CREEP CRACKING AND RUPTURE OF CONCRETE SPECIMENS IN BENDING

F. P. Zhou*

A series of tests was carried out on notched beams of plain concrete subjected to high sustained loads. The experimental creep curves exhibit three stages and the creep rate decreases first and then keeps constant, lastly increases very fast until failure. The secondary creep rate seems to be a better predictor for rupture life than sustained load level. A nonlinear time-dependent crack model has been applied to analyzing the flexural creep rupture tests. The simulated deflection, CMOD and creep rupture relations seem to agree reasonably with the experimental results. Furthermore, the model can also describe the profile of stress distribution in fracture process zone.

INTRODUCTION

Fracture of concrete is characterized by a large fracture process zone in front of a crack. Therefore it is generally agreed that Linear Elastic Fracture Mechanics cannot be directly applicable to fracture behaviour of concrete materials. Being able to properly account for inelastic behaviour of this zone, the Fictitious Crack Model (FCM) proposed by Hillerborg et al. (1), one of the most successful models, has been applied to study fracture of laboratory sized specimens of concrete. The time-dependent effect has, however, not been taken into account in those models.

In order to find an appropriate way to treat the time-dependent fracture, both experimental tests and theoretical modelling were conducted by the author. Some results will be briefly present below. Further details can be found in the dissertation by Zhou (2).

* Division of Building Materials, Lund Institute of Technology
221 00 Lund, Sweden

EXPERIMENTS

The water-cement ratio of concrete is 0.55. The maximum size of aggregate is 4 mm. The 28-day's strength is 38 MPa. Beams of dimensions 100*100*840 mm were casted and stored in a water tank until testing. Specimens at testing were average 3 month old. A 50 mm notch was sawed by a diamond saw for each beam. Beams were wrapped with plast to protect them from drying cracking under testing.

All the tests were carried out using the MTS closed loop system. Crack moth opening was measured by means of a couple of clip gauges. In each test series three beams were loaded to determine static load-crack opening and load-deflection curves. It took about one minute to reach the ultimate load. The ultimate load was calculated from the average value of the three tests. Then three sustained tests were carried out for each load level (form 0.76 to 0.92). Deflection, CMOD were registered with time.

THEORETICAL BASIS

In analyzing creep fracture of metals, two approaches are often used: stress intensity factor for brittle and net stress for plastic creep. For non-yielding materials like concrete these two parameters have very limited use because of a large, softening fracture process zone. Since the Fictitious Crack Model has been proven to be very successful to predict static fracture of concrete structures, it is natural to develop a time-dependent crack model based on the similar principle of FCM. This model has been described in Zhou (2), Zhou and Hillerborg (3).

The model consists of a modified Maxwell rheological element combined with static stress deformation curve as a crack criterion. The time-dependent incremental σ-w law (Figure 1) is expressed as:

$$\delta\sigma=\delta\sigma^{R}+\delta\sigma^{I} \qquad (1)$$

where $\delta\sigma^{R}$ and $\delta\sigma^{I}$ are stress changes due to relaxation and deformation increment δw respectively during time increment δt. The stress relaxation is assumed to be

$$\delta\sigma^{R}=(\sigma_{i}-\alpha\sigma_{0})\,(\exp(-\delta t/\tau)-1) \qquad (2)$$

where α is a constant, σ_0 is corresponding w^{I} in the static σ-w curve and τ is relaxation time. The stress change due to deformation increment is given as

$$\delta\sigma^{I}=\frac{\sigma_{i}+\delta\sigma^{R}}{w_{i}}\,\frac{\exp(-\delta t/\tau)+1}{2}\,(w_{i+1}-w_{i}) \qquad (3)$$

for $w_{i+1} \leq w_B$ and

$$\delta\sigma^I = \frac{\sigma_i + \delta\sigma^R}{w_i} \frac{\exp(-\delta t/\tau)+1}{2}(w_B - w_i) + \frac{d\sigma^0(w_B)}{dw}(w_{i+1} - w_B) \tag{4}$$

for $w_{i+1} > w_B$; here $\sigma^0(w)$ is the static σ-w curve.

RESULTS AND DISCUSSIONS

Experiment Results

Figure 2 shows the experimental creep curves at various sustained load levels. The creep rate decrease in the primary part of each curve, then keep almost constant in the secondary part. In the tertiary stage creep rate increases very fast until failure. The secondary part dominates the whole failure process.

The sustained load and secondary creep rate are plotted in Figures 3 and 4 respectively against rupture life. There are less scatters in the secondary creep rate-rupture life curve (Figure 4) than the load-rupture life curve. It seems the secondary creep rate may be a better parameter than load level concerning prediction of rupture life in creep rupture tests.

Numerical Simulations

The time-dependent crack model has been implemented in a finite element program and applied to simulating the flexural creep tests. Material properties of concrete used are tensile strength f_t=2.8 MPa, modulus of elasticity E=36 GPa, fracture energy G_F=82 Nm/m^2, relaxation time τ =25 s, α=0.7. The static σ-w curve is assumed to be bi-linear. In numerical simulations the following procedure is used. In each time increment, stress relaxation in fracture process zone is evaluated according to Equation 2 and then a pseudo load calculated from the stress relaxation is imposed on the beam, and deformation increments can be evaluated. In this way a beam subjected to a sustained load is simulated until creep rupture occurs.

In Figure 5 the experimental and simulated creep curves are compared. The sustained load level is 0.80. It seems that the theoretical curve assembles the experimental one. The three creep stages observed in the experimental creep curve can be reproduced quite well. The model is also able to predict the creep crack growth and profile of stress distribution. The effective crack propagation is depicted in Figure 6. The crack grows rapidly at first and then constantly, in the last stage moves fast until failure. Figure 7 shows the profiles of stress distribution along the section in front of the notch at different time moment. The movement of the fictitious crack tip can be observed.

