CHARACTERISATION OF 3D FRACTURE EVOLUTION IN CONCRETE USING IN-SITU X-RAY COMPUTED TOMOGRAPHY TESTING AND DIGITAL VOLUME CORRELATION

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Abstract: X-ray Computed Tomography (XCT) is a powerful technology that can accurately image the internal structures of composite and heterogeneous materials in three-dimensions (3D). In this study, in-situ micro XCT tests of concrete specimens under progressive compressive loading are carried out. The aim of the observations is to gain a better understanding of 3D fracture and failure mechanisms at the meso-scale. To characterise the fracture evolution as the deformation increases, two methods are used. The first segments the reconstructed absorption contrast XCT images using AVIZO software into different phases, namely, aggregates, mortar, cracks and voids. The second uses the digital volume correlation (DVC) technique to map the relative deformations between consecutive XCT images with high precision; bulk mechanical properties can be measured and cracks visualised via their opening displacement. The 3D crack profiles obtained by these two methods are compared, and the contributions that they can make to image-based modelling and its validation are noted.

1 INTRODUCTION

Quasi-brittle multiphase composite materials, such as concrete, bones, fibre-reinforced plastics (FRP) and ceramic/metal matrix composites are widely used in engineering structures of many industries. A better understanding of their mechanical behaviour can lead to development of materials with higher load resistance, cost-effective manufacturing processes and optimal structural designs. Due to random distribution of multiple phases from nano-, micro-, meso- to macro-scales, multiphase composite materials have intrinsically heterogeneous nonlinear mechanical properties, which in turn directly determine the performance and reliability of structures and systems. Therefore, understanding their mechanical properties including damage and fracture at different scales, through both experimental studies and computational modelling, becomes one of the most critical and challenging engineering and scientific problems [1-2].

The X-ray computed tomography (XCT) technique, a 3D imaging technique routinely used in hospitals, is now becoming more and more popular in characterising internal nano/micro/meso-scale structures of many materials, because of its high resolution, non-destructive nature, and clear visualisation of details including different phases, interfaces, pores and cracks. However, most of the existing XCT studies aim to acquire the internal structures of intact materials without external loading, or damaged materials after loading, namely post-mortem. In-situ XCT studies, which scan the internal structures of materials under progressive loadings so that the structural damage and fracture evolution can be examined and related to the loading process [3], are still rare, mainly due to the lack of in-situ XCT facilities.

In this study, in-situ micro XCT tests of concrete specimens under progressive compressive loading are carried out. The study has two purposes: to get better understanding of the 3D fracture mechanisms of concrete as the load progresses, and to serve as a benchmark for directly validating image-based 3D cohesive crack models. The following sections present the details of in-situ XCT tests, visualisation, characterisation and segmentation of aggregates, cement, voids and cracks using AVIZO. The cracks are also characterised and visualised by the digital volume correlation (DVC) technique applied to the XCT images [4-6]. The 3D crack profiles obtained by these two methods are compared, with their respective merits and demerits discussed.

2 IN-SITU XCT TESTS

Concrete cube specimens of size 40 mm and target cylinder compressive strength 15 MPa were cast in the lab. The strength and the size of specimens were chosen so that the specimens could be loaded to failure by the XCT loading rig, which has a loading capacity of 25 kN. The cement is ordinary Portland cement. The aggregates are gravels with an average size 5 mm. No fine aggregates (i.e. sand) are used, so as to ensure a simple structure.

The in-situ experiment was carried out at the Manchester X-ray Imaging Facility (MXIF), the University of Manchester, using the 320 kV Nikon Metris custom bay, as shown in Fig. 1. The loading rig, consisting of a Deben micro-test stage supporting a transparent cylinder, was mounted on the circular stage of the XCT machine. Two steel pads, glued by double-side adhesive tapes to the centre of the top and bottom surfaces of the specimen, provide a loading area of 17.5 mm×17.5 mm (i.e. 19% of sample cross-section area). They were centred inside the enclosed cylinder for tests, as in Fig. 2, where a failed concrete specimen is also shown.

