M&S highlight

Schlangen and van Mier (1992), Simple lattice model for numerical simulation of fracture of concrete materials and structures

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M&S highlight: Schlangen and van Mier (1992), Simple lattice model for numerical simulation of fracture of concrete materials and structures

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1 Background

The research theme described in paper [1] deals with fracture modelling of concrete. The method that was used in the model of Schlangen and van Mier was the discrete element approach, in which the material is discretised as a network of small beam elements. All these single elements are linear elastic and have brittle fracture behaviour once the stress reaches a predefined strength. The local properties, strength and stiffness of the elements are defined by mapping the elements to a generated grain structure which represent the heterogeneity of the concrete. The method (lattice model) discussed in the paper was seen as an alternative to finite element models that used smeared or discrete crack approaches [2] to simulate fracture processes in concrete. In the lattice model only a linear elastic analysis is performed in each simulation step. The cracks start and propagate at the position of highest local stress (relative to the local strength) by removing one element from the mesh, after which a new linear elastic analyses is performed. The main advantage of this method is that there is always convergence in the solution and that cracks can start and propagate everywhere in the sample or structure that is simulated.

2 Key contribution of the paper

The main contribution of this paper [1] was the fact that the well-known softening behaviour of concrete [3, 4] could be simulated with a lattice model that has locally brittle behaviour in the elements. By varying the local strength and stiffness of the elements, the main crack path and micro-crack distribution can be influenced and as a result the shape of the softening curve.

The model was also used in the work of two RILEM Technical Committees. TC 89 FMT, of which a subcommittee was chaired by Professor Alberto Carpinteri, was dealing with fracture energy under mixed-mode loading tested on a single-edge-notched 4-point-shear beam. For this, a round robin was organised in which laboratories from all over the world participated [5]. The modelling was used to optimise the loading frame used in the experiments.

This commentary is part of our celebration of 75 years of RILEM, highlighting Materials and Structures most highly influential and cited publications.

Highlighted paper: Schlangen, E & van Mier, J. G. M. Simple lattice model for numerical simulation of fracture of concrete materials and structure. 1992 Materials and Structures. 25(9), pp. 634–542.

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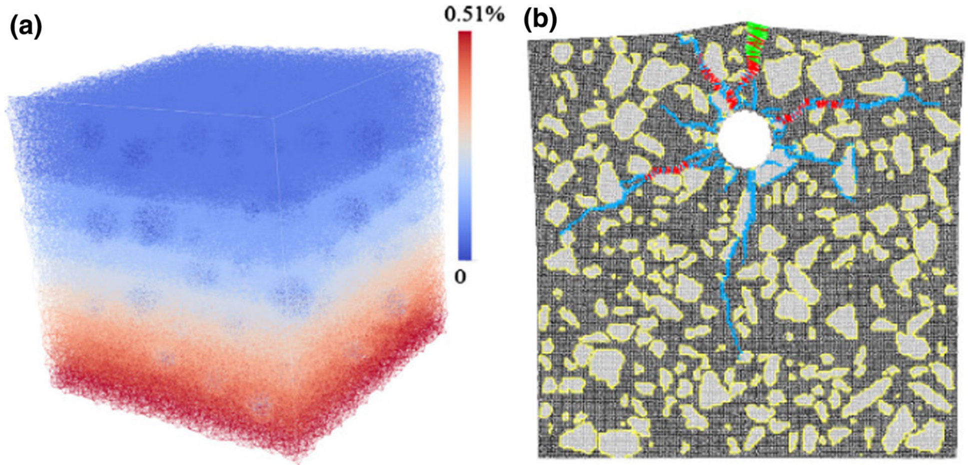

Fig. 1 **a** Chloride ingress modelling [1] and **b** cracking due to rebar corrosion [7], simulated with lattice models

This test setup and specimen in which a curved crack develops is still quite often used as benchmark test for modelling of fracture of concrete. The second committee, TC 90 FMA, chaired by Professor Lennart Elfgren, organised a round robin on the pull out of anchor bolts in concrete plates [6]. For this round robin, first all participating groups were invited to perform simulations of the fracture process in these specimens. As expected the scatter in the results were huge. After several labs performed experiments and the results were shared, another round of simulations was performed resulting in good agreement with the experimental data. This showed that predicting damage in concrete with models is quite difficult, whereas simulating the results of a well described fracture test is easy. The lattice model was one of the few that (also in the first round) predicted the fracture path in a correct way, including for those geometries that resulted in a non-symmetric crack pattern.

