

Review of Noninvasive Techniques for Detecting Microfracture

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Detection and quantification of microfracture has become an integral aspect of concrete technology. Better methods that have emerged over the last decade have led to improved understanding of fracture mechanisms and the consequent effect on mechanical properties such as toughness and durability that are critical to sustainable development. This paper focuses on the applications of nondestructive and noninvasive diagnostic methods such as interferometry and acoustic techniques to cementitious materials. For the sake of brevity, non-destructive evaluations of large-scale cracking such as delaminations and spalling have not been addressed here. The growth and propagation of microcracks is a critical factor under service loads. It is the primary cause of intrusion by degenerating substances and corrosion, and it is important to the use of concrete in environmental remediation. The techniques reviewed here are pertinent to these issues and could evolve into effective on-site monitoring tools. ADVANCED CEMENT BASED MATERIALS 1995, 2, 201–209

KEY WORDS: Acoustic, Concrete, Interferometry, Microfracture, Nondestructive evaluation, Noninvasive, Penetrant

Researchers working with concrete became interested in Griffith's theory of fracture in the late 1950s [1]. Very soon it was evident that the classical fracture mechanics parameters, such as the energy release rate G_c or the stress intensity factor K_{IC} , seem to depend on both the specimen size and the geometry of loading [2]. By the mid 1960s, it was quite evident that even in the simplest tensile loading geometry, a multitude of microcracking and other nonlinear phenomena are responsible for the deviations of concrete's fracture behavior from predictions of linear elastic fracture mechanics theory [3]. The following two decades saw an extensive research effort aimed at understanding and modeling these nonlinear phenomena. These studies evolved into two distinct approaches towards modeling nonlinearity. The first,

based on a smeared crack approach [4], involved a diffuse zone of microcracks and damage-based constitutive modeling. The second involved localized crack and ligament connections for continued transfer of stress across the crack [5], for example, the "fictitious crack model." Irrespective of their nature, the validation and calibration of these models made it essential to improve the detection and measurement of fracture.

Our ability to detect fractures with greater accuracy is also intimately connected with our ability to eliminate them through advanced materials processing technology. Very high tensile strength is now being obtained from macro defect free (MDF) cements through extrusion processing and eliminating large flaws [6]. The addition of fibers to concrete has been around for more than three decades [7]. However, more advanced processing techniques and methods of predicting mechanical behavior related to durability and toughness continue to be explored [8]. Experimental techniques to monitor the initiation and growth of microcracking is a critical step in the process of developing such advanced cementitious composites.

Review of NDE Techniques

This review of nondestructive evaluation (NDE) techniques that have been used to study concrete microfracture can be broadly classified into two categories: (1) methods based on interferometry, involving holographic or speckle interferometry, moiré, photoelasticity, and fiber-optics; and (2) methods based on acoustic phenomena, such as ultrasonic and acoustic emission techniques.

Some of the other popular methods have also been reviewed.

Interferometry-Based Methods

Laser-Based Interferometry

An excellent review of the applications of interferometry techniques to concrete up to the early 1980s was

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Received August 11, 1994; Accepted January 11, 1995

provided by Jacquot and Rastogi in 1983 [9]. The greatest positive attribute of laser-based interferometry (LI) is in its ability to visually observe microscopic changes on the surface of materials. There are a multitude of possible LI techniques, but they all share some common attributes: (1) A laser beam is used to illuminate the area of interest, from a few millimeters to about a meter in dimension; and (2) the image of the object is acquired, stored, and compared at two different stages of deformation, resulting in a fringe pattern. It is the second common attribute that has shown most of the advances in the past decade.

The simplest LI method is speckle interferometry, also referred to as speckle photography. A single laser beam is used to illuminate the object and a simple imaging system (an old-fashioned camera) with a large image plane is used to picture the specimen surface at two stages of loading. The developed photographic plate is subsequently interrogated with a narrow (un-expanded) laser beam to produce a fringe pattern corresponding to the magnitude and displacement of the point being interrogated. Ansari [10] used this approach to determine the displacements on two sides of a propagating crack tip in a direct tension experiment. The method is simple, relatively free from vibration-related problems, and accurate for displacements on the order of 10 μm .

