AFRL-SR-BL-TR-99-
0099

REPORT DOCUMENTATION PAGE

1. AGENCY USE ONLY (Leave blank)	**2. REPORT DATE** 14 Feb, 1999	**3. REPORT TYPE AND DATES COVERED** Final Technical, 15 Jan 1998 - 14 Nov 1998

4. TITLE AND SUBTITLE
Studies of Fracture Processes in Cement-Based Materials Under Compression with Microtomography and Computer Vision

5. FUNDING NUMBERS
F49620-98-1-0175

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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AFOSR/NA
801 N RANDOLPH STR ROOM 732
ARLINGTON VA 22203-1977

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
Subaward to Northwestern University

19990412 082

12a. DISTRIBUTION / AVAILABILITY STATEMENT

DISTRIBUTION STATEMENT A
Approved for Public Release
Distribution Unlimited

13. ABSTRACT ***(Maximum 200 Words)***

The primary objective of this research program was to provide experimental data to feed into the extensive modeling work of the AFOSR Shock Physics program. Two advanced complimentary experimental techniques were used: x-ray microtomography (XMT) and digital image correlation (DIC). The former is a three dimensional technique that is restricted to small specimens under static loading, while the latter is a surface-only technique that can be applied in a variety of conditions. In the initial stages of the program we sought to correlate the fracture measurements of both techniques. By doing this we hoped to be able to develop a method to extrapolate 2D surface measurements (a relatively easy process) to three dimensions (a relatively difficult process). Preliminary results indicate such a method could be developed, however confirmation over a wider range of experimental variables is necessary.

14. SUBJECT TERMS Concrete, Fracture, Damage	**15. NUMBER OF PAGES** 9
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT Unclassified	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT**

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102

DTIC QUALITY INSPECTED 2

STUDIES OF FRACTURE PROCESSES IN CEMENT-BASED MATERIALS UNDER COMPRESSION WITH MICROTOMOGRAPHY AND COMPUTER VISION

Final Technical Report
AFOSR Grant Number F49620-98-1-0175
15 January 1998 - 14 November 1999

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Introduction

It is widely known that the mechanical behavior of concrete presents an extremely difficult modeling problem. The wide range of length scales involved along with the three-dimensional nature of damage and failure make it an extremely complex material for predictive modeling. Widely varying approaches from continuum to discrete particle models have been applied. (The U.S. Army Corps of Engineers considered five different models for numerical simulation of ballistics tests). Among the reasons for the large number of models is the minimal amount of quantitative data on microstructure-property relationships for concrete. Although a qualitative picture of damage evolution has been known for some time, very little quantitative information is available for the microstructural phenomena that ultimately dictate material properties.

In response to the need for more quantitative microstructure-property relationships, we focused this work toward providing much needed experimental data to feed the existing AFOSR Shock Physics modeling program. In doing this new models based on physical processes rather than observed phenomenology may be developed.

In order to obtain quantitative experimental information we applied two emerging experimental techniques: x-ray microtomography (XMT) and digital image correlation (DIC). The strategy was to apply these techniques in a complimentary manner. XMT allows us to look inside the specimen at very high resolution under limited conditions. DIC allows us to look only at the specimen surface, however it may be used under a fairly wide range of experimental conditions.

This report covers the work completed during the first year of the project. As the Shock Physics program was cancelled after 10 months, we were not able to complete all the tasks we outlined in the original proposal.

Background

Computer Vision

Digital Image Correlation (DIC) or computer vision is a technique that can be used to measure displacement fields on the surface of an object. This measurement requires two digital images obtained from different loading stages (strains). The fundamental and well documented concept of DIC is based on the recognition of two small sub-image areas extracted from each of the two images. Each sub-image represents a distinct state of strain on the specimen surface. The random surface pattern on the sample permits any point to be identified by the light intensity pattern of sub-image surrounding it. Given a suitable pattern searching algorithm, any sub-image taken from a reference image can be matched with an extracted sub-image from a selected image for measurement. Displacements are defined as the relative distance between those two best matching sub-images. If several such displacement points can be identified, a surface displacement map can be rendered which can then be converted to a component strain map.