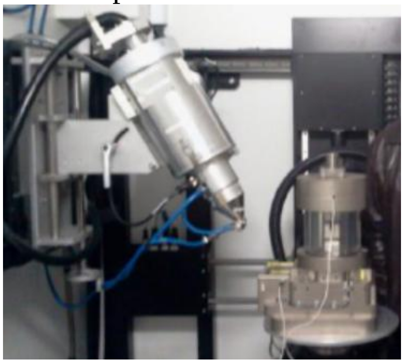


Figure 1: The in-situ XCT facility in MXIF

Figure 2: A specimen under loading and after the test

Fig. 3 illustrates the in-situ XCT test procedure. The first scan was conducted without loading. The load was then applied via compression at a displacement rate of 0.5 mm/min to 2.5 kN, at which point the second scan was carried out. The load was then released. The specimen was then reloaded to 6 kN at the same rate and the third scan was done. The fourth scan was conducted similarly at 10 kN and the fifth at 16.5 kN, after which the crack widened quickly. The loading and scanning scheme is shown in Fig. 3 (unloading data were not recordable).

Following some optimisation, each X-ray scan was conducted with 160 kV and 60 μA intensity. For each scan, the stage was rotated by 360°, resulting in 2000 2D radiographs in TIFF format with pixel resolution 37.2 µm. It took about 2 hours for each scan to complete. The 2D radiographs were reconstructed as absorption contrast images using the CT Pro and VG Studio software. Artificial defects such as beam hardening and ring effects were removed by post-processing. Each 3D data set was initially about 15 Gb in size. To reduce the data processing time, the 3D data volumes were cropped to cubes of side 37.2 mm (i.e. 1000 pixels in each dimension). This reduced the data size to 2 Gb for each scan, with the bit depth also reduceded from 32 bit float to 16. Fig. 4 shows the workflow of reconstruction process.

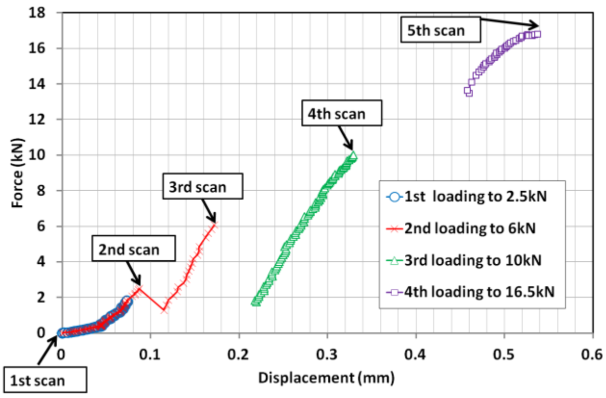


Figure 3: In-situ XCT test procedure

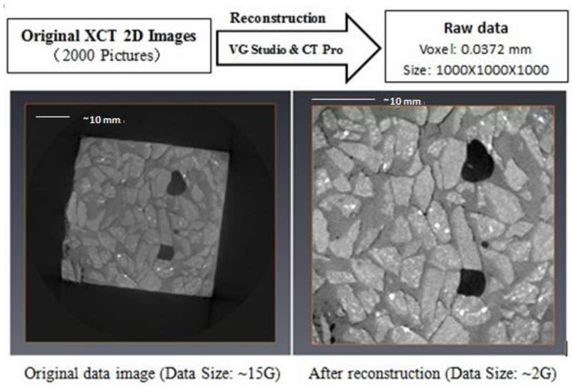


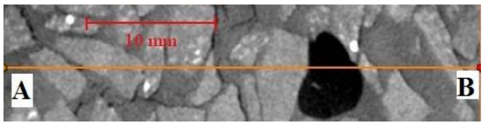
Figure 4: Workflow of reconstruction

3 VISUALISATION AND SEGMENTATION

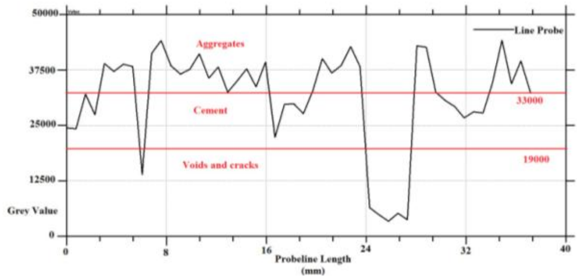
The software AVIZO® was used to visualise the 3D crack evolution during loading, and segment the XCT images into different phases for qualitative and quantitative analyses, and future image-based numerical modelling. A segmentation procedure was developed and outlined below using the images at 16.5kN as an example.

