3D meso-scale fracture modelling and validation of concrete based on in-situ X-ray CT images and cohesive crack model

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Abstract

A meso-scale finite element modelling technique is developed for simulation of complicated 3D fracture in multiphase concrete, based on realistic X-ray computed tomography (XCT) images and the cohesive crack model. It is validated against in-situ XCT tests of a concrete cube under Brazilian-like compression in terms of load-displacement curves and crack patterns. Meso-scale simulations under uniaxial compression and tension are also carried out.

Keywords: Concrete; Meso-scale fracture; X-ray computed tomography; Finite element simulation; Cohesive crack model

Introduction

As a quasi-brittle multiphasic composite, concrete has been widely used in many civil and industrial structures. Due to the random distribution of multiphases, i.e. cement/mortar, aggregates and pores, it exhibits heterogeneous mechanical properties in micro/meso-scales, which in turn determine the performances and reliability of structures at macro-scale. Therefore, understanding its micro and meso-scale mechanical behaviour, including damage and fracture, becomes an important and challenging engineering and scientific problem [1]-[3]. In particular, developing predictive numerical models capable of simulating realistic fracture propagation in three-dimensional (3D) multiphasic composites like concrete is still challenging due to difficulties in experimental characterisation as well as numerical models [4]. To date, most of the numerical models available in literature use either assumed micro/meso-scale morphologies [5] or assumed random field properties [3][6]. As such, the simulated fracture processes cannot be directly and accurately validated.

The X-ray Computed Tomography (XCT) technique is now increasingly used for characterisation of micro-structures of composite materials. Recently, we carried out in-situ micro XCT tests of concrete cubes under progressive compressive loading to elucidate the complicated 3D fracture process in concrete [7]. By directly converting high-resolution XCT images into finite element (FE) elements, realistic 3D and 2D models have been developed for complicated multi-cracking, using the continuum damage plasticity model [8] and the discrete cohesive crack model (CCM) [9], respectively, with very promising results. In this study, we further develop the XCT-image based CCM approach to 3D so that both the load-carrying capacity and discrete 3D fracture evolution can be directly validated by the in-situ XCT test.

Construction of 3D FE meshes

The in-situ XCT tests of 40mm concrete cubes under compression were conducted with a voxel resolution of 37.2 μm at the University of Manchester and the details were reported in [7]. The 3D XCT images were cropped to 37.2mm, re-sampled to 0.1mm resolution and segmented into digital models, with one example shown in Fig.1. The digital models were then converted to 3D FE meshes using AVIZO [10] and Simpleware [11]. A generated mesh from Fig. 1 is shown in Fig. 2 with 4,422,638 tetrahedral elements and 5,932,268 nodes using targeted minimum edge length 0.1mm and maximum edge length 0.5mm. The mesh information was then exported into an ABAQUS input file. Zero-thickness 6-noded cohesive interface elements (COH3D6) were then pre-inserted into the 3D mesh to simulate complex fracture processes using an in-house MATLAB code augmented from an original one for homogeneous materials [3] by accounting for multi-phases and interfaces.

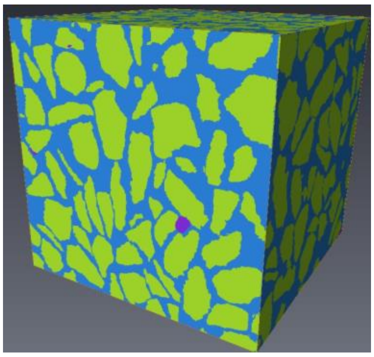


Figure 1. Segmented 3D image model

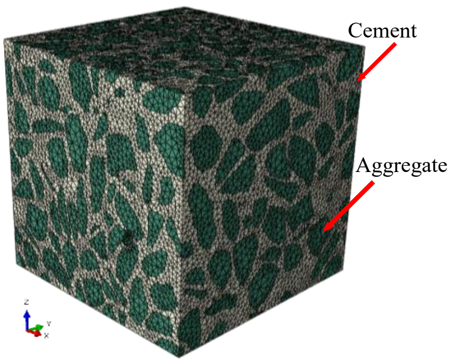


Figure 2. Generated 3D FE mesh

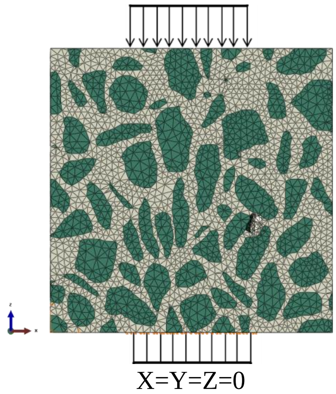


Figure 3. Boundary conditions

There are three sets of CIEs, namely, CIE_AGG within the aggregates, CIE_CEM within the cement paste, and CIE_INT on the aggregate-cement interfaces. In total, 2,939,571 CIEs were inserted into the mesh in Fig. 2. The solid elements of aggregates and cement were assumed to behave linear elastically. The Young's moduli (E) of aggregates and cement are 51 GPa and 13.6 GPa, respectively, measured by micro-indentation tests [7]. The density of aggregate and cement are 2500 kg/m^3 and 2200 kg/m^3, respectively. The cohesive strength and fracture energy for interfaces and cement are 3 MPa and 6 MPa, 0.03 N/mm and 0.06 N/mm, respectively. The shear fracture energy was assumed as 10 times the value in the normal direction. The linear tension/shear softening laws were used to model CIEs, with the quadratic nominal stress initiation criterion, energy based damage evolution, and mixed-mode BK-law fracture energy criterion.

