ACOUSTIC EMISSION AND X-RAY TOMOGRAPHY IMAGING OF SHEAR FRACTURE FORMATION IN CONCRETE

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Abstract

This paper describes how different aspects of fracture formation in concrete can be investigated using a combination of acoustic emission (AE) techniques and high resolution computed tomography (CT). AE and elastic wave velocities were measured using the Hyperion GigaRAM AE Recorder, a device developed for the ultra-detailed investigation of brittle fracture and failure of rock and rock-like materials. AE analysis includes studying complex spatial and temporal fracture development during the slow quasi-static fracture process. Predominant microcrack mechanisms were analyzed at different stages of fracture formation. CT images were used to investigate the influence of concrete microstructure on fracture topography. Combined AE and CT images revealed different aspects of fracture development, thus expanding our understanding of AE events and their mechanisms. These images show how coarse aggregates influence fracture nucleation and development, as well as event sequences and mechanisms during aggregate fracturing.

Keywords: X-ray computed tomography (CT), concrete, aggregates, shear fracture.

Introduction

Fractures in concrete are directly influenced by the complexity of the concrete’s microstructure, from nucleation and propagation to surface roughness formation. To study this influence, researchers used different techniques and approaches. One approach is to measure and analyze the fractal dimension of concrete fracture surfaces, depending on the kind of aggregate (Brandt et al., 1993) or the maximum aggregate size (Issa et al., 2003). A correlation has found between fractal dimension and fracture toughness. Another approach involves non-destructive 3D studies using AE techniques (Mihashi et al., 1991; Landis et al., 1995; Chen et al., 2004). These studies show how concrete microstructure influences the fracture process zone, fracture energy, and fracture toughness. In addition, advanced AE techniques can be used to define AE source mechanisms (Zang et al., 1998; Ohtsu et al., 1998; Grosse et al., 2003).

The detailed, nondestructive investigation of cracks inside materials has become possible with the development of X-ray Computed Tomography (CT) techniques. For example, Landis et al. (2000) calculated fracture energy using the actual surface area of internal cracks using CT data collected during loading. Chen et al. (2004) compared cracking paths, obtained by X-ray inspection, in concrete with different maximum aggregate sizes; Chen’s study discovered a correlation between the width of the crack zone and the increasing of the maximum aggregate size. Young et al. (2007) combined CT and AE imagery to relate physical features within the sample to AE locations and phases of micro-scale damage.

In order to gain improved insight into the 3D micro-mechanics of failure in concrete, this study combined AE techniques with high-resolution X-ray CT techniques. The recorded AE event source locations were related to high resolution X-ray CT images obtained from core
samples extracted from the beam after testing. Furthermore, various aspects of failure were studied by analyzing the AE mechanisms associated with the different aspects of fracture propagation through the concrete components.

**Experimental Procedure and Data Processing**

This experiment has been a part of an extensive experimental program conducted at the University of Toronto (Sherwood et al., 2007; Katsaga et al., 2008). Using the Baldwin test frame, a large, lightly reinforced, normal-strength concrete beam with large coarse aggregates (maximum size = 55 mm) was loaded to shear failure in a three-point bending test. The specimen, designed to be shear-critical, was 9000-mm long, 1510-mm tall, 300-mm wide, and was supported on rollers spaced at 8100 mm apart.

**AE setup**

One half of the specimen was instrumented with AE sensors to record the acoustic emissions induced from microcracking during loading. The concentrated array of 24 sensors, 16 receivers (V103, Panametrics), and 8 pulsers (R15, PAC) was designed to investigate diagonal shear fracture development before failure and was installed on the surface of the beam using special holders screwed into the concrete (Fig. 1b). The monitoring parameters were selected based on the results of pencil-lead break or artificial shot (ultrasonic pulse) tests: 60 dB pre-amplification and 10 MHz sampling frequency.

Signals from the sensors were recorded using a sixteen-channel recording system called the Giga Recorder (Fig. 1a). Typically, AE systems experience downtime when they record discrete AE events because the transfer of events from their random access memory (RAM) results in recording blackouts. The Giga Recorder has the ability to acquire an ultrasonic waveform continuously at high sampling rates (up to 20 MHz) and at 14-bit resolution on a circular 40 GB RAM buffer; this buffer is then locked and downloaded to disk following the critical stage of an experiment (i.e. failure of a sample). Our experiment featured a sampling rate of 10 MHz, which translates into a 2-minute continuous waveform (Fig. 1c). In addition to the continuous waveform, the Giga Recorder also records discrete triggered AE signals (Fig. 1d) during the entirety of the experiment at a rate of 15 events per second. More detailed discussion of the Giga Recorder can be found in Thompson et al. (2006).

