

3D ANALYSIS OF X-RAY MICROTOMOGRAPHIC CONCRETE IMAGES

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ABSTRACT

A threshold-based method and a motion-based method are applied to recovering and analyzing the cracks in X-ray microtomographic concrete images. The motion-based method provides better results than the threshold-based method. The recovered surfaces of segments and cracks are presented and used for statistical measurement.

Keywords: X-ray microtomography, fracture mechanics, image processing, concrete fracture

INTRODUCTION

Concrete and mortar are quasi-brittle, heterogeneous materials whose fractures are characterized by a wide range of physical processes (van Mier 1997). Although it is known that the microstructural processes ultimately govern the fracture behavior, it has typically been ignored because “understanding of this problem is particularly weak” (Bažant 1995). Due to the lack of good experimental microstructure data, most previous research in fracture modeling aimed to understand and predict only the bulk fracture response. The studies of fracture energy in 2D and 3D were also conducted at a low resolution. They did, however, demonstrate that two-dimensional models are not effective in investigating concrete, which exhibits complex 3D fracture surfaces (Nagy et al. 2003).

X-ray microtomography (Slate and Olsefski 1963; Flannery et al. 1987; Deckman et al. 1991) can generate multiple volumetric representations of the internal structures of a concrete specimen during its fracture evolution under a metered loading process at an unprecedented resolution (Landis et al. 1997; Landis et al. 1999). We have developed two methods to locate and measure the crack surfaces within a digitized volume of concrete: one that is based on intensities, and the other that is based on the motions of the fracture segments. The motion-based method, which captures distinct motions of fracture segments, depicts the boundaries of fractured segments much more accurately than the intensity-based thresholding method. By extracting the 3D polygonal models of crack surfaces, a key statistic in fracture analysis, the surface area of cracks, can be computed directly. This statistic is important as it is proportional to the work-of-fracture according to Griffith-type analysis (Broek 1986; Bažant 1996). These polygonal surface models are also suitable for visualizing the 3D crack surfaces interactively.

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We will first discuss the threshold-based method, followed by explanation of the motion-based method. The results from the motion-based method are presented next. We conclude our paper by summarizing the advantages of motion-based method.

THRESHOLD-BASED METHOD

In the threshold-based method, cracks are analyzed by thresholding followed by connected component (CC) analysis (Ronse and Devijver 1984; Samet 1989; Borgefors et al. 1997). We applied a robust CC algorithm developed by Franklin (Franklin 1999) that is both space- and time-efficient. In testing a concrete data set of size $800 \times 800 \times 765$ (489,600,000 voxels), it finds six million six-connected components in 200 seconds (400 MHz Pentium with 640Mbytes of RAM), with about one third of the time spent on I/O. In addition to listing every connected component with its constituent voxels, the program reports the volume, surface area (number of free faces) and the number of foreground runs in each component. Based on this connected-component analysis implementation, some routines were developed to analyze the volume distribution, the histogram of free surfaces, and the surface area to volume ratio of the largest components. Most of the statistical results can be found in (Nagy et al. 2001).

This method yields over one million connected components at each threshold. The excessive number of connected components was caused by the non-uniform intensity of the material, the many dark micro-cracks and air-holes, and the side effect of long cracks being divided into shorter cracks at constrictions narrower than the point-spread function of the imaging system. Although we were able to derive some information about the bulk growth of crack volume and tortuosity under load, visualization of so many small connected components with convoluted boundaries was slow and yielded little insight into their structure.

Since this approach processes each image individually, the large number of connected components also makes it difficult to compare or find consistencies between the results from different images. We therefore developed a new method based on motion.

MOTION-BASED METHOD

In the motion-based method, the cracks are recovered in three phases: (a) *preprocessing*, which extracts the concrete region of interest, (b) *motion estimation*, which estimates a 3D displacement vector field from pairs of images, and (c) *motion segmentation*, which recovers multiple fractured concrete segments by grouping the displacement vectors according to the principle of Minimum Description Length (MDL) (Rissanen 1978). For measurement of surface area and visualization, the triangulated surface meshes of multiple fragments and cracks are generated with the Marching Cubes algorithm (Lorensen and Cline 1987). For efficiency, the last two steps are iterated in a multi-resolution scheme that takes advantage of results at a lower resolution to process the data at the next higher resolution. Each phase is briefly discussed in the following. Additional details can be found in (Zhang and Nagy 2003).