3.1 Determination of thresholds for phases

The Line-Probe command was used to determine a proper threshold of grey value to segment each phase. Straight lines were drawn on 2D images of the sample cross-sections, and the variations of the grey values (i.e. absorption contrast) along the lines were obtained. These variations were then carefully compared with the 2D images to determine the appropriate threshold for each phase. Figure 5 shows an example. The sensitivity to location was examined to verify that the threshold values reliably segmented each phase. The chosen threshold was >33000 for aggregates, <19000 for voids and cracks; values between them were identified as cement. The full grey scale is 0~65535.



a) Line-probe path AB



b) Variation of grey values along AB

Figure 5: Determination of thresholds for phases

3.2 Segmentation

The thresholds are then used in AVIZO to segment the XCT images into three phases (cement, aggregate, voids and cracks) under different loadings. However, using thresholds alone to segment microstructure is unreliable, due to issues from connected aggregates and missed areas (“islands”). As the objective was to extract an image-based 3D model of the microstructure, a series of manual operations on the 2D slices are carried out to supplement the initial assignment of microstructure by thresholding; this included separation of connected aggregates and addition of missed areas. Fig. 6 and Fig. 7 show the segmented aggregates, voids and cracks on a typical slice, respectively. The segmented cement is shown in Fig. 8, obtained by an image operation that subtracts aggregates, cracks and voids from the original image. The detailed segmentation procedure can be found in [7].

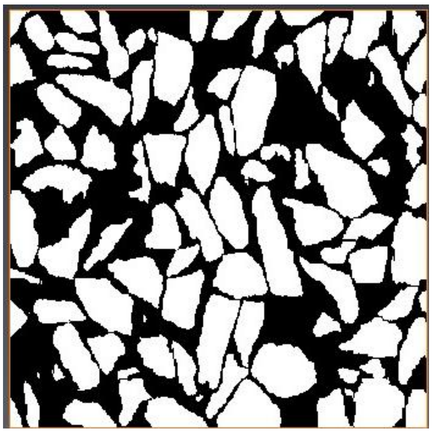


Figure 6: Segmented aggregates

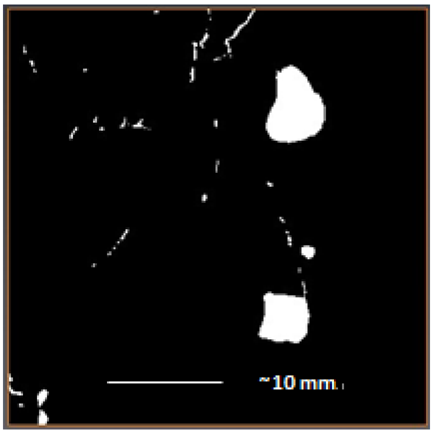


Figure 7: Segmented voids and cracks

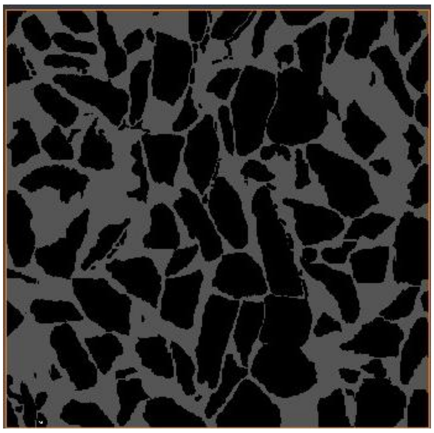
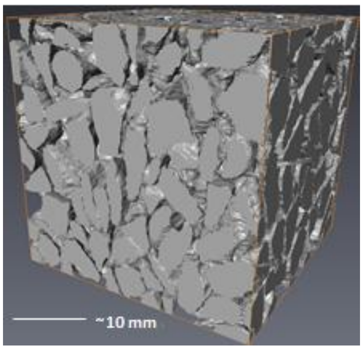


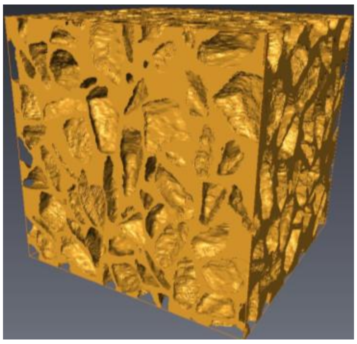
Figure 8: Segmented cement

3.3 Visualization of three phases in 3D

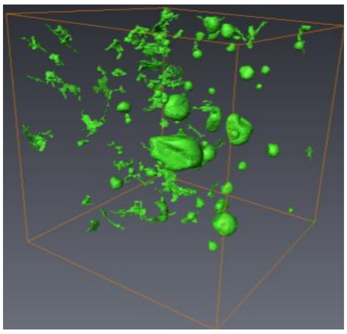
From the segmented 2D image slices in three directions, the 3D aggregates, cement, voids and cracks can be visualized. Figs 9(a-d) show the segmented aggregates, cement, cracks and voids, and the combined concrete of the specimen without load. The segmented cracks and voids, and the combined concrete at the peak load 16.5kN are shown in Fig. 10a and 10b, respectively. The definition of cracks is based on the threshold of grey values (19000 in Fig. 5) and is thus not entirely objective, there may also exist initial cracks in the unloaded specimen as shown in Fig. 9c. The major cracks on the specimen surface in Fig. 10b are roughly vertical, which is a feature of concrete specimens fractured under uniaxial compression. Comparison of Fig. 9c and Fig. 10a clearly demonstrates the effects of loading on the crack propagation. The complex multi-crack pattern is essentially 3D. Although both the specimen geometry and the loading and boundary conditions are almost symmetric, the crack pattern is not symmetric. This reflects the effects of the random distribution of aggregates and thus the heterogeneous nature of mechanical properties of concrete.



