3D MESO-SCALE IMAGE-BASED FRACTURE MODELLING OF CONCRETE USING COHESIVE ELEMENTS

*Wenyuan Ren1, Zhenjun Yang1,2 and Rajneesh Sharma1

1 School of Mechanical, Aerospace and Civil Engineering, the University of Manchester, M13 9PL
2 College of Civil Engineering and Architecture, Zhejiang University, China, 310000

*Wenyuan.ren@manchester.ac.uk

ABSTRACT

This paper extended the 2D meso-scale image-based models to 3D by using a small volume proportion of images obtained from an X-ray computed tomography test. The real microstructure of concrete specimen was characterized as three phases: aggregate, cement and voids (which is empty areas). Zero-thickness cohesive interface elements were embedded in cement phase to represent the potential cracks (no cracks allowed to propagate through aggregate particles). The average stress-strain curve of the 3D mesh under uniaxial tension was compared with a 2D simulation result. The crack propagation process in 3D was illustrated together with the final crack surfaces.

Keywords: Concrete; X-ray computed tomography; Image based modelling; Cohesive interface element; Meso-scale model

1. Introduction

As a quasi-brittle composite material, concrete has been widely used in many civil and industrial structures. Due to the existence of intrinsic heterogeneity at nano, micro, meso and macro scales, it is very complicated to model fracture behaviour of both microcracks and macrocracks, such as initiation and coalescence. Traditionally, numerical models are obtained by computer programmes and the material heterogeneity is realized either by random distributed material properties controlled by correlated functions [1-3] or by randomised positions and shapes of inclusions [4-7]. Monte Carlo simulation method can be used to get the statistical analysis because of the ease of using computer programmes. However, most of these studies assume the morphologies, which are mathematical representations.

The innovation of this paper is to build the 3D meso-scale model with realistic internal microstructure by transforming images obtained from X-ray computed tomography (XCT) into a 3D finite element (FE) mesh, which is acknowledged as image-based modelling method [8]. In the companion paper [9], the two-dimensional (2D) meso-scale FE meshes based on XCT images were used along with pre-embedding cohesive interface elements to simulate crack propagation processes in concrete under uniaxial tension loading. In this paper, a three-dimensional (3D) model is built by cropping a 10×10×10 mm³ volume from the whole image model (size of 37.2×37.2×37.2 mm³). The zero-thickness cohesive interface elements (CIEs) are embedded in cement using an in house computer programme to simulate potential cracks.

2. Image-based modelling

The proposed method involves the following steps:

1) Creating the 3D image model from XCT test. The detailed reconstruction and segmentation process of the concrete specimen from XCT test can be found in [10]. Here, a randomly selected small volume cube (10 mm³) was cropped from a large specimen. Figure 1 shows the 3D image, in which blue and grey colours represent aggregates and cement paste respectively;

2) Generating mesh. The software package of Simpleware [11] is used to directly transform the 3D image into a fine 3D Mesh;
3) Inserting the cohesive interfaces elements (CIEs). The CIEs (known as COH3D6 and COH3D8 in Abaqus [12]) are inserted in cement and on aggregate-cement interfaces (different material properties are assigned) using the same approach as used for 2D in [9]. The cracks are not allowed to be propagated in aggregates due to their high strength. The final image-based 3D mesh is shown in figure 2;

4) Assigning material properties and conducting analysis. The material properties used for 2D simulations [9] are considered and shown in Table 1. Due to the lack of experimental data, the shear components of initial stiffness and cohesive strength are assumed to be the same as the normal ones. The periodic boundary conditions are applied. A displacement controlled loading of un-notched specimen under uniaxial tension is simulated. Abaqus/Explicit solver is selected because of its high efficiency and convergence advantage for simulations of material degradation.

