International Journal of Solids and Structures 67–68 (2015) 340–352

Contents lists available at ScienceDirect

International Journal of Solids and Structures

journal homepage: www.elsevier.com/locate/ijsolstr

3D meso-scale fracture modelling and validation of concrete based on in-situ X-ray Computed Tomography images using damage plasticity model

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A R T I C L E I N F O

Article history:
Received 22 January 2015
Received in revised form 23 April 2015
Available online 9 May 2015

Keywords:
Mesoscale modelling of concrete
In-situ X-ray Computed Tomography
Voxel hexahedron meshing
3D image based modelling
Damage plasticity model

A B S T R A C T

Three-dimensional (3D) meso-scale finite element models of concrete based on in-situ X-ray Computed Tomography (XCT) images are developed and validated in this study. The micro-scale images from a Brazilian-like XCT test are first compressed and then transformed into manageable meso-scale 3D meshes using a voxel hexahedron meshing technique with a stacking algorithm. The continuum damage plasticity model is used to simulate complicated damage and fracture behaviour. Excellent qualitative agreement is found between modelling and the XCT compression test in terms of damage evolution and fracture process on both the surface and interior of the specimen. 3D uniaxial tension tests are also simulated, and it is found that the distribution of voids have profound influences on the strength and crack patterns. The image-based 3D models are proved very promising in elucidating fundamental mechanisms of complicated crack initiation and propagation behaviour that 2D studies are incapable of modelling.

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1. Introduction

Traditional concrete fracture models assuming homogeneous material properties often predict unrealistically smooth or wrong crack paths and load-carrying capacity of unknown reliability due to its multi-phase, heterogeneous internal structures at micro/meso-scales (Bocca et al., 1991; van Vliet and van Mier, 1996; Schlangen and Garboczi, 1997; Gutierrez and De Borst, 1999; Yang and Xu, 2008; Yang et al., 2009; Su et al., 2010). It is highly necessary to conduct micro/meso-scale modelling for accurate understanding of complex damage initiation and evolution until failure, and relationships between physical properties of multi-phases and macro-scale mechanical responses (Baxter et al., 2001; Vořechovský, 2007; López et al., 2008; Grassl and Rempling, 2008; Grassl and Jirásek, 2010; Ren et al., 2014).

As to meso-scale modelling, the meso-structures can be directly represented by different phases artificially generated and randomly distributed in space (Lilliu and van Mier, 2003; Caballero et al., 2006; López et al., 2008; Man and van Mier, 2008a; Song and Lu, 2012; Du et al., 2013), or be indirectly modelled by random fields satisfying certain correlation functions describing heterogeneous material properties (Baxter et al., 2001; Graham and Baxter, 2001; Vořechovský, 2007; Yang and Xu, 2008; Yang et al., 2009; Su et al., 2010). However, most of these studies use assumed meso-scale morphologies or random fields that are not the same as real internal structures so that the numerical models cannot be directly validated. In addition, most of the existing studies are in 2D and cannot predict non-planar 3D fracture surfaces in reality. Consequently, the simulated results may be neither representative nor fully verifiable. This has led to development of numerical models that are converted from images captured by digital cameras and microscopes, etc. (Yue et al., 2003; Young et al., 2008; Michailidis et al., 2010). In this way, more accurate micro/meso-structures can be directly simulated.

Recently, the high-resolution, non-destructive X-ray Computed Tomography (XCT) technique with multi-length scale capabilities becomes increasingly popular to characterise microstructures and properties of many materials, such as geological materials (rock, soil and fossils) (Carlson, 2006), metals and alloys (Babout et al., 2006; Marrow et al., 2006; Qian et al., 2008), porous materials (Kerckhofs et al., 2008), composites (Drummond et al., 2005), asphalt mixtures (Song et al., 2006), cement (Meyer et al., 2009)