To detect cracks of even smaller dimension (1 μm or smaller), which is necessary for studying the aggregate-mortar interface, Maji and Shah [11] used holographic interferometry. This involved recording the interference between a reference beam and an object beam on a highly sensitive (≈ 2000 lines/mm) film. It was possible to visualize the initiation of bond cracks and the progressive joining-up of smaller cracks through different loading stages. In concurrent research, Miller et al. [12] were able to quantitatively measure the profiles of crack-opening displacements.

Although the sensitivity of these techniques was an order of magnitude better, the techniques introduced a multitude of problems from extraneous vibrations and the complexity of the optical set-up. However, the ability to visually observe and quantify the real-time propagation of cracks resulted in a number of interesting applications of holographic interferometry over the next few years.

Stroeven used holographic interferometry with fiber reinforced concrete to investigate the debonding of fibers during pull-out [13]. By keeping the imaging plate close to the specimen, Ferrara and Morabito [14] made white light holograms that could be visualized without laser illumination in white light (e.g., sunlight). They were able to study various cracking mechanisms in a four-point shear test. Mobasher et al. used the same method to observe the progressing formation and lo-

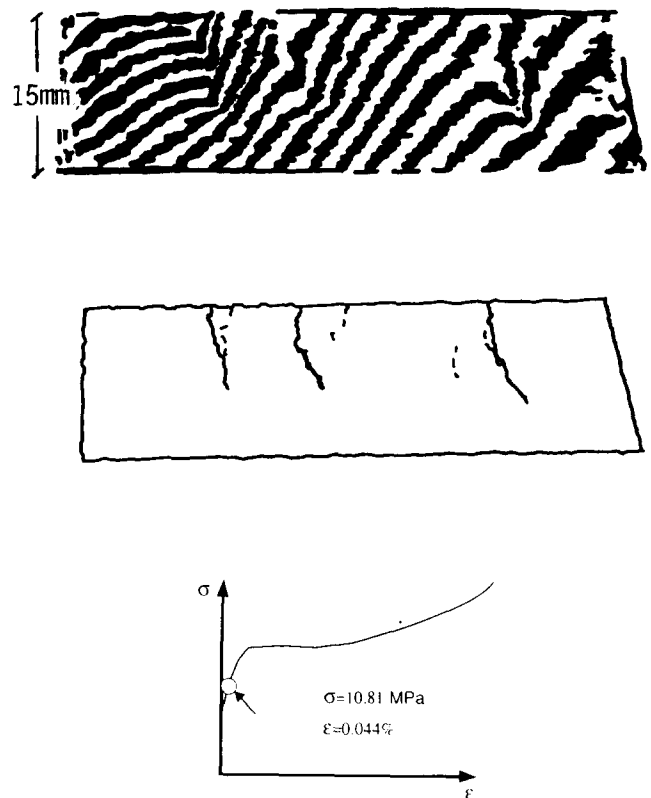


FIGURE 1. Holographic interferometry of fiber reinforced concrete [15].

calization of microcracks in fiber reinforced cement composites [15]. Figure 1 demonstrates how the distortions in the fringe pattern correspond to microcrack locations. The breaks in the fringe pattern (Figure 1a) show the location of cracks. Figure 1b shows the actual cracks, and Figure 1c shows the loading stage at which the cracking took place. Tasdemir et al. [16] also used an imaging plate close to the specimen to view a mixed-mode crack from various angles. The set-up allowed them to measure all three displacement vectors simultaneously. Castro-Montero et al. [17] performed more accurate measurements of three-dimensional displacement and strain fields by using multiple illumination directions (Figure 2). Although all of the aforementioned studies involved holographic interferometry, they involved progressively more complex optical set-up for one-dimensional and three-dimensional quantitative measurements.

