INFLUENCE OF MICROCRACKING ON DUCTILITY OF MULTI-PHASE MATERIALS

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ABSTRACT
Microcracks in multi-phase materials are important for durability predictions, since they influence the transport mechanisms. In this paper lattice type models are discussed that can be used to simulate fracture and distrbution of microcracks. It is found that the ratio between the strengths of the components in a material determines the width of the fracture process zone and also the ductility of the material.

1 INTRODUCTION

When fracturing multi-phase materials like concrete a quasi brittle behaviour is observed. In continuum mechanics often the concrete is shematized as a material showing a softening behaviour. This behaviour can be measured and fitted with some general function which is implemented in the models as a constitutive law. However since the early 90’s attention has been focussed on the mechanism behind the softening. Experimental studies have shown that if we zoom in on the material, we can explain why we have a softening behaviour. A zone of micro-cracks is formed and crack bridging, branching and friction effects all have a contribution to the toughness of concrete. The micro-structure of the material has a large influence on the crack patterns in concrete. Cracks follow the weakest link in the material which is often the interfacial transition zone (ITZ). Transport of gases, moisture and ions takes place through the pore structure of the concrete. Also transport follows the easiest route through the microstructure. Larger porosity in the ITZ and also cracks will enlarge this transport (Jacobsen et.al [1]). It has been observed that also (not interconnected) microcracks in a material increase the diffusivity, especially when the material is loaded in tension and the microcracks are open (François and Arliguie [2]).
Durability of concrete structures is determined by the concrete in the cover zone on the reinforcement. The microstructure of this part of a concrete structure is different from the bulk material due to wall effects and variations in water cement ratio. Furthermore concrete structures are in general designed to crack in this region. Durability predictions should therefore take into account both the porosity in the microstructure as well as cracking. The ITZ is then a key parameter. Multi scale modelling of formation of microstructure, damage and transport is the way to go to obtain more insight in durability mechanisms (Schlangen et.al [3]). To be able to model transport through a heterogeneous material with (micro-)cracks fracture models that predict crack patterns and cracks widths accurately is inevitable.
Fracture of disordered materials can be simulated very well with network or lattice models (Herrmann and Roux [4]). In these models the material is represented by a network of small springs or beams (see figure 1a). All the single elements have a linear elastic behaviour. Heterogeneity is implemented in the network by variation of properties. After loading the network a crack is formed by just removing an element of which a limit (strength or strain) is exceeded.

With this method realistic crack patterns can be obtained. Furthermore a ductile global behaviour of the material is found while the local behaviour is brittle.
The method of simulating fracture with a lattice model is applied for concrete a lot in the last decade (e.g. Schlangen and van Mier [5]). Heterogeneity of the concrete is implemented following various methods (Schlangen [6]):

- using a distribution of strengths and stiffness of the elements in the lattice,
- making use of a generated or digital image of a microstructure of the concrete and implementing different properties to elements representing the different phases in the microstructure,
- using a random orientation of the elements in the lattice

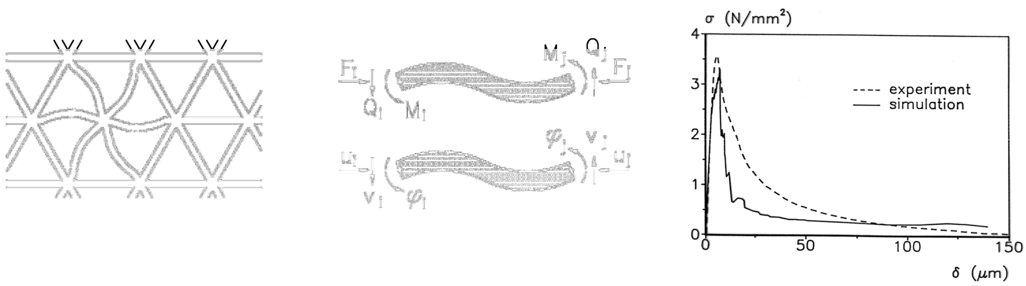


Figure 1. a) Network of beam elements (left); b) Forces and degrees of freedom in elements (middle); c) Stress deformation curve of uniaxial tensile test of concrete, experiment and simulation with lattice model (Schlangen [6]) (right).

