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EFFECT OF MODEL FRACTURE LAW AND POROSITY ON TENSILE SOFTENING OF CONCRETE

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Abstract
It is a common observation that fracture of concrete starts from existing stress concentrations like pores and initial microcracks in the cement paste-aggregate interfacial zone. The effect of these weaker links on the softening behaviour was studied using a meso-level lattice model. The weaker links have been generated randomly through the matrix phase of the lattice model in order to simulate bonds around small particles but also larger pores. The other parameter affecting the softening behaviour is assumed to be the stress-strain characteristic of the lattice elements. Delayed crack growth is modelled by stepwise reduction of the Young's modulus of the lattice elements after the tensile strength was reached. A double-edge-notched uniaxial tensile specimen has been analyzed using the proposed model. Comparison from the simulations presented in the paper with experimental data indicates a substantial improvement of the global softening behaviour.

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1 Introduction

Early attempts to simulate concrete fracture by means of lattice modelling has shown that the method is highly effective of modelling crack growth with a simplicity in assumptions and computations, (Schlangen and Van Mier,1992). This is one of the main features of the method that gives an opportunity to model the material behaviour without using complicated constitutive equations.

Besides the perfection of crack development simulation capability, the lattice model representation of the overall stress-deformation behaviour of the material is rather poor. This behaviour may be caused by ignoring two basic facts in real behaviour namely; effects of third dimension, and the existence of smaller particles (like sand) and voids. The research presented in this paper is an initial attempt to include these effects in the simulation in order to obtain behaviour closer to reality. Some further improvements are also expected in the simulation of crack growth processes.

The study may be divided into two main successive steps: (1) including of the 3D effect, and (2) including smaller particles and voids.

The simulations have been performed on a double-edge-notched uniaxial tension specimen. The geometry and dimensions of the specimen are shown in Fig 1. A wide range of deformation controlled experiments have been carried out on this tensile specimen by Hordijk (1991) and Schlangen (1993). The main assumption in the lattice model is to relate the crack growth to mode-I fracture at the meso-level only. This is a fact which has been observed even in global shear and torsion specimens.

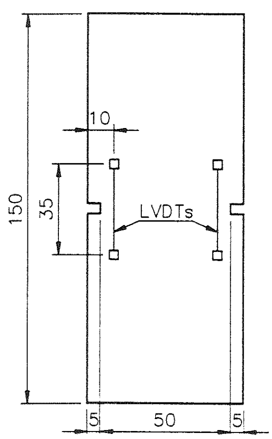


Fig.1. Uniaxial tensile specimen.

Lattice modelling of concrete fracture has been developed and used for this specimen by Schlangen and Van Mier(1992).In spite of the very good agreement of the simulated crack patterns with experimental observations, the resultant overall stress-deformation curve is not so well compared to the experimental curve. The lattice modelling represents a relatively brittle behaviour beyond the ultimate load as can be seen in Fig.3. It might be concluded from this behaviour that some parameters which might provide a further stiffness to the specimen are still missing. It has been assumed in this study that the main parameter ignored in previous attempts is the 3D effect.

In the fracture analysis of heterogeneous media, it may not be possible to simulate experimental observations more accurately simply by considering elements with unit thickness. The third dimension can not be neglected due to the nature of the fracture process. Neglecting friction and multiple fracture in the third dimension may be the reason for the mis-fit of stress-deformation response.

An early attempt to 3D lattice modelling was carried out by Schlangen and Van Mier (1994). The results indicated that the 3D effect could not be neglected. The importance of the thickness effect has been pointed out experimentally by Van Mier and Schlangen (1989). Single-edge-notched uniaxial tensile specimens were tested with two different thicknesses. A substantial increase in the ductility has been measured with increasing thickness. This result confirmes the importance of including the third dimension into the analysis.

2 Lattice model

The generation of the lattice, the inclusion of the heterogeneous material structure of concrete, and the main lattice parameters used in this study were similar to earlier work of Schlangen (1993). The fundamentals of lattice analyses have also been extensively described in various papers. A regular lattice has been used in the analysis. However, other investigations have shown that assumptions in the model, like the procedure of calculating stresses, and the mesh size and shape, highly influence the fracture process, Schlangen et al.(1995). Therefore, the results should be looked at in a qualitative way only.