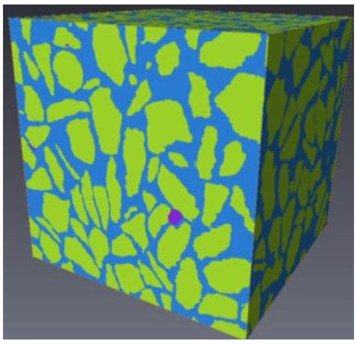
a) Aggregates



b) Cement

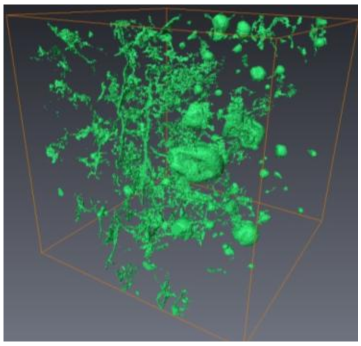


c) Voids and cracks

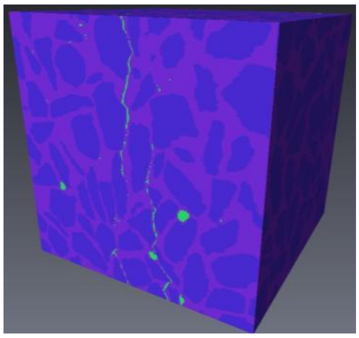


d) Concrete

Figure 9: 3D Segmented phases without load



a) Voids and cracks



b) Concrete

Figure 10: 3D segmented phases at peak load

3.4 Evolution of voids and cracks

The volumes of the voids and cracks (with grey values lower than 19000) in the specimen under different loads are calculated in AVIZO and Figure 11 shows the void fraction under continuous loading steps. The observed volume of voids and cracks first decreases as the load increases. This is attributed to compaction of the concrete under compression; this causes part of the observed void population to fall below the detection threshold of XCT at this resolution. As the load increases further, cracks gradually occur, leading to higher volume of cracks and voids. Near and after the peak load, major vertical cracks propagate fast, leading to dilation in the specimen.

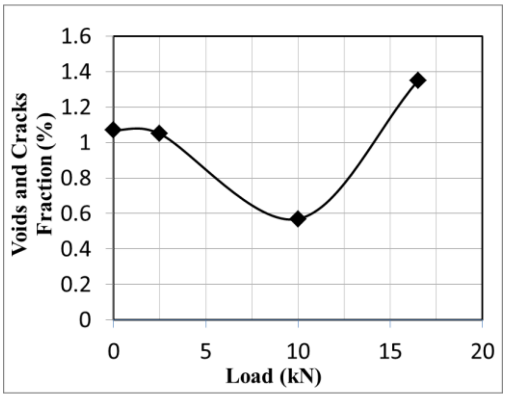


Figure 11: Evolution of cracks and voids

4 DIGITAL VOLUME CORRELATION

Measurements of the full 3D displacement field within the material by the 3D digital volume correlation (DVC) technique [4-6] can provide useful insights and quantitative measurements of the processes of damage development. In particular, DVC can measure crack opening displacements that are smaller than the voxel size, and so identify cracks that are too narrow to be detected by threshold-based segmentation [5].

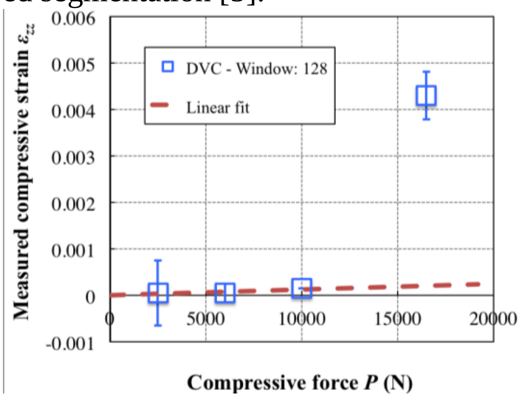


Figure 12: Measurement of elastic strains and damage development by CT and DVC.