General trend of all the simulations (in which a brittle fracture law of the elements is adopted) with the lattice models applied to concrete is up to now that the crack patterns look very realistic, but the load-displacement response is not correct. In tension the behaviour is too brittle and in compression the peak loads are too high and the behaviour is too ductile. An example of such a result, a simulation of a uni-axial tensile test, is shown in figure 1c.

Different causes and possible solutions for this too brittle behaviour found in simulatons of tensile fracture are discussed in various papers:

- In the generated (and scanned digital images of) microstructures of concrete the small particles are ommited. This results in less microcracking at the weak interface between particles and matrix. Smaller sizes of the beam elements are needed to overcome this problem (Schlangen [6]);
- Most of the lattice simulations are performed in 2D, whereas the real fracture in the material is a 3D process. 3D lattice simulations are performed (Schlangen and van Mier [7], Lilliu and van Mier [8]) but show mostly no real improvements, because the size of the elements is then increased due to computational limitations;
- The fracture law, which decides which element to break, can be altered. The fracture law can consist of different combinations of normal force, bending moments and or shear forces. This only leads to minor changes in the reponse (Schlangen and Garboczi [9]);
- To create a more global ductile response also a ductile or softening behaviour on the local scale of the elements can be implemented (Bolander and Saito [10], Ince et al. [11]).

However doing this the simplicity of the model is lost. Non linear iterative steps are needed in stead of sequential linear elastic analyses;

- In a heterogeneous material like concrete, eigenstresses are present due to variation in properties of the components. Thermal or hygral variations lead to differences in shrinkage strains which results in eigenstresses. This also has an effect of the global material response (see Schlangen et al. [12]).

In this paper an other possible effect is worked out. Cracks will not close completely when a concrete material is unloaded. To close the cracks a closing pressure is needed.

2 IMPLEMENTATION OF CLOSING PRESSURE

To decide in each loading step which element breaks in the lattice model the stress in the elements is calculated as a combination of the forces in each element. For the simulations in the present study only the normal force is used. The stress (σ) in each beam is equal to $\sigma = F/A$. The element breaks when the stress is larger than the strength of the element. The elements only break in tension, not in compression. The stress strain curve is shown in figure 2a. It is known that cracks which have formed under load will not close completely when the load is removed. (see for instance Hordijk [13]). Pressure has to be apllied to close the cracks. To take this effect into account in the lattice model a spring is put at the position of the broken beam, which has a characteristic as shown in figure 2b. If the crack is open (a crack opening equal or larger than the deformation at which the original beam failed) the force in the spring is zero. If the crack opening is smaller the spring will be loaded in compression. This compressive force in the spring will give tensile stresses in the neighbouring elements. This will definitely lead to better performance when compression tests are simulated with the lattice model, but probably also gives better behaviour (more ductile) when simulating tensile tests. Note that non-linearity is put into the lattice model, which could give convergence problems. However for the simulations discussed in this paper these problems were not encountered.

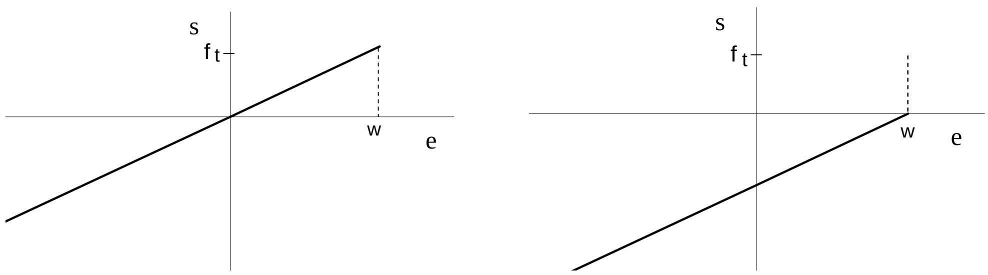


Figure 2. a) Initial local stress strain curve of beam elements (left); b) Local stress strain curve of spring elements after breaking of beam (right).