![Figure 1: 3D image of concrete specimen](image1)

![Figure 2: Image based 3D mesh](image2)

<table>
<thead>
<tr>
<th></th>
<th>Elastic modulus (MPa)</th>
<th>Poisson’s ratio</th>
<th>Density (kg/m³)</th>
<th>Initial stiffness (MPa/m)</th>
<th>Tensile strength (MPa)</th>
<th>Fracture energy (N/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aggregate</td>
<td>700000</td>
<td>0.2</td>
<td>2500</td>
<td>/</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>Cement</td>
<td>25000</td>
<td>0.2</td>
<td>2200</td>
<td>/</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>CIE_CEM</td>
<td>/</td>
<td>/</td>
<td>2200</td>
<td>10⁷</td>
<td>6</td>
<td>60</td>
</tr>
<tr>
<td>CIE_INT</td>
<td>/</td>
<td>/</td>
<td>2200</td>
<td>10⁷</td>
<td>3</td>
<td>30</td>
</tr>
</tbody>
</table>

3. Numerical simulation results

Figure 3 shows the energy curves of model, including Kinetic energy, Strain energy, Internal energy and External work. Figure 3 concludes that the energy balance is obtained: the kinetic energy remains less than 5% of the internal energy; meanwhile, the internal energy is almost identical to the external work) as expected for a quasi-static analysis.

![Figure 3: Energy curves of the whole model](image3)

![Figure 4: Stress-strain curves of 2D and 3D models](image4)
Figure 4 shows the average stress-strain curves of the 3D simulation and a 2D model having the same material properties and boundary conditions. The pre-peak stiffness is identical for both, however with different peak values (4.94 MPa for 3D and only 3.01 MPa for 2D). One reason is that microcracks in 3D are more difficult to get interconnected to form macrocracks due to the arbitrary shapes of the 3D aggregate particles. The 3D model seems to be more brittle (stiffer softening slope) than 2D.

Figure 5 shows the process of initiation and coalescence of microcracks and macrocracks (corresponding to the points marked A, B, C, D and E in figure 4). The blue areas in figure 5 represent aggregates. The orange and red (darker) colours represent the microcracks exist on aggregate-cement interfaces and within cement. A lot of microcracks first only initiated on aggregate-cement interfaces (Point A). At point B, more microcracks appeared on aggregate-cement interfaces. Some of interfacial ones begin to coalesce and get connected by newly formed cracks in cement. Most of interfacial cracks formed before peak value (point C), meanwhile more and more cracks in cement increased gradually (point D) and finally the specimen failed into two pieces (point E). The cracked specimen is shown in figure 5(f).

![Figure 5](image1)

The final cracked surfaces are shown in figure 6 and the 3D visualisation of crack path is plotted in figure 7. The numbers ((1)-(5)) represent five aggregates (in blue colour) around the cracking surface.

![Figure 6](image2)

![Figure 7](image3)
As no cracks are allowed through aggregates, the crack surfaces always formed around particles. The numbers (①-⑤) in figure 7 are the corresponding places in Figure 6 which caused the resulting crack path.

4. Conclusions

3D meso-scale FE image-based model is developed to simulate crack propagation process in concrete under uniaxial tension loading. The average stress-strain curve of the 3D mesh is compared with a 2D analysis by using same material inputs and boundary conditions. The curves show that the 3D model predicts a higher peak strength and stiffer softening slope. The features of initiation and coalescence of microcracks into macrocracks were illustrated. The final 3D crack surface shows that cracks are always formed along the surfaces of aggregates. The proposed imaged-based modelling technique shows a powerful way to study fracture mechanics of the composites with realistic internal structures. Moreover, the meso-scale simulation results could be also used to predict more realistic macro behaviour of concrete by multiscale analysis. Though there is a limitation of proposed modelling method: the computational cost. It is high due to the use of a very fine mesh and a large amount of inserted cohesive elements. This is unavoidable as the particles in the real materials always exhibit highly heterogeneous and the resultant mesh is very fine. However, with the help of parallel computing, the computation time could be greatly reduced when explicit solver is selected.

Acknowledgements

The research is funded by a Royal Society Research Grant and an EPSRC grant (No. EP/J019763/1).

References