The displacement-controlled loading scheme was used for all the simulations using the ABAQUS/Explicit solver with a step time of 0.01s, which was found to be sufficiently long to ensure the quasi-static loading condition. The modelled boundary conditions are shown in Fig. 3, where only a 17.5mm central square on the top and bottom surfaces was constrained respectively, as in the tests.

Validation against in-situ XCT tests

Fig. 4 compares satisfactorily the simulated force-displacement (F-d) curve with the in-situ test data that were calculated from a digital volume correlation (DVC) analysis of XCT images [7]. In particular, the predicted peak load 16.3kN is very close to the test value of

16.5kN. The post-peak softening stage which cannot be obtained from the test was also well captured.

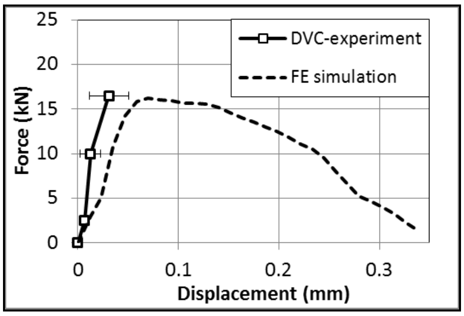
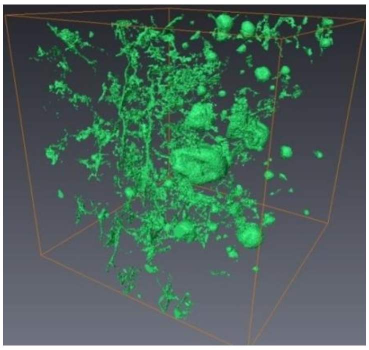
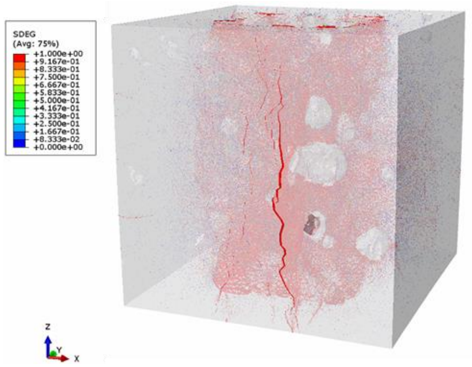


Figure 4. Comparison of *F-d* curves of XCT test and 3D FE simulation

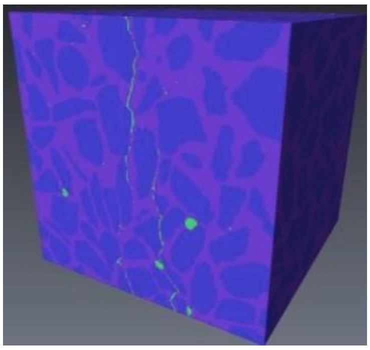
Fig. 5 compares the cracks (pores are also shown) in the segmented XCT image and the simulated cracks represented by CIEs with high damage index (*SDEG*>0.99) at the peak load, with Figs 5a and b showing the internal and Figs. 5c and d the external, respectively. A qualitative similarity can be seen, especially the crack paths on the surfaces.



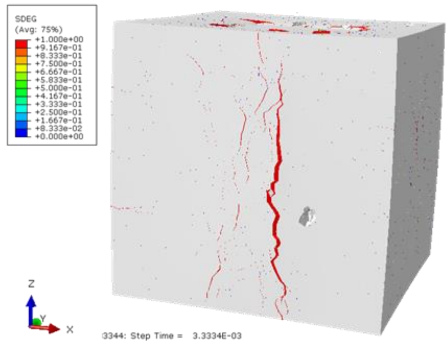
(a) Cracks and pores from in-situ test



(b) Pores with predicted cracks (*DSF*=10)