A typical result obtained with the lattice model including the new feature of closing pressure is shown in figure 3. A load deformation curve is given of a simulated tensile test in which the permanent crack opening is shown after unloading at several spots in the descending branche. The result is plotted without the initial elastic regime.

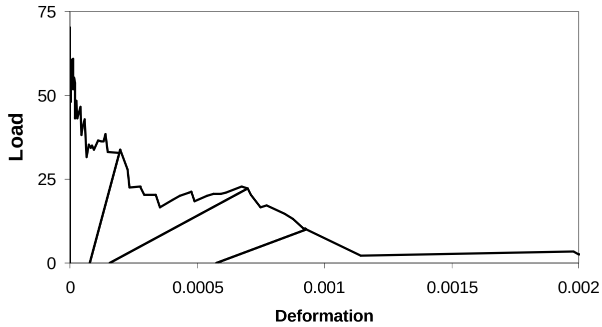
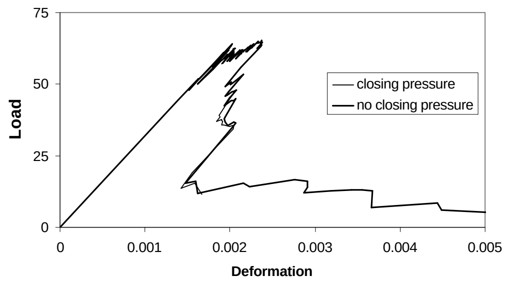


Figure 3. Load deformation curve of simulation of tensile fracture with closing pressure after breaking of elements, showing the permanent deformation of the system after unloading.

3 RESULTS

To test the procedure, simulations on a lattice under tensile loading are performed. The boundaries where the load is applied are non-rotating. For all the simulation a regular triangular mesh is used. As input for the simulation the following values are used for the beams: young's modulus E=30000, thickness b=1, height h=1, length l=1. The strength of the elements in the lattice is varied. In the lattice, elements with two strengths are randomly placed; 25% of the elements have a low strength, and 75% of the elements have a high strength. The value of 25% is taken to be below the percolation threshold value. The low strength has always a value equal to 1. For the high strength the values are equal to 2, 3, 3.25, 4 and 5 respectively. For all the simulations both a run with and without closing pressure is performed to see the effect on the global behaviour with different amount of microcracks.



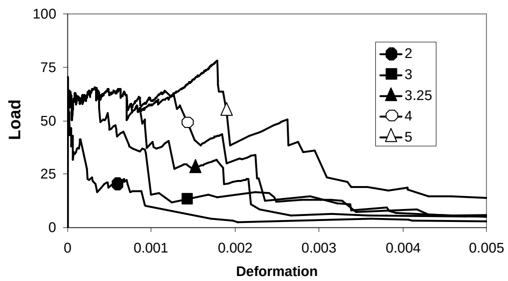


Figure 4. a) Load deformation curves of simulation of tensile fracture with and without closing pressure after breaking of elements; b) Load deformation curves of simulation of tensile fracture in which the strength ratio of the elements is varied.

In figure 4a the results of two runs (with and without closing pressure) are compared. It was surprisingly to see that there was almost no difference. The behaviour was the same if the amount of microcracks increase. Explanation for this is that in the descending branche the applied load on the lattice is decreasing while the cross section of the complete network decreases. The localized crack is growing from one side to the other in the network. The localized crack is open over the