CONCLUSIONS

The creep curve displays three stage in flexural creep rupture tests. The creep rate decreases initially and then keeps constant, and increases very fast until failure. The secondary creep rate seems to be a better predictor for rupture life than the stress level.

The numerical analysis indicates that the proposed time-dependent crack model is able to describe the observed the creep crack process of concrete beams subjected to sustained loads. Furthermore it can also predict profile of stress distribution with time.

SYMBOLS USED

a_0 = initial crack length

a_f = effective crack length measured from crack mouth to fictitious crack tip

CMOD = Crack Mouth Opening Displacement

FCM =Fictitious Crack Model

f_{net} = nominal flexural strength of a notched beam

f_t = tensile strength

w = deformation in fracture process zone

α = material constant in the model

τ = relaxation time

REFERENCES

(1) Hillerborg, A., Modeer, M. and Petersson, P.E., Cement and Concrete Research, Vol. 6 , 1976, pp. 773-782.

(2) Zhou, F.P., "Time-dependent Crack Growth and Fracture in Concrete", Ph.D. Dissertation, TVBM-1011, Division of Building Materials, Lund University, Sweden.

(3) Zhou, F.P. and Hillerborg, A., "Time-dependent Fracture of Concrete: Testing and Modelling", the first Int. Conf. on Fracture Mechanics of Concrete Structures, Breckenridge, Colorado, USA, 1992.

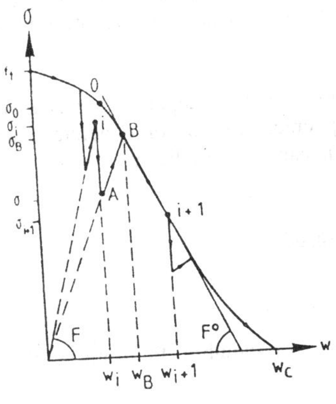

Figure 1. Illustration of the time-dependent crack model.

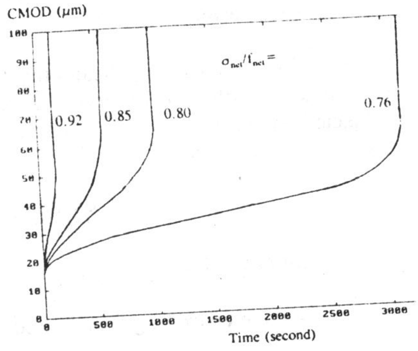

Figure 2. Creep curves in bending of notched beams.

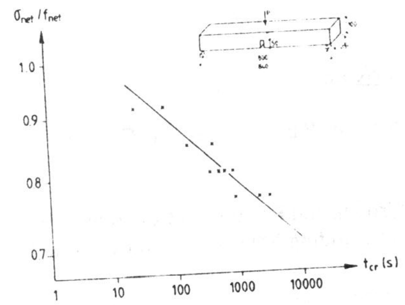

Figure 3. Stress-rupture life curve.

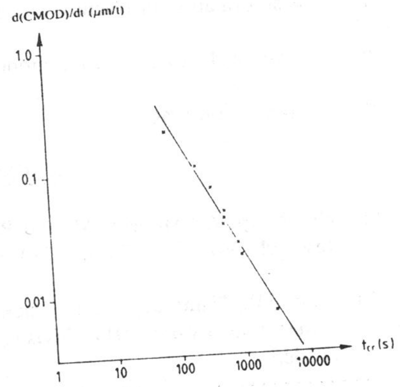

Figure 4. Secondary creep rate-rupture life curve.

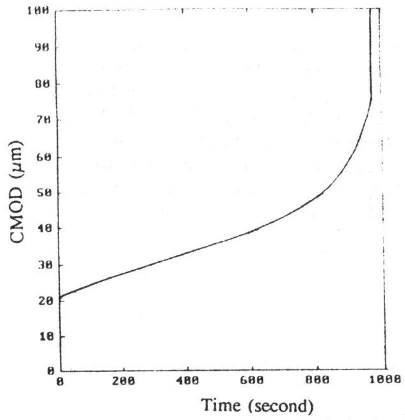

Figure 5. Comparison between the experimental and simulated creep curve.

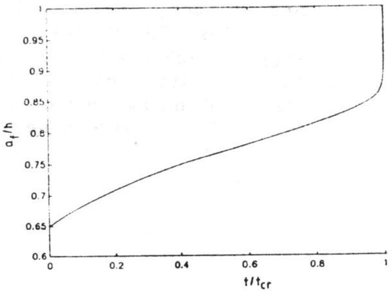

Figure 6. Simulated creep crack growth. Sustained load level=0.80.

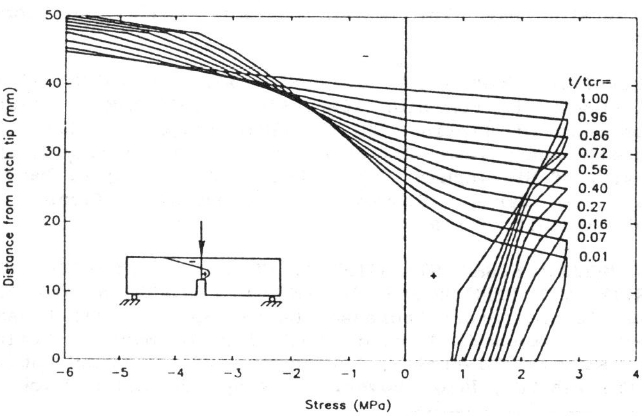

Figure 7. Calculated stress distributions across the notch section, sustained load level = 0.80.