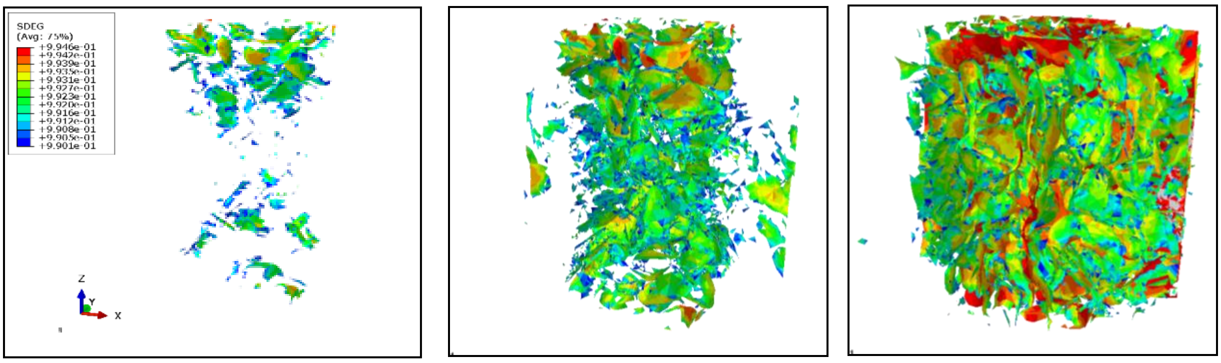
(c) XCT segmentation



(d) Predicted crack path (*DSF*=20)

Figure 5. Comparison of cracks at peak load (*DSF*=deformation scale factor)

Fig. 6 shows the detailed internal cracking process. It is clearly indicated that the damage initiated near the loaded surfaces, then propagated towards the centre in the loading direction, and finally expanded in the horizontal direction.

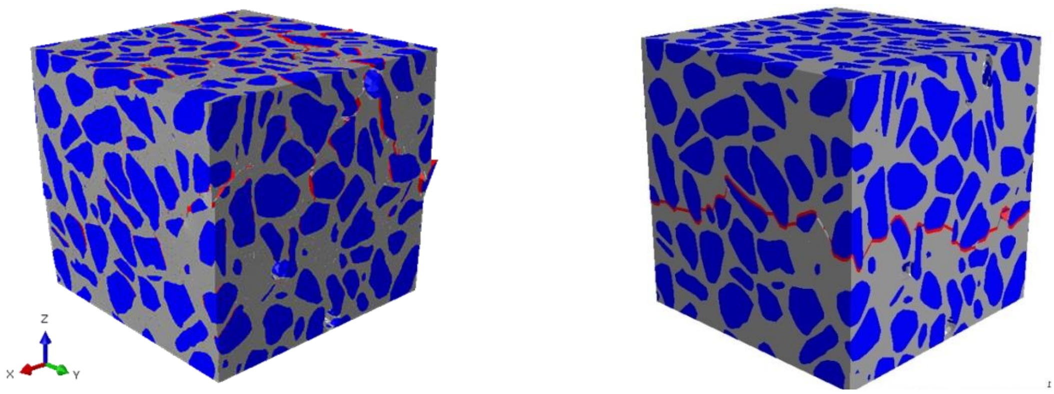


(a) *d*=0.020mm (b) *d*=0.033mm (c) *d*=0.073mm

Figure 6. Crack propagation process (*DSF*=10, *SDEG*>0.99)

Simulations of uniaxial compression and tension

The FE model in Fig. 3 was also simulated under the uniaxial compression and tension loading conditions. Fig. 7a shows that the distributed crack pattern under uniaxial compression is quite different from that under the previous Brazilian-like compressive loading case. In Fig. 7b, the 3D crack surfaces under uniaxial tension are linked to form a major crack path.



(a) uniaxial compression (b) uniaxial tension

Figure 7. Simulated crack patterns (*DSF*=10)

The predicted stress-strain curves from the 2D statistical modelling results [9] and the 3D simulation under uniaxial tension are compared in Fig. 8. It can be seen that the results in the initial elastic stage and the final cracked stage are close between 2D and 3D cases, but the predicted tensile strength of 5.0MPa in 3D is much higher than the mean value of 3.3MPa in 2D. The main reason is that the formation of 3D cracks needs higher fracture energy than in 2D, due to the resistance from randomly distributed aggregates and the larger crack surfaces providing higher normal tractions across the cracks in 3D [6].

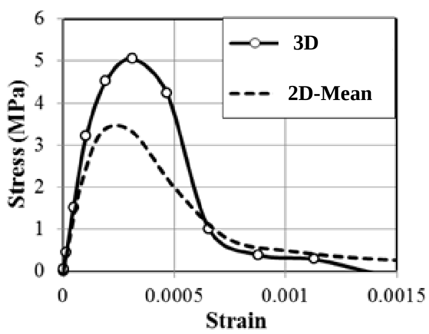


Figure 8. Stress-strain curves predicted by 3D simulation and 2D statistical analysis

Conclusions

In this study, a 3D meso-scale XCT-image based cohesive crack modelling technique is developed for complex fracture analysis of concrete. Direct comparisons of FE simulation results with in-situ XCT tests have been made with good quantitative agreement between the peak forces and satisfactory qualitative agreement between the crack patterns. The 3D simulation of uniaxial tension loading predicts a higher strength than the mean value of 2D statistical results. Although further works are needed, the combination of the in-situ XCT tests and image-based cohesive crack modelling proves very promising in studying the complicated 3D fracture mechanism in quasi-brittle composite materials like concrete.

Acknowledgements

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