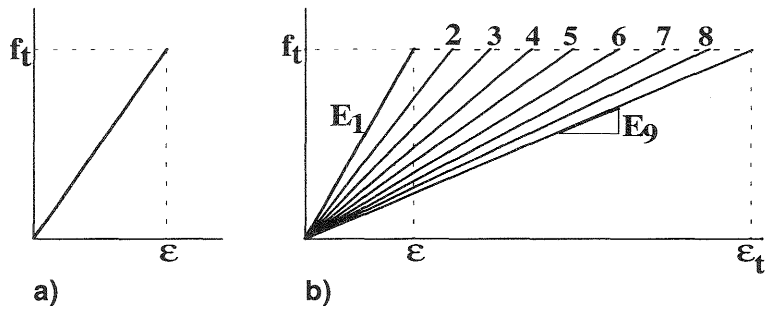


Fig.2. a) Stress-strain relation of lattice elements in linear elastic analysis,
b) Calculation procedure in non-linear elastic analysis.

3 Procedure for numerical simulations

3.1 Model fracture law and inclusion of small particles

The basic question at the beginning of the paper was how to increase the overall stress value for a certain deformation at/or beyond peak load? It is assumed that this can be achieved by simply delaying the crack growth in high stiffness elements in successive calculation steps.

A new, so-called non-linear elastic fracture law has been implemented for the matrix beams only, see Fig 2. As soon as the maximum tensile strength has been reached in an element, the stiffness is reduced to E_2, but the strength is kept constant. The model allows to continue this process for nine steps, i.e. until E_9 is reached, and final fracture occurs. Decreasing the Young's modulus means that a lattice element is only partially cracked over the thickness. As a consequence other lattice beams which are close to their critical strength might fracture before the Young's modulus must be reduced again in the previous lattice element.

Three different tail lengths have been considered, other than the purely linear-elastic solution, in order to study the tail length effect on the softening behaviour. These includes 3ε, 6ε and 9ε lengths, where ε is unit strain in the linear-elastic case.

An additional parameter was investigated as well, namely the existence of smaller particles in the matrix. In the present model, the minimum aggregate size is 3 mm; the size of the lattice beams is 5/3 mm. The model imposes a limitation, because the smallest possible particle would be of single beam size, i.e. 5/3 mm. In order to study the effect of small particles, it was decided to assign selected beams, randomly choosen throughout the matrix, a higher stiffness (equal to the aggregate stiffness) but a lower tensile strength (equal to the bond strength between aggregate and matrix).

3.2 Porosity

To understand what mechanisms are responsible for the fracture process in cement paste and concrete, in addition to considering the heterogeneity caused by large aggregates, small particles and pores must also be taken into consideration. Stress concentrations in the specimen depend on the size and shape of the pores and small particles in the matrix phase, and voids in the interfacial zone. Many observations are now leading to the conclusion that one of the main effects on the fracture process in cement paste is the total porosity (Lawrence,1977).

The existence of porosity in real materials has generally been ignored in numerical simulations. The porosity seems particularly important in the behaviour of concrete which is a porous multi-component material, and should be taken into account in numerical modelling. It is attempted to include the porosity into the numerical modelling of fracture behaviour of concrete. However, due to limitations of hardware, only 5/3 mm long lattice elements have been used. Consequently, the pores in the numerical concrete are equal or larger than 5/3 mm. Owing to this fact, the simulated porosity percentages are kept relatively low.

From previous analyses (Arslan et. al. 1995) it has been observed that the non-linear elastic fracture law with a 6ε tail length seems most promising for further investigation. A 5% small particle ratio has been used in the analyses. The porosity was distributed in the matrix and bond phase of the material only. It has been assumed that no pores exist in the aggregate phase at least not larger than 5/3 mm. This assumption is also realistic when real natural aggregates are considered.

In this paper we will only show results of analyses with 0, 6.35 and 12.77% total porosity in the matrix and interface phases. The pores were simply placed into the material by means of randomly generated numbers over element numbers.

4 Results and discussion

4.1 Effect of fracture law and small particles

In this section we show the effect of fracture law and small particles on ductility. Generally, it has been observed that ductility increases with increasing amount of small particles and with an increasing length of the tail of the fracture law. Full details are given in Arslan et al.(1995).