Microtomography

X-ray microtomography (XMT) is a technique by which the internal structure of a material may be determined from maps of its x-ray absorptivity. Three dimensional maps are reconstructed from hundreds of through transmission radiographs of the sample taken from different angles. Microtomography is similar in practice to conventional medical CAT-scans. The primary differences are the x-ray source and detector. Microtomography uses synchrotron radiation for the x-ray source and a high resolution x-ray detector. A spatial resolution of less than 2 μm is possible, although 13 μm to 6 μm pixels were used in the preliminary experiments described here. The data that results from a scan is a series of images which represent cross-sectional "slices" through the material. The advantage of microtomography for investigations of damage in cement-based materials is its ability to measure internal structure in three dimensions at high resolution.

It should be noted that an extremely important issue related to both these methods, is that no single experimental technique is adequate to answer all questions that arise over damage accumulation and fracture. XMT provides extremely high quality three dimensional data, but the samples and experimental conditions are somewhat limited. DIC strain mapping is easily adaptable to a wide variety of applications, however, it provides surface measurements only. Thus, the motivation for combing the two techniques is for an optimized experimental program.

Summary of Work

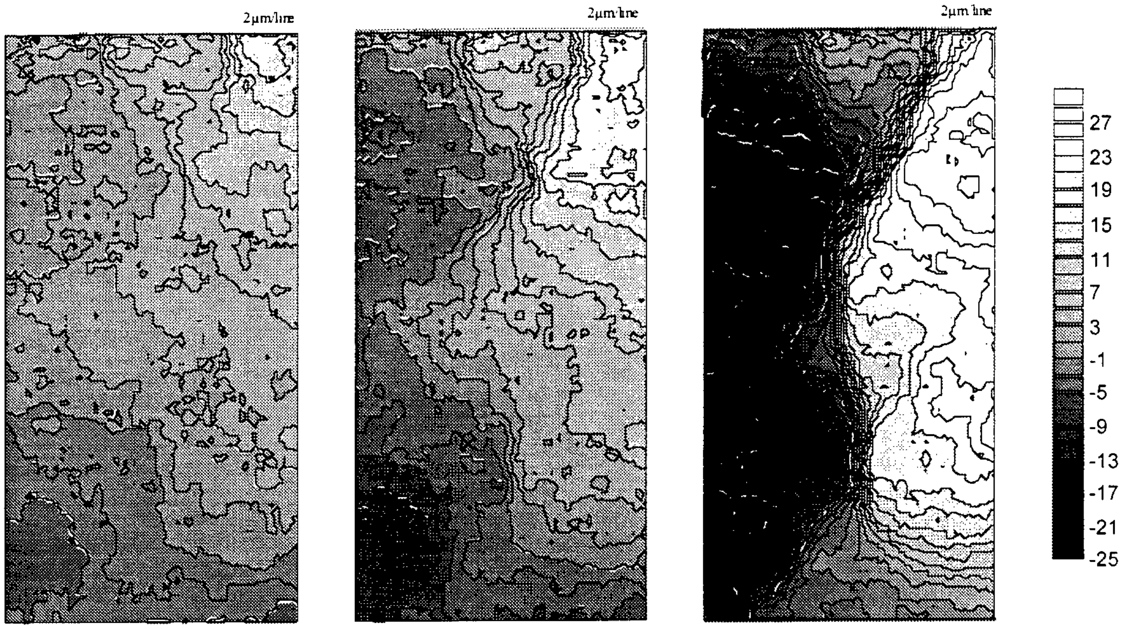
The focus of the first year was parallel XMT-DIC experiments. The issue we wished to address was the experimental differences in measuring fracture processes in two versus three dimensions.