Over the past decade, a significant fraction of interferometry applications have involved image acquisition with charge-coupled-device (CCD) cameras [18]. The ability to substitute film processing with a CCD camera and an image processing system increased real-time measurement capabilities. It also made interferometry techniques more rugged and user-friendly. Advances in data acquisition and storage hardware have

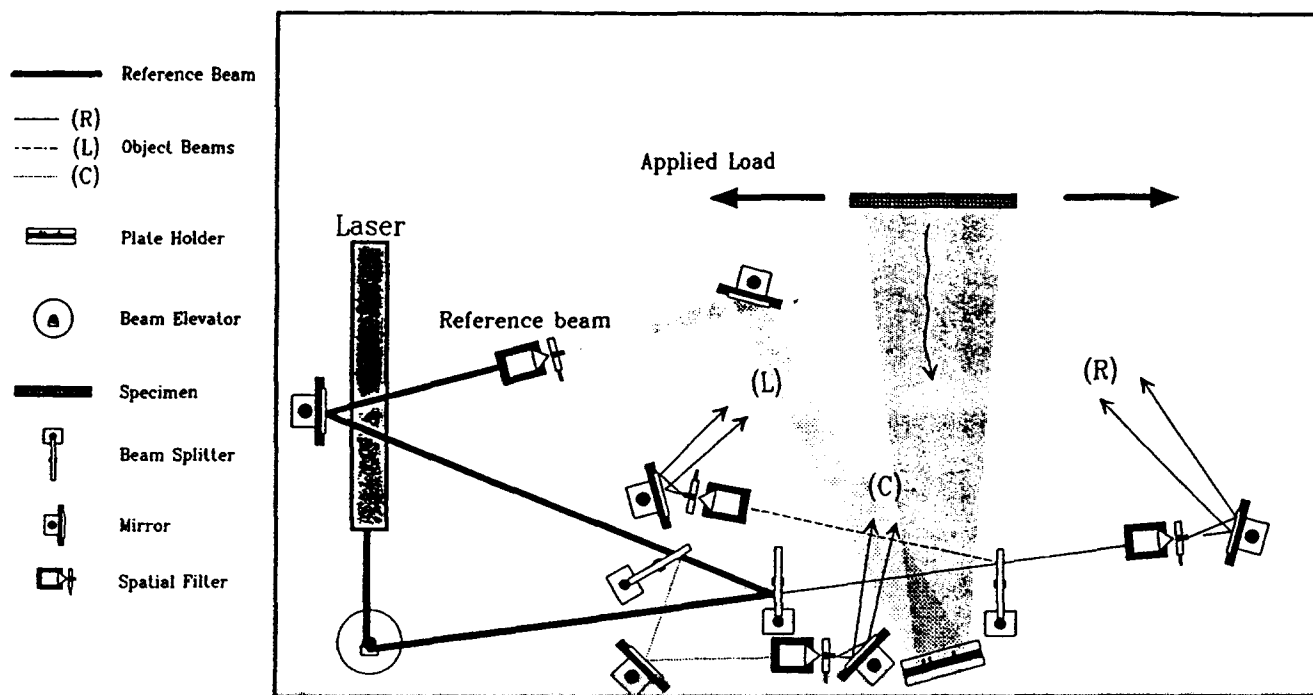


FIGURE 2. Multiple (3) object-beam holographic interferometry set-up [17].

extended these capabilities to personal computers. This development was further augmented by the easy availability of software for automatically evaluating the interferometric fringe pattern.

TV-holography was used by Hansen [19] to study flexural cracking in concrete and to observe crack arrest and crack branching in real-time. Maji et al. [20] used the electronic speckle pattern interferometry (ESPI) technique to measure crack-opening profiles in fiber reinforced concrete specimens. Using this technique, it was possible to observe the deformations, strain concentrations, and final onset of failure in a movie format. Zia and Shah [21] extended this technique with multiple illuminations to measure the in-plane displacements in carbon fiber reinforced concrete specimens. The ESPI method is superior in many ways, but it lacks the resolution and clarity of fringe pattern observed in holographic or moiré interferometry. Figure 3 shows the fringe concentration at the tip of a propagating crack observed through ESPI. The fineness or the resolution of the displacement fringes is limited by the spots on the image that correspond to the speckles. This limitation arises from the speckle size that is a function of the wavelength of the illuminating laser and the specimen's surface roughness. Other limitations are imposed by the characteristics of the imaging system, such as the pixel size of the CCD array, the size of the frame-grabber, and the resolution diameter of the imaging lens system.

The LI methods allowed researchers, for the first

time, to measure displacements and strains surrounding a crack in real-time with high precision. The high sensitivity also allowed them to pinpoint the exact location of the propagating crack tip. Although these advances were confined to laboratory experiments, field applications of ESPI and electronic shearography are currently being pursued for the evaluation of steel highway bridges.

