stage marked in (a). The coloured mid-crosssections indicate elements with an equivalent crack width $\bar{w}_{\rm c} > 2\ \mu{\rm m}$.

corrosion penetration and b) crack patterns at peak pressure. The peak of the pressure versus crack penetration curve is taken as the strength of the thick-walled cylinder for which the critical corrosion penetration is reached.
The influence of creep is presented in Figure 3 in the form of the critical corrosion penetration, i.e. the corrosion penetration at the strength of the cylinder, versus the corrosion rate.

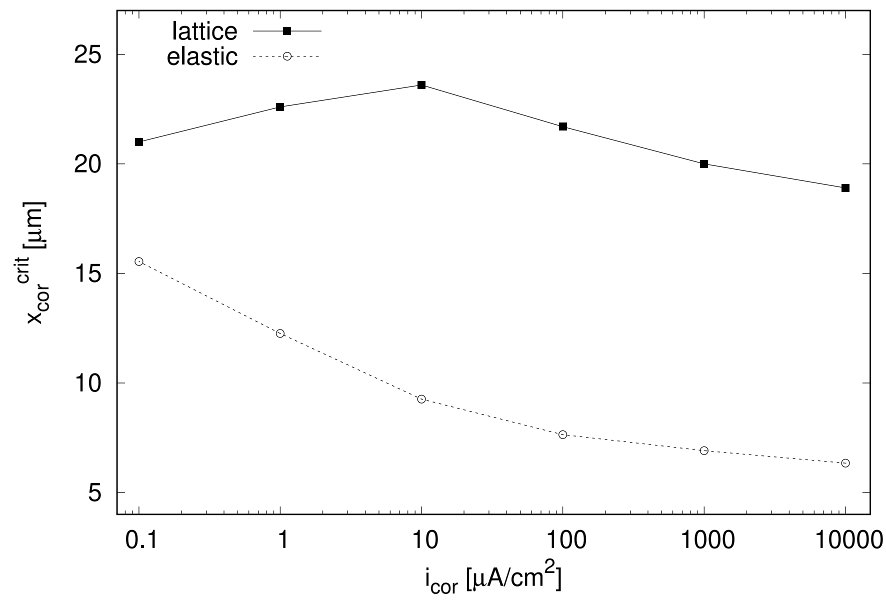


Figure 3: Critical corrosion penetration versus corrosion rate for lattice and elastic model.

From the results it can be seen that the axisymmetric model with its elastic pre-peak response shows a strong dependence of the critical corrosion penetration on the corrosion rate. The critical corrosion penetration at an accelerated rate of $i_{\rm cor} = 100\ \mu{\rm A/cm}^2$ is only half of the penetration at a natural rate of $i_{\rm cor} = 0.1\ \mu{\rm A/cm}^2$. However, for the three-dimensional lattice model, which exihibts a strongly nonlinear response in the pre-peak, the corrosion rate has a very small influence on the corrosion penetration.

4 Conclusions

Investigating the influence of creep on the prediction of corrosion induced cracking has shown that the importance of creep depends strongly on the type of modelling used. For an axisymmetric model with elastic pre-peak response creep has a strong effect on the critical corrosion penetration. For low corrosion rates, the critical corrosion penetration is significantly greater than for high corrosion rates. On the other hand, for the lattice model, the critical corrosion penetration is similar for low and high corrosion rates.

Acknowledgements

Ismail Adellaa acknowledges the financial support from the Ministry of Higher Education - Libya. The lattice simulations were performed with the finite element program OOFEM (Patzák, 2012).

References

Alonso, C.; Andrade, C.; Rodriguez, J., and Diez, J. Factors controlling cracking of concrete affected by reinforcement corrosion. *Materials and Structures*, 31(7):435–441, 1998.

Andrade, C.; Alonso, C., and Molina, F. J. Cover cracking as a function of bar corrosion: Part I-Experimental test. *Materials and Structures*, 26(8):453–464, 1993.

Athanasiadis, I.; Wheeler, S. J., and Grassl, P. Hydro-mechanical network modelling of particulate composites. *International Journal of Solids and Structures*, 130–131:49–60, 2018.

Bažant, Z. P. and Jirásek, M. *Creep and hygrothermal effects in concrete structures*, volume 38. Springer, 2018.

Bažant, Z. P. Physical model for steel corrosion in concrete sea structures: theory. *Journal of the Structural Division, ASCE*, 105(6):1137–1153, 1979.

Bažant, Z. P. and Baweja, S. Creep and shrinkage prediction model for analysis and design of concrete structures – model B3. *Materials and Structures*, 28:357–365, 1995. RILEM Recommendation, in collaboration with RILEM Committee TC 107-GCS, with Errata, Vol. 29 (March 1996), p. 126.

Broomfield, J. P. *Corrosion of steel in concrete: understanding, investigation and repair*. Taylor & Francis, 1997.

Grassl, P. and Davies, T. Lattice modelling of corrosion induced cracking and bond in reinforced concrete. *Cement and Concrete Composites*, 33:918–924, 2011.

Jirásek, M. and Havlásek, P. Accurate approximations of concrete creep compliance functions based on continuous retardation spectra. *Computers and Structures*, 135:155–168, 2014.

Molina, F.; Alonso, C., and Andrade, C. Cover cracking as a function of rebar corrosion: Part II-numerical model. *Materials and Structures*, 26(9):532–548, 1993.

Patzák, B. OOFEM – An object-oriented simulation tool for advanced modeling of materials and structure. *Acta Polytechnica*, 52:59–66, 2012.

Tepfers, R. Cracking of concrete cover along anchored deformed reinforcing bars. *Magazine of Concrete Research*, 31(106):3–12, 1979.

Timoshenko, S. P. and Goodier, J. N. *Theory of elasticity*. McGraw-Hill, New York, 1987.

Tuutti, K. Corrosion of steel in concrete. Doctoral thesis, Swedish Cement and Concrete Research Institute, 1982.

Yip, M.; Mohle, J., and Bolander, J. E. Automated Modeling of Three-Dimensional Structural Components Using Irregular Lattices. *Computer-Aided Civil and Infrastructure Engineering*, 20(6):393–407, 2005.