Toward this end rectangular mortar prisms of square cross-section, approximately 0.5 in. x 0.5 in. x 1.0 in. were fabricated. The size of total volume scanned and reconstructed is limited by the height and width of the x-ray source beam to 0.1 in. and 0.5 in., respectively. This dictated the dimensions of the specimens used. While this may seem small compared to conventional concrete samples, it is three times larger than previous applications of this microtomography. The mixture proportion of the mortar was 1:2:0.6 Type I portland cement: sand: water. The largest sand grains had a maximum size of 600 μm with 90% of the sand sized between 300-600μm. The specimens were cured under water for 10 days before the load was applied. The average compressive strength of the mortar prisms was 29.7 MPa.

Each specimen surface was allowed to dry so that a speckle pattern of black paint could be applied to provide a random intensity pattern which aids in DIC matching performance. The specimen was then loaded in displacement control using a closed-loop MTS machine with a 5 kip load cell to distinct load levels past the peak load and then unloaded. The loading rate used was 0.254 μm/s. Table 1 provides a list of the loading level when specimen was unloaded. A spherical seating platen was used above the specimen and a rigidly mounted platen below. Digital images of the specimen were captured at multiple

Table 1. Percentage of Peak Load at Unloading

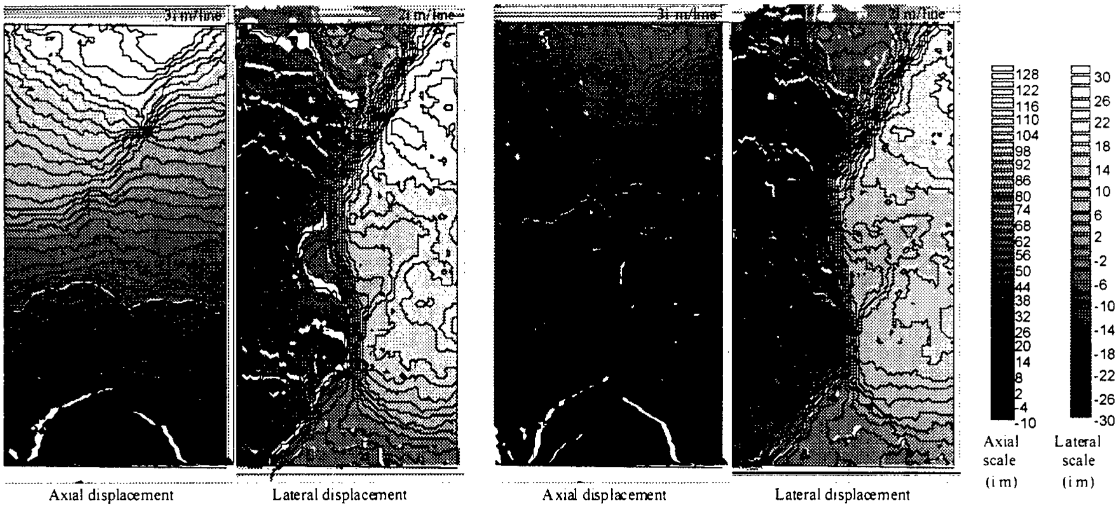
Specimen ID #	Percentage of peak load
M90	88
M80	81
M70	71
M60	61



89% of axial strain at peak   at peak load   116% of axial strain at peak

Figure 1. DIC sequence of lateral displacements for specimen M70

times during the loading and unloading sequence in order to fully describe the crack growth. Fig. 1 shows the contour maps of lateral displacement which depicts the evolution of crack growth for one of these specimens at three loading stages. It can be seen that the majority of the observable fracture occurs after the peak load is reached. Fig. 2 illustrates the axial and lateral displacements of the specimen at the final recorded load level and after unloading. While unloading allows the specimen to recover significantly in the axial direction, the crack closes less than 25%.