Preprocessing

The images in the original concrete sequence are of different sizes. They also exhibit large areas of dark background without concrete. In preprocessing, we first crop each image to a uniform size, large enough to cover all concrete region, by resampling around its centroid.

To prevent motion estimation in the void region outside concrete, a ‘shrink-wrapping’ procedure, implemented using a fast-marching level set method (Malladi et al. 1995), is applied slice by slice. Figure 1 displays several snapshots of shrink-wrapping one sample slice. This model-based segmentation preserves the protrusions and indentations on the boundary of ob-

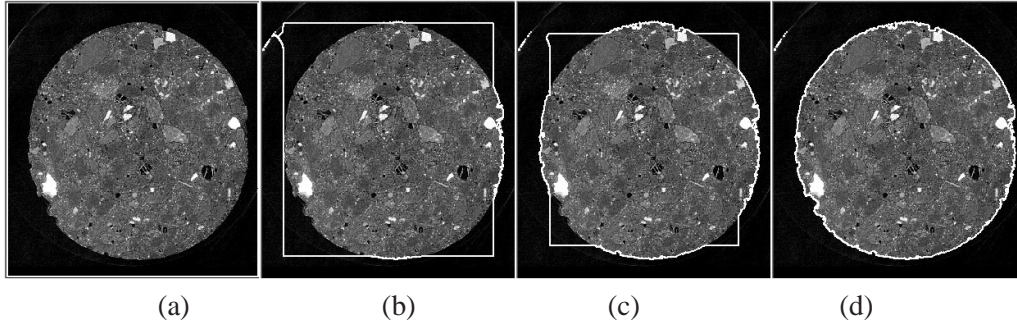


FIG. 1. A fast-marching level set method extracts the material region by shrinking the contour at each iteration until it reaches an edge with high gradient: (a) the contour at initialization; (b) the contour after 2400 iterations; (c) the contour after 4800 iterations; (d) the contour after convergence.

jects. The largest connected components from every slice are stacked together and form the concrete region of interest.

Estimation of 3D Displacement Vector Field

A block-matching method is applied to estimate 3D displacement vectors using intensity-based registration. Each displacement vector is estimated by finding the maximum normalized cross correlation between a correlation window in the first image, and a same-sized region in a larger search window in the second image.

Sequential similarity detection algorithms (SSDAs) developed by (Barnea and Silverman 1972) achieve fast computation by calculating the sum of absolute differences between pixel pairs. In adapting SSDAs to 3D, we further improved their efficiency by restricting the number of voxels used in the search window and the size of the search space. Figure 2 shows two examples of sparsely estimated 3D displacement vector fields.

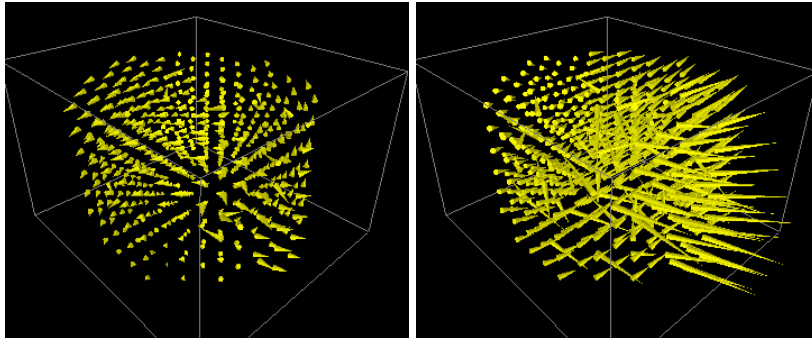


FIG. 2. Sample 3D displacement vector fields with small and large motions. The height of directional cones is proportional to the amplitude of the displacement vectors, and is magnified for viewing.