**AE data processing**

*InSite* (ASC, 2008) software was employed to analyze AE events, continuous waveforms and velocity data. Before AE data processing, P-wave velocities were defined, assuming straight ray-paths between pulsers and receivers. Wave velocities transmitted through the concrete beam before loading did not show any preferred direction in velocity variations; therefore, a homogeneous-isotropic velocity structure was assumed to exist throughout the concrete volume. A combination of Simplex and Geiger methods was used for locating AE events, a combination that provides faster solutions with improved error analysis.

One of the advantages of recording continuous waveforms, is the possibility of extracting discrete events by applying new settings. The program SeisAcq (ESG) was used to process the continuous records and to “re-harvest” triggered data from them. An AE event was triggered if signals on five channels exceeded the 80-mV threshold. By contrast, initial experimental settings used seven channels and a 100-mV threshold. None of the discrete events extracted from these
continuous waveforms were lost because the transfer of events from RAM involved no downtime. The detailed logic diagram of our equipment and software use is presented on Fig. 1.
The relative comparison of the size of AE events was done based on their instrument magnitude, which was calculated based on equation (1). An instrument magnitude is calculated for the event by averaging over the instruments used in the source location,

\[ M = \log_{10} (r \cdot W_{RMS}) \]

where \( r \) is the source to receiver distance and \( W_{RMS} \) is the peak signal amplitude on the RMS waveform (ASC, 2008).

Fig. 2 a) 300-mm cores extracted from the beam: the jagged black line identifies fracturing that has occurred in the cores; b) CT images for two cores (section view); c) reconstructed image across the core length perpendicular the fracture.

To analyze the microcrack mechanisms and their evolution during shear fracture formation, P-wave first-motion polarities were defined and analyzed using a first-motion polarity method (Zang et al., 1998),
\[ pol = \frac{1}{k} \sum_{i=1}^{k} \text{sign}(A_i) \]  

where \( A \) is the first-motion amplitude and \( k \) is the number of sensors. In this study, positive polarity represents compressional pulses initiated by tensile fractures. Events are considered as tensile if \( pol \) is between 0.25 and 1, shear if \( pol \) is between -0.25 and 0.25, and crushing (implosion) if \( pol \) is between -0.25 and -1.

**Computed tomography imaging**

After the failure of the beam, four core samples containing the fracture that preceded the final failure were extracted from the beam (Fig. 2). The location of the coring was defined by studying AE event locations. Two samples were sent to the University of Texas for high-resolution X-ray Computed Tomography (Ketcham et al., 2001). The samples were imaged separately using a high energy scanning system designed for scanning large samples. Horizontal CT images were taken at 1 mm intervals across the sample diameter, with a resolution of 1024 x 1024 pixels (6.6 pixels per 1 mm) (Fig. 2b). These images were reconstructed to provide a view across the length perpendicular to the fracture plane (Fig. 2c).

Through the consequential CT sections, the 3D microstructure of the material can be non-destructively reconstructed. Different densities of concrete matrix and aggregates as well as strongly marked interface between them cause variation in X-ray attenuation, giving a clear picture of the microstructure. The density of fractures and air voids contrasts sharply with the rest of material, thus making them easily distinguishable on CT images. In this work, CT images were used for two purposes: to analyze the influence of the microstructure on fracture propagation and to reconstruct the temporal and spatial scenario of fracture formation using combined CT and AE data.

**Combination of AE and CT data**

The combination of CT and AE data is what the custom AutoCAD built-in dialog-based Visual Basic Application (VBA) was designed to do (Fig. 3). This application allows us to study the CT scan images in precise relation to the AE locations, using the advanced viewing and graphical tools of AutoCAD. VBA application loads data from an event parameter text file created by InSite and processes it in AutoCAD. The main features of this application are event filtering and drawing properties. Events can be differentiated by size, shape and color based on calculated instrument magnitude and time of occurrence.

CT images were imported in AutoCAD and placed in separate layers at their exact positions (Fig. 4a). Then fractures were traced and differentiated by color: black represented fractures that propagated through concrete matrix, blue through matrix-aggregate interface zones, and red through an aggregate (Fig. 4b). All of these traced cracks allowed us to reconstruct the complicated 3D topography of the fracture surface inside the material (Fig. 4c). As the next step, AE signals were imported (Fig. 4d) and filtered by ±7mm slices from the plane of the images and were superimposed onto these images (Fig. 4e).