Axial displacement   Lateral displacement   Axial displacement   Lateral displacement

Loaded   Unloaded

Figure 2. Axial and lateral displacement maps before and after unloading

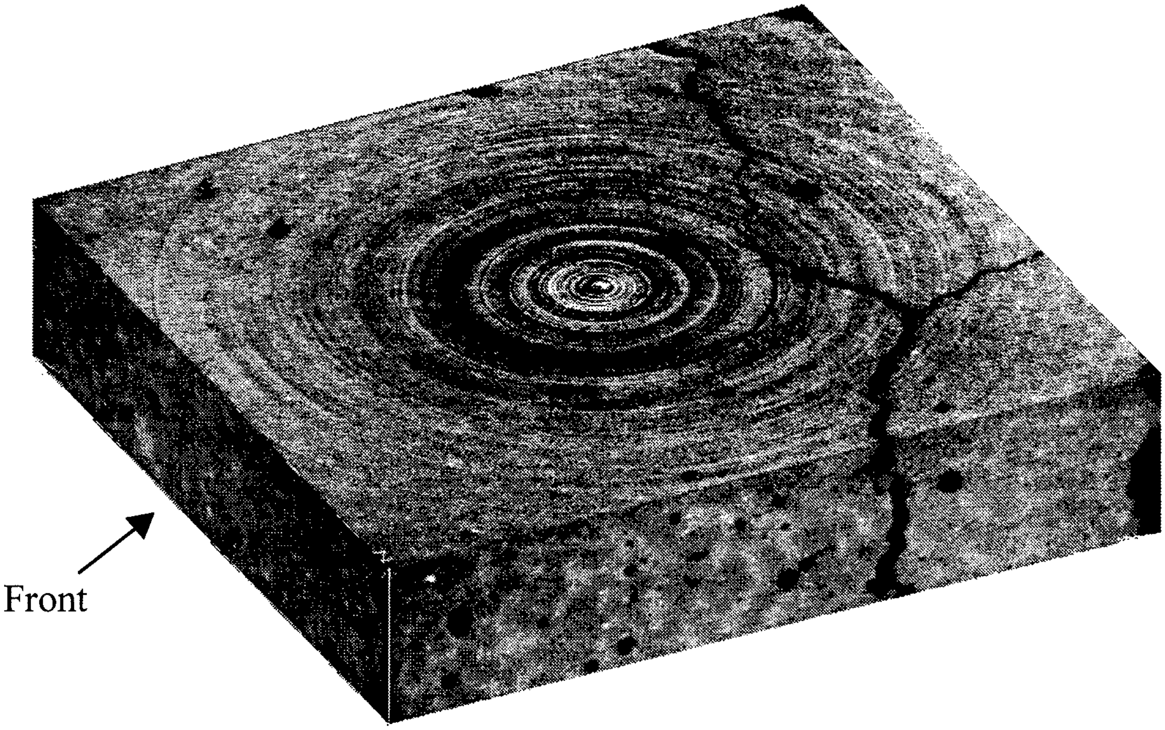


Figure 3. XMT volume for specimen M90

Those specimens which showed significant cracking on the imaged face were taken to Argonne National Labs for scanning with XMT in the unloaded state. This was performed on the central region of the specimen, approximately one-tenth of an inch high. After the three-dimensional information was reconstructed it was input into software written to render views of the material data from any desired perspective. In Figure 3, a view of the outer surfaces of the XMT volume for specimen M90 is displayed. Since the brightness value of the pixel is proportional to the x-ray opacity of the material, cracks and voids which are air are imaged as dark gray and black. On the other hand, the paste matrix is nearly white in response to its higher opacity resulting from the iron content of the cement. The in-plane rings seen in this image are a result of inconsistencies in the detector and are an artifact which should be ignored. Individual sand particles take the form of round gray lumps. In the figure, one can see the path of the crack has been influenced by these features and followed the surface of the aggregate particles.

Since all faces of the specimen could not be imaged with DIC simultaneously during the initial loading, the specimens were reloaded to reveal the location of cracks in the remaining faces. For each face, the specimen was loaded to 40% of the original end loading while DIC images were captured at various points in the loading process. After unloading, the specimen was rotated 90° for the next imaging sequence. Since DIC measures displacement, the cracks were reopened under the small load which allowed their locations to be determined. The results of this can be seen in Fig. 4, which depicts the lateral-displacement contour map and the corresponding view of the XMT data. The DIC map of the front face describes deformation after unloading while the DIC maps of the remaining faces describe the deformation under the maximum reapplied load. It can be seen that the crack locations identified by XMT and DIC coincide closely.