full length. This means that inside the crack the closing pressure will be zero. Only the part of the material that unloads will have a clossing pressure. The microcracks outside the main crack are closing and have a closing pressure, which gives an extra strain to these parts. However the microcracks which are in the zone of the 'crack tip' are not closing. They are still open. The microcracks around the 'crack'tip actualy determine the global strain in the descending branche. This means the effect of the closing pressure in a tensile test is negligible. However in a compression test, or a fatigue test, the closing pressure will certainly have large influence.
If the simulations with the variation in high strength values are compared, some interesting observations can be made. First of all the maximum load that can be put on the lattice is the same for all simulations (except for the highest strength). This means that the maximum load is determined by the low strength elements. The ductility of the global response increases if the high strength value increases, see figure 4b. The amount of microcracks in the network, before localization starts, also increases with increasing high strength value, see figure 5. This means that the ratio between the strengths in the lattice determines the width of the zone with microcracks (fracture process zone) and also the ductility of the global response. In the case of high strength value equal to 5, first all the low strength elements crack, after wich the maximum load on the network has to be increased again to get failure. For the latter some resemblence with (fiber) reinforced concrete can be made, where first cracking of the concrete takes place after which the reinforcement will fail (due to pull out, plasticity or breaking of the reinforcement).

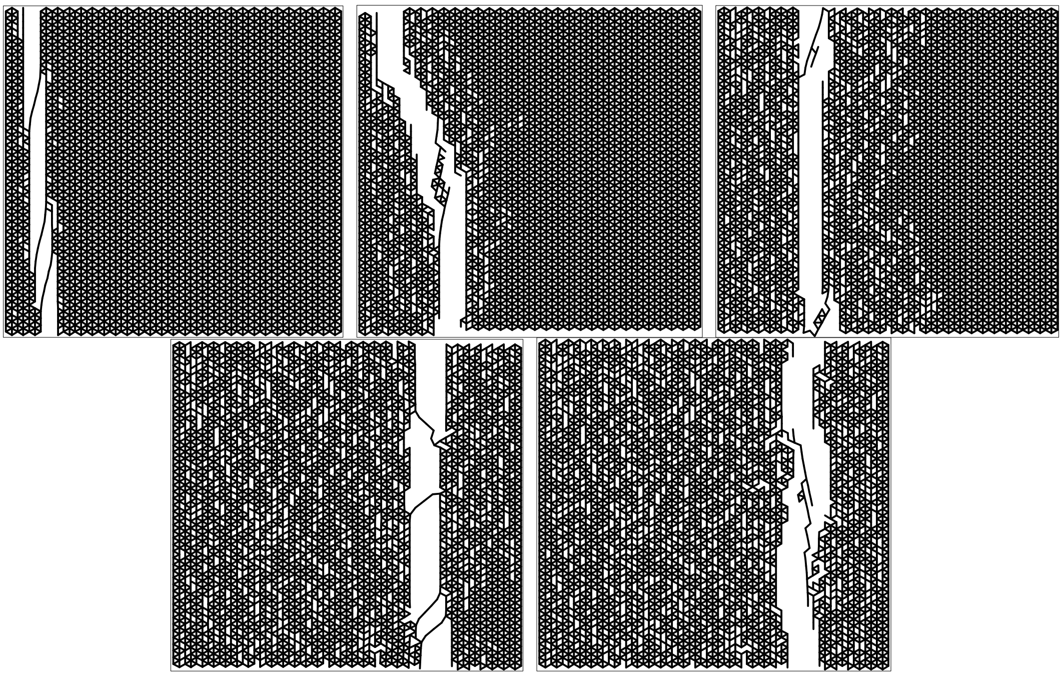


Figure 5. Cracked and deformed lattices after simulation of tensile fracture with variation of strength ratio; Top (from left to right) strength ratio is 2.0, 3.0 and 3.25; Bottom (from left to right) strength ratio is 4.0 and 5.0.

4 CONCLUSIONS

In this paper the implementation of a closing pressure in the lattice model is proposed to obtained a more ductile global response in tensile loading. The results of the simulations show that the closing pressure has no influence since the microcrakcs around the 'crack tip' determine the global behaviour under tensile loading. However under compressive loading the implementation of closing pressure will certainly have an influence. From the simulations it is found that the ratio between the strength in the lattice determines the width of the fracture process zone and also the ductility of the material. In the simulations with two strength values in the lattice the lowest strength determines the maximum load. In real materials (e.g. concrete) the strength values will not be constant but follow a certain distribution. Future work will take this into account.

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