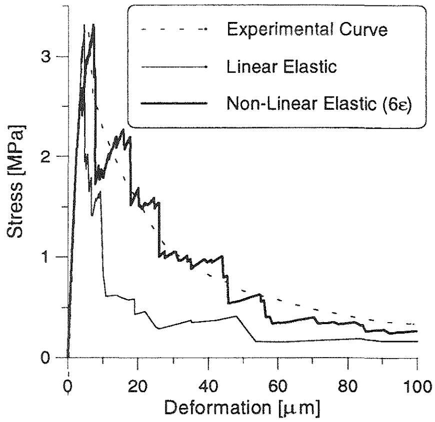


Fig 3. The effect of the fracture law on load-deformation response.

Load-deformation curves obtained from numerical analyses have been normalised with experimentally predicted peak stress value. Fig. 3 shows the effect of the fracture law on the stress-deformation diagram in tension. The dashed line is an experimental result; the thin and thick solid lines are for a linear-brittle and non-linear elastic analysis (6ε) respectively. The amount of small particles in these analyses was 5%. It can be seen that increasing the ductility in the fracture law leads to a more ductile global response. However, it is not clear how this tail length should be chosen for a certain thickness of the specimen.

The fracture energies in each analysis have been calculated from the numerically obtained load-deformation curves. In order to prevent confusion about the obtained values, they have been normalised to the numerical fracture energy of the linear-elastic solution. The variation of relative fracture energy by tail length in the non-linear elastic fracture law is given in Fig. 4 for three different particle percentages included in the model, i.e. 0, 5 and 15% particles in the matrix. The fracture energy increases with increasing tail length.The reason might be that by extension of the tail of the fracture law, a relatively higher number of weaker element is involved in fracture process. Consequently, the specimen fails in a relatively ductile manner. The results for the 15% simulation differs from the others, because a uniform distribution of small particles through the matrix phase could not always be achieved in each trial.

4.2 Effect of porosity

Figure 5 shows the effect of porosity on the tensile load-deformation behaviour. The load deformation curves have been normalised with the ultimate load value of the no-porosity specimen. The effect of total

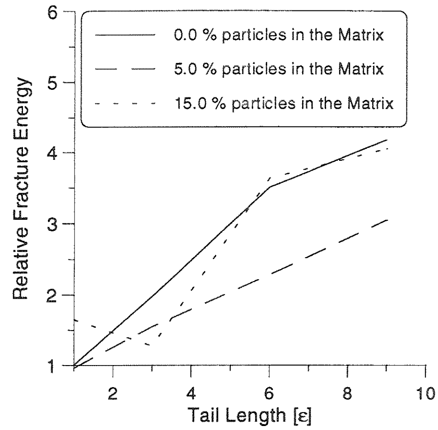


Fig 4. The effect of tail length in the fracture law and the particle ratio on the fracture energy

porosity percentage on the load-deformation behaviour is quite obvious. The ductility of the specimen increases with increasing porosity. The other specific indications are also observed like higher strain value at peak load, decrement in the obtained overall strength and the decrement in the initial stiffness.

The final fracture paths of the three porosity analyses are illustrated in Fig 6. The increment in the number of cracks to failure with increasing porosity can be seen clearly. However, it must be noted that all matrix elements which do not have their original stiffness are plotted as cracks. The other important observation is that the number of crack blocks with a relatively short lengths increases when the porosity is higher. Consequently, the lengths of the matrix cracks connecting the various crack blocks is significantly lower in the high porosity analysis.