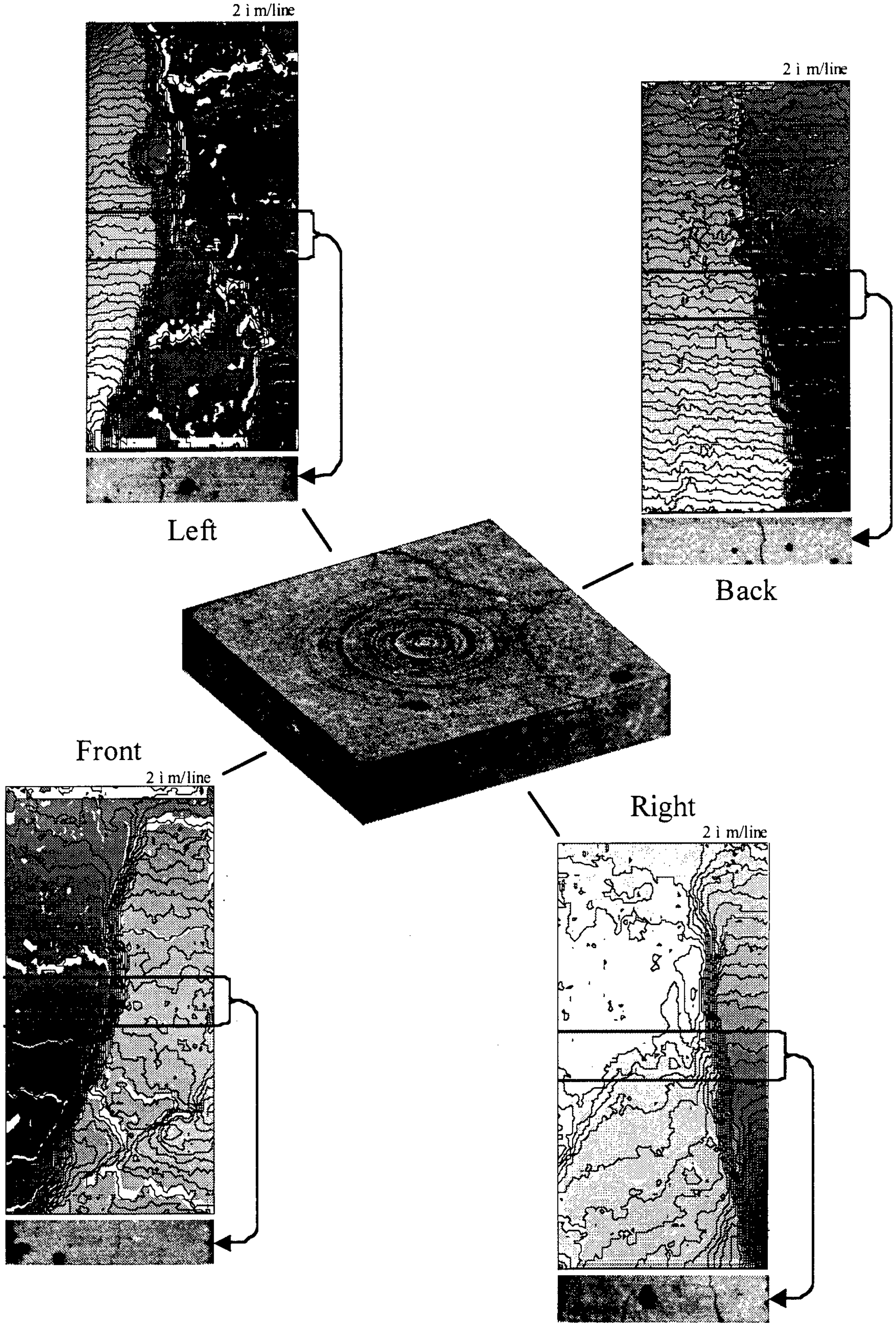


Figure 4. DIC maps and corresponding XMT faces for specimen M60 volume

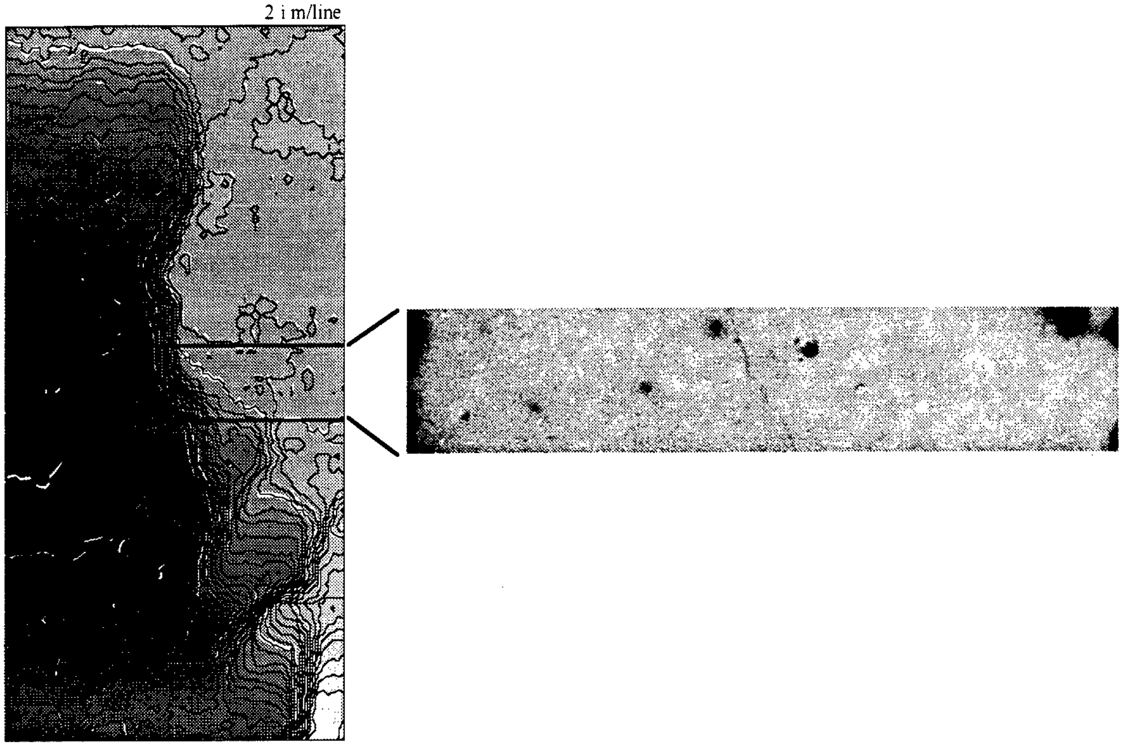


Figure 5. DIC map and XMT face for front of specimen M80

For wider cracks, the contour maps of the DIC results lost some of their effectiveness at portraying crack shape though crack width information is clear and accurate. This results from the method used to draw contours from the grid of node data. However, as can be seen in Figure 5, the shape and size of the narrow crack, approximately 25 µm, in the front face of specimen M80 is very clear in the DIC contour though it is only inconsistently evidenced in the XMT data since the crack width is close to the XMT imaging resolution of 20µm. The XMT images provide additional data not included in the DIC measurements such as material features like pores and aggregate particles, which effect the crack behavior.

The conclusion we can draw here is that the two techniques give complementary information about the fracture process. DIC is more effective than XMT at determining crack width and shape of small cracks (less than 40µm) but it is less successful with larger cracks. The DIC matching process is disrupted by the occurrence of large cracks where a high correlation is impossible. Also, the shape represented in the contour map is dependent on the layout of the node grid when the discontinuities get large. Alternately, XMT depicts the shape of larger cracks very well due to the image-based nature of the method and shows the influence of particle features like sand on the path of fracture. Refining the XMT process would allow more information to be extracted from XMT data such as volume and surface area of cracks. The work presented here demonstrates that simultaneous DIC and XMT analysis could be used to provide a more complete picture of fracture behavior in future testing.