Grouping of Displacement Vectors

The neighboring locations in the same object undergo the same or similar motions, while those in different objects have distinct motions. We iteratively cluster the displacement vectors according to the principle of Minimum Description Length (Rissanen 1978) to achieve segmentation.

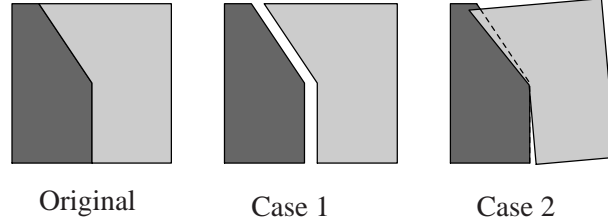


FIG. 3. Motion and connectivity constraints as a result of object fragmentation: Case 1 is a possible situation where two child objects move apart; Case 2 is an impossible situation where two child objects inter-penetrate. Each child object is one connected component.

1. Start with each voxel as a single connected component whose motion parameter is based on its displacement vector. Calculate the total description length.
2. Try merging every pair of neighboring connected components that collide under motion. For every candidate merge, re-estimate the motion model parameters and calculate the change in total description length.
3. If the largest change among all candidate merges decreases the total description length, replace the minimum description and reiterate. Otherwise, the procedure ends.

Two constraints are applied during grouping to ensure valid segmentation. *Connectivity Constraint*: each recovered object must be a connected component. *Motion Constraint*: objects cannot collide or inter-penetrate as one object splits into multiple objects with individual motions (Figure 3).

The connectivity constraint is satisfied by the structure of the algorithm because every merge of two neighboring connected components becomes another connected component. To preserve topological integrity, different connectivity must be used for foreground and background. We postulate cubical voxels, face-connectivity for foreground, and vertex-connectivity for background. Edge-connectivity is not used.

The motion constraint is satisfied because the connected components that collide under motion are merged unless they only touch without inter-penetration. The implementation of collision detection between connected components is based on Gottschalk’s simple and efficient solution that uses the *separating axis theorem* to detect whether two 3D rectangular bounding boxes collide (Gottschalk et al. 1996).

Multi-resolution Scheme

We first sparsely estimate a displacement vector field and recover the fragmented concrete segments at a low resolution. This coarse result is then used to estimate the displacement vector field at the higher resolution and to update the boundary surfaces of fragmented objects. This process continues until reaching the highest resolution.

The multi-resolution scheme greatly improves processing efficiency on large 3D concrete data sets for several reasons. Firstly, the propagation of the displacements, from the lower resolution to their neighborhoods at higher resolutions, provides accurate initial estimates of the displacement vectors. Secondly, collision between two connected components needs to detect only the neighboring voxels at the lower resolution, and only the collision regions at the higher resolution. Thirdly, interior voxels are assigned to the same object directly, without any MDL calculation.

RESULTS

Sequence-B, composed of four images, is used for testing. We refer to each image as B1, B2, B3 and B4. B1 has no cracks. Widening cracks are observable from B2 to B4. The size of each preprocessed image is $704 \times 768 \times 512$. Because the specimen crumbles near the top and bottom, the fractures are detected only within the section from slice 64 to slice 448. Each test starts at the lowest resolution, where the fractured objects are identified based on a displacement vector field sparsely estimated at every 64-th voxel position. Then the boundary surfaces of fragments are updated based on new displacement vector fields estimated at higher resolutions of every 32nd, 16th and 8th voxel positions. All tests were conducted on a computer with Xeon 2.4G CPU running Linux OS. We intend to push the resolutions even higher, but this will require either multi-day runs or cluster computing.

Fractured Segments in B2

Two segments are identified, occupying about 64% and 36% of the total volume (Table 1). Their centroids remain stable as the resolution increases. The centroids and relative sizes of these two segments are better illustrated by a bubble plot (Figure 4), where the area of each circle is proportional to the object size, and the center is at the object centroid. Since objects are in 3D, we have two plots for each resolution, projected on the XY and XZ planes.