3 Influence on RILEM work, and research in general

The use of lattice models or similar discrete elements models like LDPM, spring or beam network models or peridynamic models have become more and more popular since this first publications 30 years ago. These type of models are often used as research tools to design or support experiments and to get insight into various fracture mechanisms. While 30 years ago these models were limited to 2D, nowadays full 3D simulations on various scales are possible. Another feature that is added to these models is the possibility to perform diffusion or transport simulation using the same discrete elements or a coupled dual lattice mesh. This opens the possibilities to perform coupled transport and fracture simulations to study durability performance of concrete elements and structures. Many of these applications have been published in RILEM-supported conferences and in International Journals. Below several examples from the Delft group will be discussed, although a lot of other groups work also on simulations with lattice type models. The intention here is just to provide an idea of possibilities, not to give a complete overview.

An example of such an application of coupling of transport and mechanics is given in [7, 8] where chloride ingress in cracked concrete is simulated and as a result corrosion and expansion of reinforcing bars with further degradation of the concrete. Other applications of durability related issues that are studied with lattice models are freeze–thaw damage [9] and ASR [10].

Another application closely related to the work of several RILEM TC's is the development and application of fibre reinforced concrete, and especially the strain hardening type materials. With the model discrete fibres can be 'mixed' into a cement based matrix and by varying fibre and interface dimensions and properties, mixes can be designed to tailor strain hardening behaviour [11], see Fig. 2. The same technique was applied in the work discussed in [12], where repair systems for concrete were developed.

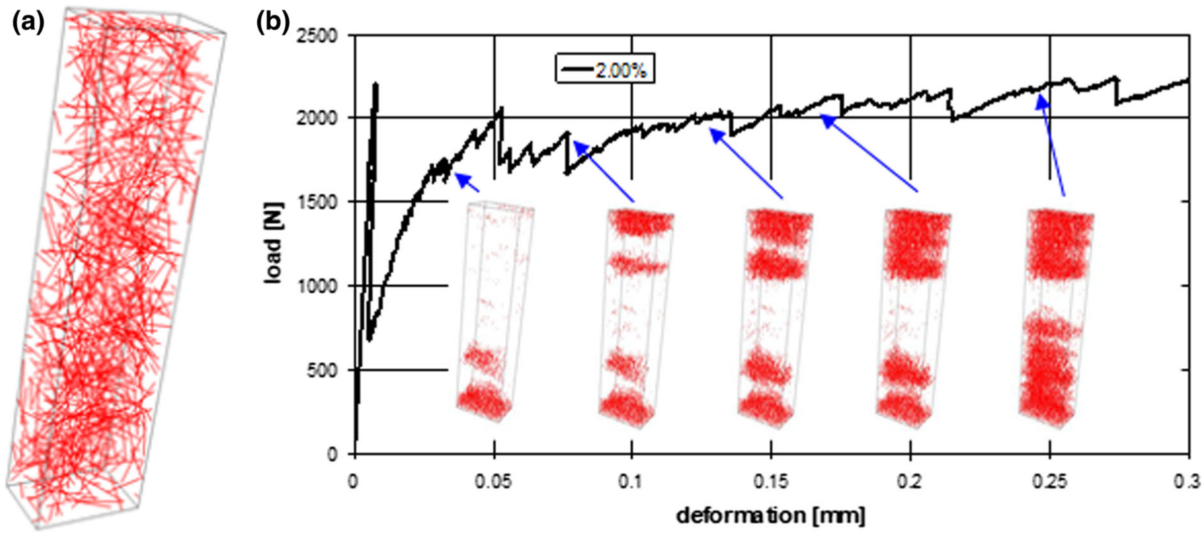

Fig. 2 **a** Distribution of discrete fibres and **b** Simulation of a tensile test on a fibre reinforced cement based material showing strain hardening behaviour with the lattice model [11]

A third application for which lattice modelling was applied in work closely related to activities of RILEM is the design and optimisation of self-healing concepts for concrete. Here simulations are performed to model the crack growth in samples and subsequently the closing of the cracks due to incorporation of a certain self-healing agent. Modelling is also adopted to check how cracks propagate through or around spherical or elongated capsules that contain healing agent [13]. The stiffness and bond strength of the capsules is an important parameter that can easily be studied by simulations.

Finally it has to be mentioned that the Delft group has organised every year since 2008 a PhD course on Multi-Scale-Modelling for concrete, which is supported by RILEM-EAC. Each year this course is attended by 30 to 50 PhD students from all over the world. One of the main items in the course is applying lattice type models for different research projects.

4 Current and future research directions

The future trend is to develop multiscale models for predicting and explaining behaviour of materials and design the material from the properties of the ingredients and the individual components. This field is extremely important when we are going to use new binders and different aggregates (eg. recycled aggregates or waste material) to make concrete [14, 15]. In this case we cannot simply rely on experience for designing these new mixes. Modelling can be of great help. Testing on each scale of the material is needed in order to obtain input parameters for the models. and also to validate the outcome of the simulations. In Fig. 3 an example of multiscale modelling making use of the lattice model at different scales is shown. The simulations are supported by tests at different scales as shown in Fig. 3a, which gives the schematic overview of a small cantilever containing cement paste and an ITZ with an aggregate that is tested by loading it with a nano-indenter. The properties of the ITZ in the model are subsequently fitted back from a simulation on the same sample (3b). The sample is scanned in a CT-scanner to obtain location of phases and porosity and local nano-indentation is performed to get mechanical properties of individual phases. The resulting properties of the ITZ are then input for the simulation on mortar cubes (Fig. 3c, d).