Other Work Completed

It can be noted that in the experiments just described, the XMT scans were made on specimens that were loaded and unloaded at a separate facility. Another approach we have taken is to load the specimens in situ. That is we have previously developed a loading frame

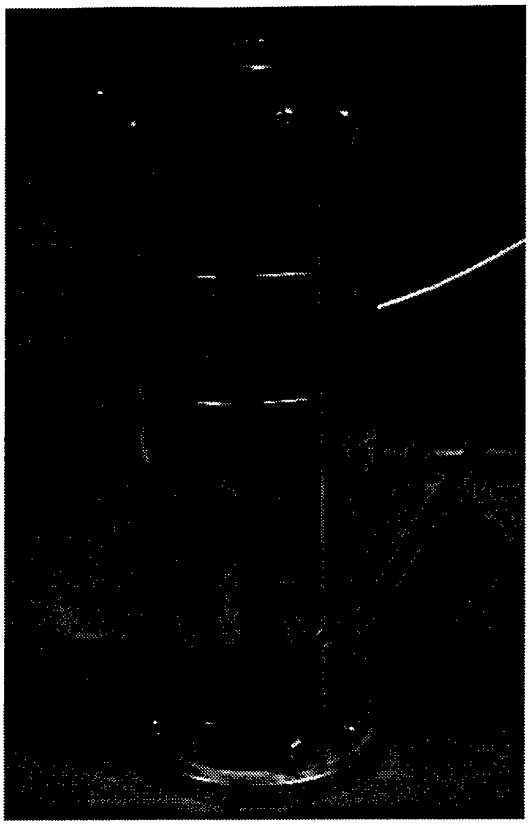


Figure 6. Photograph of newly developed closed loop loading frame for in situ microtomography.

that can be mounted in the XMT chamber for simultaneous loading and scanning. Work previously done (partially supported by AFOSR Grant F49620-96-0377) included a simple thumb-screw loading apparatus. While useful for preliminary experiments, it lacked the control necessary to perform more sophisticated fracture tests. Because of this limitation we developed a new loading frame that has closed-loop loading control. The biggest design constraint was the fact that the apparatus must be small (max height 200 mm) yet able to deliver a 300 pound load to a specimen in a closed-loop control configuration. We ultimately settled on a piezoelectric stack actuator in combination with a hand-screw adjustable loading platen. The cross-head position is controlled by a laptop computer with a PCMCIA analog input/output card. Load (measured by an in-line load cell) and deformation (as measured by two LVDTs) are recorded on the computer hard drive while the real-time load-deformation curve is plotted on the screen. A photograph of the loading frame is shown in Figure 6.

Conclusions

The combination of x-ray microtomography and computer vision were found to be an exceptional combination for examining relationships between material microstructure and fracture properties of concrete and cement-based materials. Although we were not able to carry out the program to completion, we were able to initiate a program that will provide valuable data for constitutive models of heterogeneous materials.

Acknowledgments

This work was sponsored (in part) by the Air Force Office of Scientific Research, USAF, under grant/contract number F49620-98-0175. The views and conclusions contained herein are those of the authors and should not be interpreted as necessarily representing the official policies or endorsements, either expressed or implied, of the Air Force Office of Scientific Research or the U.S. Government.

Parts of this research was conducted at the National Synchrotron Light Source, Brookhaven National Laboratory, which is supported by the U.S. Department of Energy, Division of Materials Sciences and Division of Chemical Sciences (DOE contract number DE-AC02-76CH00016.)

Portions of this work were performed at the DuPont-Northwestern-Dow Collaborative Access Team (DND-CAT) Synchrotron Research Center located at Sector 5 of the Advanced Photon Source. DND-CAT is supported by the E.I. DuPont de Nemours & Co., The Dow Chemical Company, the U.S. National Science Foundation through Grant DMR-9304725 and the State of Illinois through the Department of Commerce and the Board of Higher Education Grant IBHE HECA NWU 96. Use of the Advanced Photon Source was supported by the U.S. Department of Energy, Basic Energy Sciences, Office of Energy Research under Contract No. W-31-102-Eng-38.

Papers Published Acknowledging This Grant

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