Resolution	64	32	16	8
# Segments	2	2	2	2
Size(%)	63.99 36.01	63.24 36.76	63.35 36.65	65.06 34.94
Centroid (x,y,z)	449,421,246 223,304,275	450,422,252 222,304,264	451,420,253 219,307,260	445,421,255 218,299,258
Surface area of cracks	475558	539469	600997	650349
% of Total surface area	79	76	73	70
Processing time (s)	2	5	91	6315

TABLE 1. Statistics of the two segments recovered based on the displacement vector field between B1 and B2.

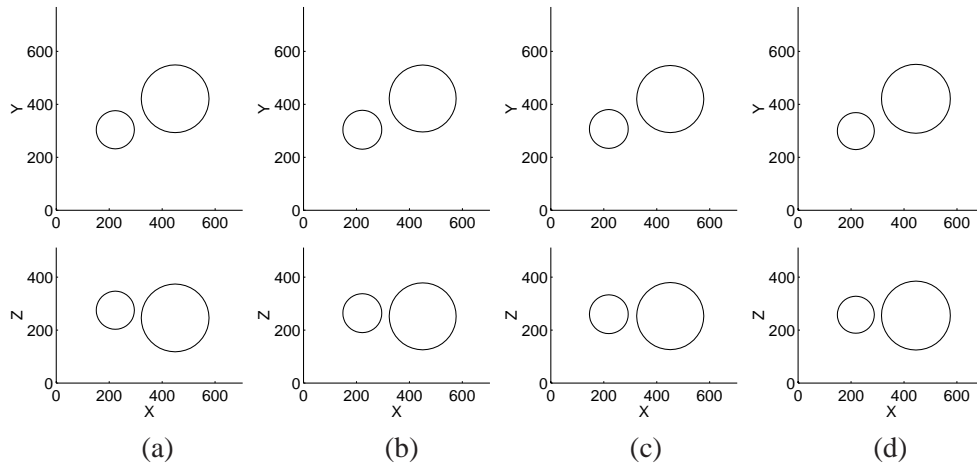


FIG. 4. Bubble plots of the two recovered segments in B2 showing their relative sizes and centroids at resolutions of (a) 64, (b) 32, (c) 16, (d) 8.

The total crack surface area includes two parts: *crack surfaces*, where the concrete concrete segments have been separated, and *non-crack surfaces*, where concrete segments are still in contact. The crack surface and its percentage with respect to the total surface area are listed in the table. The percentage of crack surface area tends to decrease slightly as the result of locating pivotal connections among segments as the resolution increases. The fact that 30% of the total surfaces remains in contact indicates that part of the crack between these two segments remains invisible at the 8 cubic voxel resolution.

Fractured Segments in B3

Four segments are located at every resolution (Table 2). Among these four segments, the largest two cover most of the volume. As the resolution increases, their relative sizes stay quite stable, as observed from the bubble plots (Figure 5). Unlike load case B2, the percentage of crack surfaces with respect to the total surface area in this case is close to 100%. This indicates that the specimen is almost fully separated with some minor pivotal connections.

Resolution	64	32	16	8
# Segments	4	4	4	4
Size(%)	51.74	51.72	51.62	51.44
	41.68	42.00	42.01	42.04
	4.02	4.32	4.10	4.21
	2.56	2.33	2.27	2.31
Centroid (x,y,z)	483,420,254	481,422,255	482,421,256	483,421,255
	218,372,262	218,369,261	217,368,260	217,369,260
	361,90,291	366,99,269	363,102,269	361,102,263
	466,105,155	475,109,155	480,112,166	482,111,177
Surface area of cracks	570426	754281	847101	921769
% of Total surface area	100	100	99	99
Processing time (s)	1	5	129	11909

TABLE 2. Statistics of the four recovered segments in B3.