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http://dx.doi.org/10.1016/j.ijsolstr.2015.05.002
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and concrete (Garboczi, 2002; Wang et al., 2003; Trtik et al., 2007; Landis and Bolander, 2009; de Wolski et al., 2014). However, 3D XCT images have only occasionally been used to build geometrically realistic numerical models to study the mechanical behaviour of materials, for example, by Hollister and Kikuchi (1994) for trabecular bones, Terada et al. (1997) for metal matrix composites, Ali et al. (2009) for carbon/carbon composites, McDonald et al. (2011) for foams and Manning et al. (2009) for dinosaurs. In most of these studies, simple linear elastic stress analyses were carried out, or effective stiffness constants based on homogenisation methods were calculated. Modelling nonlinear damage and fracture of materials with complex, realistic microstructures has received increasing but still limited attention. For example, Mostafavi et al. (2013) modelled crack opening and fracture process zone in poly-granular graphite and Sharma et al. (2012) modelled interfacial damage in carbon/carbon composites, both using XCT image-based models. Man and van Mier (2008b, 2011) built XCT image-based lattice models and analysed the size effect of 3 point bending concrete beams with length up to 50 mm. Asahina et al. (2011) built lattice models for concrete made of mortar and spherical glass beads as aggregates, and the simulations captured the peak loads and crack patterns in good agreement with the XCT test results.

More recently, the authors carried out in-situ XCT tests and observed damage evolution and fracture process in concrete cubes under compression (Yang et al., 2013). The XCT-images were converted to finite element (FE) meshes using commercial packages AVIZO and Simpleware, for 2D and 3D cohesive fracture modelling with limited success (Ren et al., 2014, 2015) and 3D homogenisation of elastic properties (Sharma et al., 2014). However, in the commercial packages, 3D surface contours are extracted from image datasets and then discretised in mesh generation (Canton and Gilchrist, 2010), which often results in many distorted FE elements when large element sizes are used, or otherwise millions of elements that are beyond the power of conventional computers.

In this study, we develop a novel 3D XCT-image based meso-scale FE fracture modelling method for concrete, and attempt to validate 3D damage initiation and evolution until failure predicted by the models. The voxel hexahedron meshing method (Keyak et al., 1993; Hollister and Kikuchi, 1994; Crawford et al., 2003; Mishnaevsky Jr, 2005) is augmented with image compression and slice stacking algorithms to efficiently generate 3D FE meshes. It avoids the problem of commercial packages and is able to control the mesh density while maintaining the original 3D morphology. The concrete damage plasticity (CDP) model in ABAQUS is used to simulate complicated damage initiation and evolution in concrete under compression and tension. The in-situ XCT test of a concrete cube under Brazilian-like compression (Yang et al., 2013) is modelled to validate the developed method, followed by detailed investigation of conventional uniaxial compressive and tensile tests using the image-based models.

2. XCT-image based hexahedron mesh generation

Most of the existing image-based 3D FE models using voxel hexahedron meshing are constructed by direct conversion of voxels in images to the same-sized cubic finite elements (Hollister and Kikuchi, 1994). They cannot readily adjust element size while faithfully maintaining the original morphology. In this study, a bottom-up algorithm with the following steps is proposed and fully automated in a MATLAB code.

2.1. 2D image processing

For each slice of images from the in-situ XCT test (Yang et al., 2013), there are 372 pixels of 0.1 mm in both directions in the reconstructed and sampled image dataset (Fig. 1a). The grey value of pixels ranges from 0 to 255 and drastically fluctuates near the phase interfaces. Segmentation is conducted on each slice using proper thresholds, resulting in ternary images with 1 for aggregates, 2 for mortar and 3 for voids (Fig. 1a, refer to (Ren et al., 2015)). To build lower resolution models, the segmented images are compressed by re-building connectivity of aggregate pixels. Adjustment of grey value of a small number of pixels is then carried out to maintain the morphological details. Fig. 1b and c show the compressed images with 0.2 mm and 0.4 mm pixels, respectively.

2.2. Slice stacking

The 2D image slices are then stacked along the loading direction (z axis) to generate voxels (Fig. 2). In the widely-used stacking algorithm (Terada et al., 1997; Huang and Li, 2013), each voxel is directly converted into an eight-noded hexahedral element and used for modelling inclusions of simple shapes. However, to model complicated aggregates and voids in concrete of this study so as to maintain the true internal morphology, further operations on the voxels are carried out to avoid cases such as contact between aggregates, mortar inside aggregates etc. Furthermore, stacking along other directions is done as a double check and the effect of stacking direction is discussed in Section 2.4. Fig. 3a and b shows the resultant morphology of aggregates and mortar, respectively. The initial cracks and voids are shown in Fig. 3c.

2.3. Identification of interfacial transition zone (ITZ)

In this step, the mortar voxels connected with aggregate voxels are identified and used to model the weaker aggregate-mortar

(a) 372×372 pixels (0.1mm) (b) 186×186 pixels (0.2mm) (c) 93×93 pixels (0.4mm)

Fig. 1. Image compression.

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