Another application of such lattice simulation is the optimisation of the process of 3D printing. In [16] a first attempt is made for studying the effect of the green strength of the material on the printing speed and the typical failure modes of the printed object that happen during the printing process.

Lastly, these models also find their introduction into structural applications. In [17] the lattice model is applied for predicting the shear capacity of reinforced

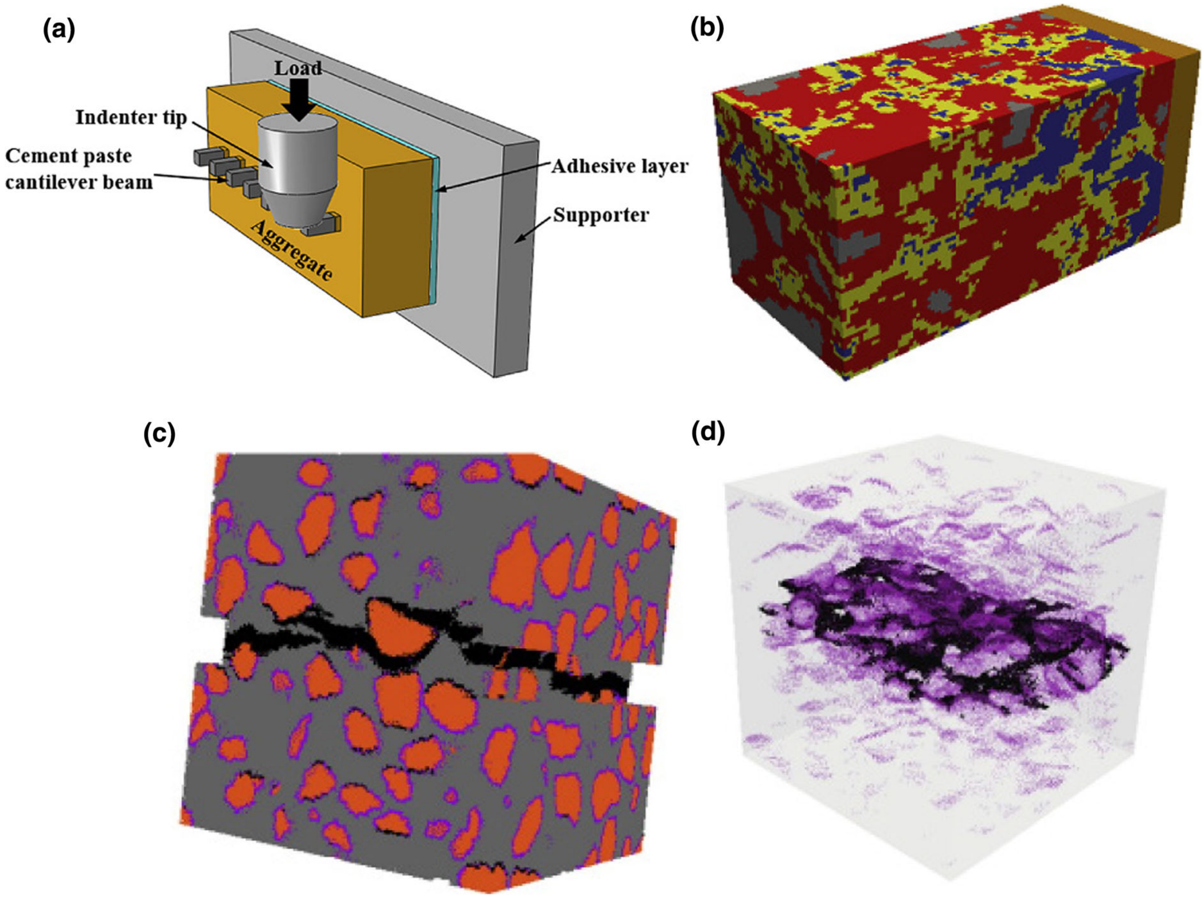

Fig. 3 **a** Miniature bending test [14] on cantilever beam with ITZ between paste and aggregate, **b** lattice mesh for simulation of cantilever test (specimen size 220 × 100 × 100 µm), (3) tensile fracture simulation of double side notched 10 mm mortar cube [10] and **d** major (black) and micro (purple) cracks in the simulation. (Color figure online)

concrete and SHCC structures. The multiple crack patterns and complicated failure mechanisms in these structural elements seem to be predicted accurately with the lattice type models.

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