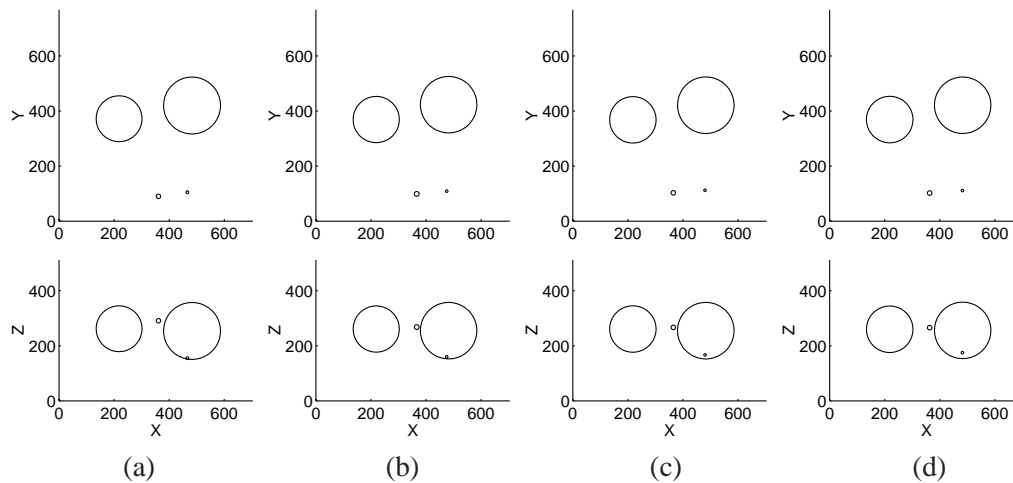


FIG. 5. Bubble plots of the four recovered segments in B3 showing their relative sizes and centroids at resolutions of (a) 64, (b) 32, (c) 16, (d) 8.

Fractured Segments in B4

Six segments are located at the lowest resolution of 64. At higher resolutions, two more small segments are identified (Table 3). The bubble plots of recovered segments are in Figure 6. Comparing the sizes of the largest four segments with the largest two in B3, it is seen that the largest segment in B3 has been separated and becomes the first and third largest in B4. The second largest in B3 is also separated and becomes the second and fourth largest in B4.

Resolution	64	32	16	8
# Segments	6	8	8	8
Size(%)	33.09	33.09	32.92	33.06
	29.98	29.04	28.91	29.06
	18.65	17.47	17.34	17.31
	11.52	12.66	12.98	12.90
	4.39	2.95	2.91	3.04
	2.38	2.23	2.17	2.17
		1.41	1.60	1.31
		1.14	1.19	1.15
Centroid (x,y,z)	465,511,246	465,515,252	466,513,254	465,512,253
	219,445,267	219,443,264	217,444,264	217,444,264
	515,253,270	520,249,272	522,249,272	523,249,271
	215,194,245	217,198,254	217,198,252	217,199,252
	360,91,283	360,103,200	364,105,210	363,104,214
	473,108,158	476,110,154	481,112,161	481,112,164
		374,93,405	364,367,103	363,353,109
		357,376,107	366,96,406	364,95,405
Surface area of cracks	1035413	1304762	1482249	1633643
% of Total surface area	100	98	96	97
Processing time (s)	1	8	212	9316