**Image analysis**

After the cracks on the CT images were traced, they were separated into three different groups: matrix cracks, aggregate cracks, and interfacial cracks. The cracks were then converted into bitmap images and processed, using an automated image-processing program (Launeau et al., 1996) to investigate the influence of the concrete’s microstructure on fracture propagation. This program is based on the intercept method, which involves scanning a drawing with a set of
parallel lines at specified angular intervals and counting the number of intercepts with the crack lines. The results of the intercept counts were used to build a rose of directions for each group of cracks and to analyze statistical data.
Results and Discussion

Crack topography

Images of three groups of cracks are presented in Fig. 5a. The results of intercept counting showed that, for this slow fracture propagation, interface cracks take 45.4% of the overall crack length, matrix cracks 43.6% and aggregate cracks 11%. Direction Rose diagrams extracted from the analysis showed that aggregate cracks and matrix cracks have the same main crack direction (15° from 0) and almost the same maximum intercept directions (3.019 and 2.944). However, the situation is different for the interface crack: the direction of the main crack is almost the same (14°), but has a number of secondary intercept directions (Fig. 5b). These secondary
Fig. 5. Microstructural observations: a) crack path divided into matrix cracks, aggregate cracks and interfacial cracks; b) direction rose diagrams for each group.

directions show that interface cracks are responsible for the fracture surface’s high degree of roughness.

Studying CT images revealed that large coarse aggregates have the largest impact on a fracture path. Figure 6a illustrates that large aggregates change the fracture direction locally and the fracture travels along one side of the aggregate. In this case, the fracture surface’s roughness depends on the roughness of the aggregate. It was found that if a long aggregate crosses a fracture, the aggregate is more likely to be fractured (Fig. 6b). This phenomenon could be explained by the fact that in this case the fracture spends more energy traveling around the aggregate than fracturing it. Figure 6c shows the general cases of the fracture traveling around small and medium aggregates along aggregate-matrix interfaces. Aggregates of this size range thus control the fracture roughness in general. Therefore, by controlling the size and the shape of coarse
Fig. 6. Microstructural observations: a) large aggregates change fracture path; b) cleavage of the long aggregates; c) roughness formation through smaller aggregates.

aggregates, it is possible to create the rougher fracture surfaces necessary to improve aggregate interlock, an effect that plays an extremely important role in the transferring of shear stresses (Sherwood et al., 2007).

Acoustic Emissions

AE source locations, divided into time periods A to E, are presented from the top point of view in Fig. 7. Events for each time period are represented by different colors. Symbol sizes are scaled according to their event magnitude. Periods A, B, and 36 seconds of period C show triggered AE events, while the rest of periods C, D and E show AE events extracted from continuous waveforms. AE locations exhibited non-uniform event distribution along the fracture surface width. During period A, five isolated events occurred in the space ahead of the fracture front. During period B, several events nucleated near the front surface of the beam. Period C showed AE event development in two directions: forward and sideways, across the width of the beam in a narrow band leaving uncracked concrete between the band and the primary fracture front. During period D, the sideways fracture connected with the primary fracture front and propagated a few centimeters forward. Overall, 121 events were located. At the end of period D, microcracking was observed throughout the region of eventual fracture surface. Period E showed 120 events occurring, due to the shearing of the cracked surfaces at the fracture.
AE mechanisms, obtained using first-motion polarities, were investigated for each of the shown periods. The events during Period A, which signify fracture nucleation, are dominantly tensile (80%). The number of tensile events decreases gradually with the fracture development (from 80% to 25%). The number of shear events stays almost the same for periods B, C and D (32-33%) and increases dramatically during period E (66%). It was also found that the shear events released large amount of energy and produced high magnitude events compared to tensile events. The implosion events were similar in magnitude to shear events. However, they were not presented in the first two periods and were rare during the final periods of the fracture formation (8-9%), except for the period D (19%). A close analysis of the implosion events is presented in the next section.