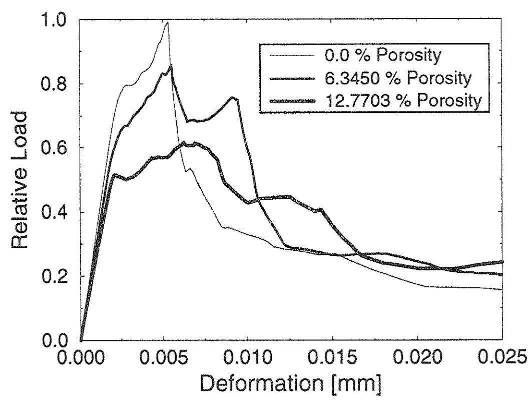
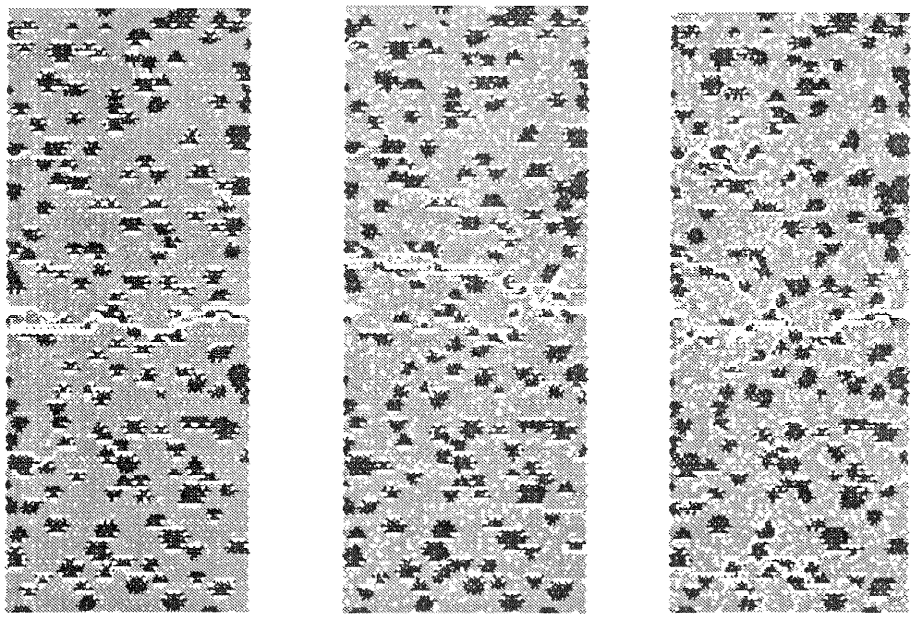


Fig.5. The effect of porosity on load-deformation behaviour.



a) 0.0% porosity b) 6.35% porosity c) 12.77% porosity

Fig.6. The crack patterns of specimens with different porosities.

The matrix cracks occur well distributed in the highest porosity analyses which prevents the sudden load drop just after peak to occur. While the other two specimens (0% and 6.35%) complete the bond and particle cracking only at around 0.005 mm, the high porosity specimen completes the cracking at at 0.008 mm. This provides to the higher porosity specimen some additional ductility.

The maximum numerical loads were normalised with the value of the no-porosity specimen. The resulting relative strength versus total porosity ratio is illustrated in Fig 7. The expression suggested by Powers(1958) was applied to the numerically obtained values. Powers suggested a power function for strength-gel/space ratio in mortars as;

$$\sigma_c = \sigma_o(1-p)^n$$

where σ_o is a constant representing the intrinsic strength of the cement gel with no porosity, p is the total porosity, and n is a constant having values in the range of 2.6 and 3.0, depending on the characteristics of the cement.

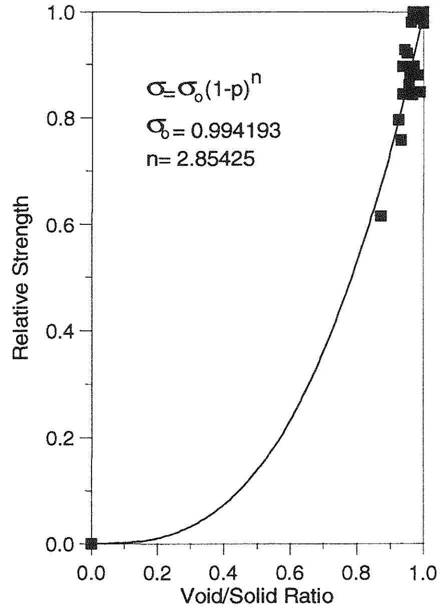


Fig.7. Comparison of numerically determined strenghts and Power's law

In spite of the fact that the above expression was derived for compression strength, the same formula was used for the numerically obtained tensile strength-porosity relationship. The relative intrinsic strength σ_0 was 0.9942, as expected it is quite close to 1. The coefficient was found as n=2.8543 which is in good agreement with the results of Powers(1958).

5 Conclusions

The general conclusions can be summarised as follows:

-For modelling multi-phase materials like concrete appropriately, the 3rd dimension and smaller particles must be included in the discretization.

-The 3D or thickness effect on the specimen behaviour can be satisfactorily modelled by appropriate changes in the assumed fracture law. However, it is felt that the optimum situation would be to carry out full 3D analyses using an elastic-brittle fracture law.

-The assumed fracture law and porosity have major effects on the simulated load-deformation behaviour. The presence of smaller particles and/or voids also provides a substantial enhancement in the ductility of the specimen.

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