In the first analysis, a large interrogation window size (128x128x128 voxels with 2 passes and 50% overlap) was used to calculate the overall distribution of strain. This provided data to measure the bulk strains in the sample. In the second analysis a smaller integration window was selected (128x128x128 voxels, 50% overlap and 2 passes followed by a 64x64x64 voxels, 50% overlap and 2 passes). Decreasing the window size decreases the precision of DVC measurement, but is useful to visualisation of cracks.

Figure 12 shows the bulk compressive strain calculated by DVC (large window size). To measure the strain, the vertical displacements of top and bottom slices were extracted from DVC analysis. The compressive strain was then obtained as the ratio of the relative vertical displacement between opposing points on the top and bottom slices to their vertical separation. The figure shows the mean and standard deviation of these measurements. A linear fit to the data up to 10.5 kN gives a modulus of 51 GPa; beyond this the damage to the specimen from cracking causes the strain to increase significantly as the specimen softens. The expected modulus of concrete is of the order of 30 GPa; the smaller area of load relative to the sample cross-section is the likely cause of the apparently higher modulus.

Figure 13 shows a comparison between the same vertical slice near the specimen centre in the XCT and DVC data as the load is increased from 2.5 kN (left) to 16.5 kN (right). The DVC analysis shows the nominal maximum principle strain, which reveals the complex pattern of cracking in a more sensitive manner than segmentation of the XCT data. However, artefacts, due to errors from large pores, can also be seen in the DVC data; these might be removed by post-processing guided by the XCT absorption data.

An example of a 3D visualisation of the crack using the DVC nominal strain data at 16.5 kN is shown in Figure 14. The surface is not well defined, due to the window size that is used in the analysis, but the crack profile is more completely defined than that in Figure 10.

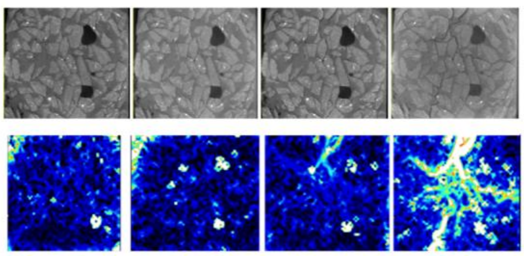


Figure 13: Comparison of damage development in a vertical slice of the data; by XCT (top) and DVC (bottom), as the applied load increases from left to right.

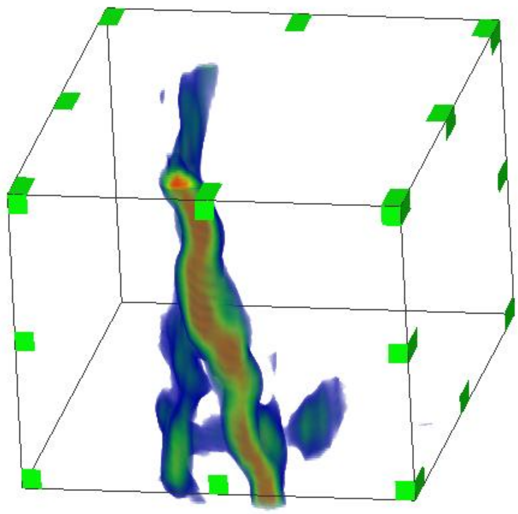


Figure 14: A three-dimensional representation of the macromechanical crack, using the DVC measured nominal maximum principle strains. Hotter colours (red) are higher crack opening displacements.

5 CONCLUSIONS

In this study, in-situ micro XCT tests of concrete specimens under progressive compressive loading have been carried out to help obtain a better understanding of 3D fracture and failure mechanisms at the meso-scale. Two methods have been used to quantify and visualise the fracture evolution as the deformation increases. The segmentation procedure is able to separate the concrete into three distinguished phases and the cracks are visualised directly by specifying a threshold. Damage may be quantified by the variation of volume fraction of cracks and voids. Features below the segmentation threshold, such as narrow cracks and small voids, are not resolved, but the segmented microstructures may be used as inputs for image-based finite element models. The DVC technique maps the relative deformations between consecutive XCT images with high precision; bulk deformation can be measured and cracks visualised indirectly via their opening displacement or strain, which may be quantified. The 3D crack profiles obtained by the two methods are comparable. In principle, the DVC measured displacements may be used to validate the predictions of image-based finite element models, which are derived from segmented XCT data. The combined use of these techniques is therefore a valuable tool for the study and modelling of damage mechanisms in materials such as concrete.

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