TABLE 3. Statistics of the recovered segments in B4

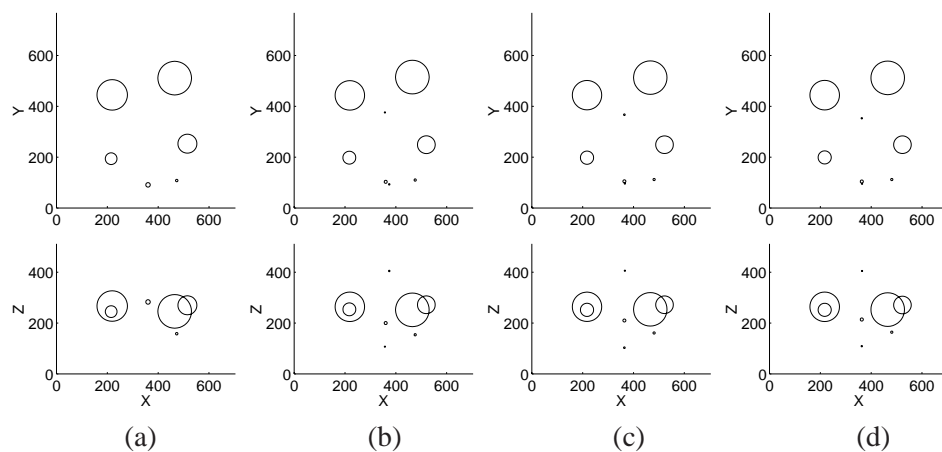


FIG. 6. Bubble plots of the recovered segments in B4 showing their relative sizes and centroids at resolutions of (a) 64, (b) 32, (c) 16, (d) 8.

Surfaces of Fractured Segments & Cracks

Figure 7 displays the surfaces of fractured segments and cracks at the lowest and highest resolutions. All of these surface models can be visualized interactively. We used a fixed set of colors with good contrast to represent each object. The color is determined by the rank of an object's size.