**AE and Crack Topography**

AE and CT techniques both carry significant amounts of information about different aspects of fracture in material. CT techniques show the connection between crack topography and material microstructure, whereas AE techniques reveal its spatial and temporal characteristics. Combining both of these techniques creates a unique opportunity to investigate the specifics of fracture formation and propagation. This investigation explained a number of important observations, including event sequences and the nature of the event mechanisms. Figure 8 shows a 70-mm section and corresponding AE events filtered by ±7 mm from the plane of this section. This section was chosen because, at this level, the first event nucleation occurred during period B (Fig. 7). A combined AE and CT image (Fig. 8) shows that the first events during nucleation...
Fig. 8 CT image at 70-mm section (see its poison on Fig. 7) and corresponding AE events and their mechanisms: □ - tensile events; ◻ - shear events.

were initiated by fracturing at the edge of an aggregate. First motion polarity analysis showed that these events were actually a single tensile and shear event. At this level, the rest of the events during this period were tensile events that occurred at the interface of aggregates. During period C, a number of events the majority of which were also tensile events at the interface of large and small aggregates occurred along the fracture path. One large shear event appeared next to the tensile events from stage B. During period D, the character of events changed: most were large magnitude shear events which occurred at new positions and next to events from the previous period. Events from stage E were only shear events distributed along the fracture path. We can, therefore, assume that stage E shows the shearing of fracture surfaces that were formed before stage E.

The combination of CT images and AE events revealed why the spatial development of the fracture during period C was not uniform (Fig. 7). Large particles of coarse aggregate were found on both sides of the AE band. Because these large aggregates strengthened material locally, the fracture was forced to propagate only between aggregates.

In the section “Crack topography”, it was shown that 11% of the fracture path was through aggregates. It was also illustrated that some of these aggregates were elongated. However, analyzing CT images, we found a number of equiaxed aggregates fractured. Studying AE events related to these fractured aggregates showed that most of them were fractured during period D, which can be explained by the accumulation of higher stresses during this period. Figure 9a demonstrates a sequence of events and their mechanisms during the fracturing of an aggregate. A smaller tensile event (marked as 1) initiated the fracturing and three large magnitude shear events concluded the process. Only one normal-shaped aggregate was found fractured during Stage C (Fig. 9b). This aggregate was located at the level 195 mm (Fig. 7). As discussed above, during Stage C events were propagating non-uniformly in a narrow band between large aggregates. The presence of these aggregates caused a high local stress redistribution that forced the fracture to propagate through the aggregate located in middle. The sequence of events during the fracturing of this aggregate is similar to the previous case: a small tensile event (Fig. 9b, 1) is followed by a large shear event (Fig. 9b, 3). However, in this case, a large implosion event (Fig. 9b, 4) occurred.
between these two events. The analysis of further fractured aggregates and related AE events revealed more implosion events involved in aggregate fracturing (Figs. 9d, 9e, 9f). The fact that the most aggregate fracturing occurred during period D explains the large number of implosion events at this period, compared to the other periods. Some implosion events during period D were found in the concrete matrix. For example, in Fig. 9g, three large implosion events (Fig. 9g, 5-7) are shown in the space marked by the tensile events that occurred earlier (Fig. 9g, 1-3).
Conclusions

The combination of AE and CT imaging provides us with a unique opportunity to study AE events in relation to the microstructure of material.

High-resolution CT images in our study resulted in a detailed picture of the concrete microstructure, including the aggregates, cracks, and air voids. The influence of the concrete microstructure on the topography of the fracture surface was analyzed using these images. It was found that large aggregates can change the direction of a fracture path locally and that the fracture roughness is controlled by interface cracks. It is, therefore, possible to optimize aggregate interlock by controlling the size and shape of coarse aggregates.

The AE event locations revealed a complex, non-uniform spatial and temporal fracture development in the concrete with the large aggregates at the slow quasi-static stage of fracture propagation. The early stages of fracture formation were associated mainly with tensile events, the number of which decreased with fracture development. Finally, the number of shear events became dominant (66%) due to the shearing of the cracked surfaces. Therefore, studying the predominant mechanisms during monitoring or inspection can be helpful in defining the stage of fracture development.

As expected, the cracks on the CT images showed a close correlation with AE events. Analyzing the temporal and spatial evolution of AE events in relation to the CT images allows us to reconstruct the failure sequence precisely. Coarse aggregates are shown to play an important role in fracture nucleation and development: aggregate fracturing is found at the place of fracture nucleation and the non-uniform development of events is explained by the influence of large pieces of aggregates. A close analysis of combined AE and CT images showed that the events at the new location were mainly tensile events and subsequent events at the nearest position were shear events. A similar sequence of events is found when the fracture propagates through aggregates. Additionally, a number of implosion events were involved in the process of aggregate fracturing. It was revealed that aggregates were fractured mostly during the final period of fracture surface formation, which explained the large portion of implosion events compared to the other periods.

The overall results of the work show that the combination of AE and CT imaging provides an extremely effective tool for the investigation of the process of fracture formation in materials with complicated microstructure.

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References