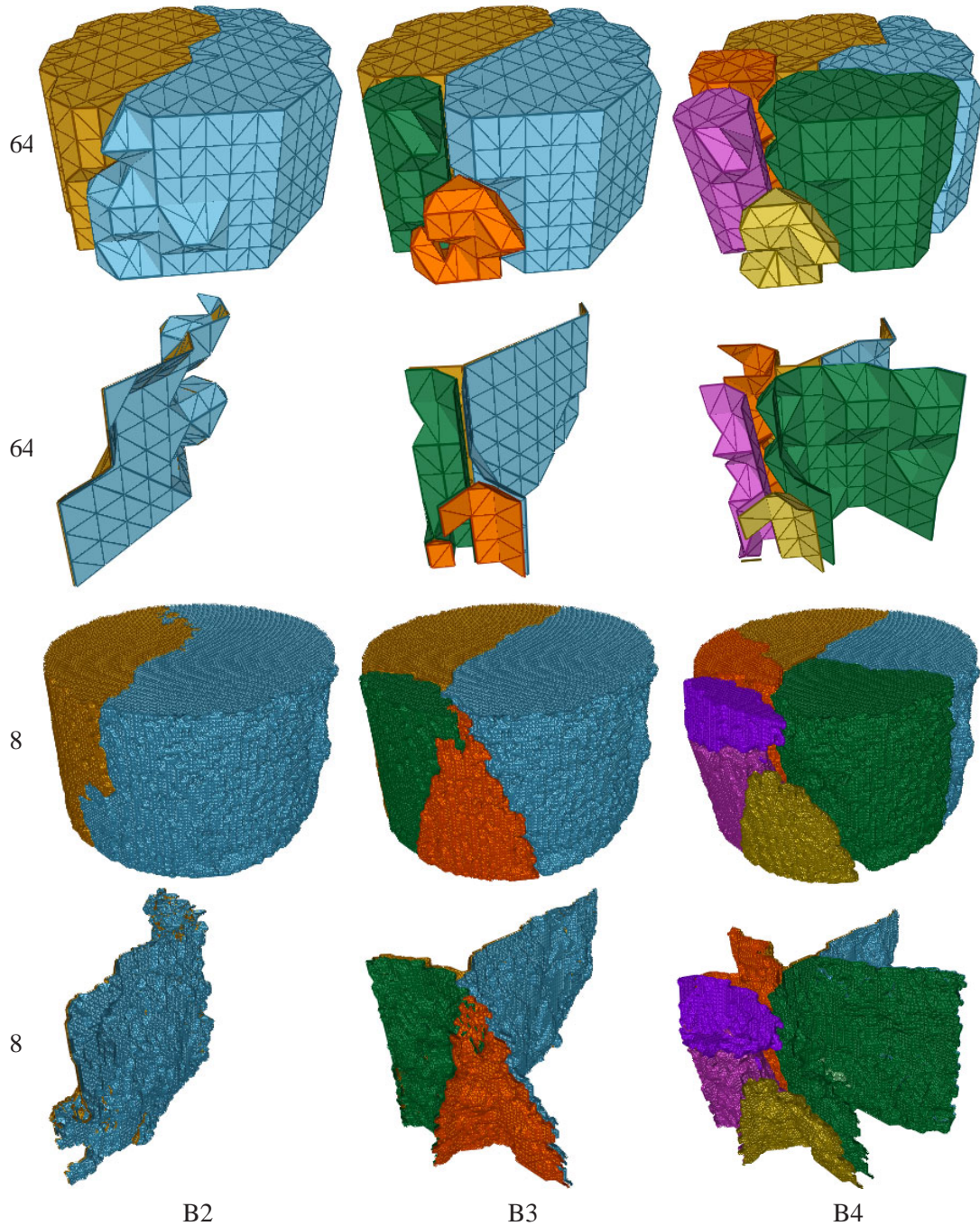


FIG. 7. Surfaces of fractured segments and cracks at the lowest and highest resolutions in B2, B3, B4.

Surface Area & Validation

The surface area of cracks in B2, B3, and B4 at different resolutions are summarized and plotted in Figure 8 (a). Similar trends of increase in the surface area of cracks are observed at every resolution. To validate the accuracy, we first calculate the normalized correlations between each pair of images. Based on the recovered motion parameters, we warp the first image in each pair and re-calculate the normalized correlation between this warped image and the other. The results are plotted in Figure 8 (b). As the specimen breaks apart, the cross-correlations decrease from 0.83 (B1-B2) to 0.59 (B3-B4) as each separated segments move apart. The increase in cross-correlations to 0.95 (B1-B2) and 0.91 (B3-B4) at the highest resolution after warping by motion fitting demonstrates the accuracy of the recovered motion parameters.

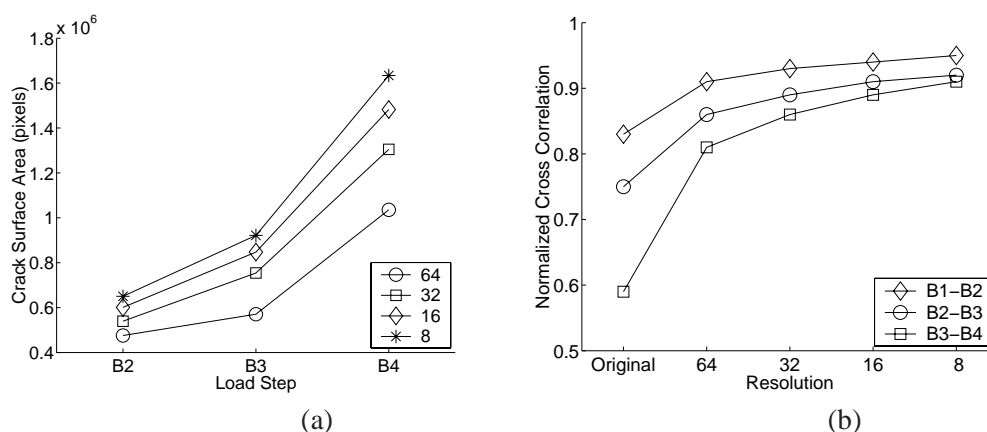


FIG. 8. (a) The surface area of cracks at different resolutions in B2, B3, and B4. (b) The normalized cross correlations before and after motion fitting.

CONCLUSION

We have discussed two methods applicable to identification and measurement of the fractured segments and surface area of cracks. Compared with the threshold-based method, the motion-based method has several advantages: (a) the intensity-based registration in motion estimation does not rely on a specific threshold, and is robust to imaging noise; (b) the motion parameters are estimated accurately based on a large number of globally distributed displacements; (c) the surfaces of latent and narrow cracks, difficult to identify at any threshold, can be inferred by motion interpolation; and (d) air holes are not confused with cracks. We have demonstrated that the recovered surfaces of segments and cracks are useful for both statistical measurement and interactive visualization. We will continue working towards better characterization of concrete cracks with respect to the microstructural properties.

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