Moiré Interferometry

Moiré interferometry, which involves creating an interference grating on the surface under investigation, has been used for studying various aspects of concrete



FIGURE 3. Electronic speckle pattern interferometry fringe concentration at a propagating crack tip [20].

fracture, including a study of the progressive localization of the strain field [22], study of the crack-opening profiles in the process zone [23], and a study of the stress–crack-opening relation [24]. Shao and Shah [25] used the high resolution of the moiré method to investigate interface debonding and matrix cracking in steel fiber reinforced concrete. Transferring the moiré grating to the concrete surface is a formidable task, but the fine resolution of the resulting fringe pattern (Figure 4) is a worthwhile reward. A comparison of Figures 1–3 and the corresponding length scales further illustrates this point.

Photoelasticity

Another interferometry-based method that can be implemented with or without laser light is reflection photoelasticity. Although not strictly noninvasive, because since it involves gluing a photoelastic coating on the specimen surface, the simplicity of the technique is appealing. Lierse and Ringkamp [26] have discussed the technical issues pertaining to reflection photoelasticity and its application for studying various fracture processes. However, the interpretation of the photoelastic fringe pattern was difficult, due to the limited resolution of the technique and the influence of photoelastic coatings on the behavior of the specimen surface. The coating has to be sufficiently thin (0.25–3.0 mm) to minimize its influence on the concrete specimen being studied. As a consequence, the coating material should also possess high photoelastic sensitivity. Plastic behavior of the photoelastic layer makes it difficult to infer what is happening in the underlying brittle concrete. Brittle photoelastic coating (unpolymerized Araldite) was therefore found to be more appropriate for studying cracking in concrete.

Fiber-Optic Sensors

Sensors based on optical fibers have extended the application of interferometry techniques to measurement

of cracking and damage [27]. The main advantage of optical fibers over conventional electrical or piezoelectric sensors is the ability to embed them in various materials and hence monitor behavior internally. Ongoing research efforts are directed toward sensor development, signal acquisition, processing, new fibers, coatings, and installation procedures. Interpretation of signals coming from the fibers is complicated by the fact that both the strain and the temperature simultaneously effects the propagation of light in the media. There are also a number of strain quantities at any particular location in a structure. It is, therefore, necessary both to install the sensor(s) and to interpret its output judiciously to separate the parameters contributing to the output signal. Some of the popular interferometric configurations—Mach Zehnder, Michelson, and Fabri-Perot—have been discussed by Jackson [28] from the perspective of engineering applications. In each of these sensors, the measurand induces a change in the phase in one leg of the propagating light, which results in a variation in the intensity of the output beam. Using a bimodal fiber, which allows light to propagate through with two different modes, one can effectively incorporate two sensors within the same fiber, and hence determine two physical quantities, such as strain and temperature, simultaneously [29]. Claus et al. [30] describes the uses of the extrinsic Fabri-Perot sensor for strain measurements. In an extrinsic sensor, interference occurs outside the optical fibers, as opposed to inside, which is the case with intrinsic sensors. A common configuration involves glass-air interfaces at the fiber ends located in a cavity; this reflects light and modulates the light intensity observed at the output end. These sensors have been used in the temperature range of -200 to 900°C , with $0.01\ \mu\epsilon$ resolution in the differential mode. Most applications to date have been in the measurement of quasistatic strains. The difficulty in measuring dynamic strains arises from the problem of determining whether the strain is increasing or decreasing from the measured intensity changes caused by interference. Using two strain signals separated 90° in phase can resolve the directionality issue.

Although the use of fiber-optic sensors is widespread in aerospace and mechanical engineering applications, its use in concrete structures has been very limited. Maher and Nawy [31] have applied the fiber-optic Bragg grating (FOBG) (intrinsic) sensor to demonstrate the feasibility of remote monitoring of the condition of concrete beams. A number of issues such as sensor placement, bonding, and instrumentation were addressed in this study. This is an example of an intrinsic fiber-optic sensor, because the feature responsible for sensing is internal to the fiber. Figure 5 shows a schematic of the sensor involved and the data ob-

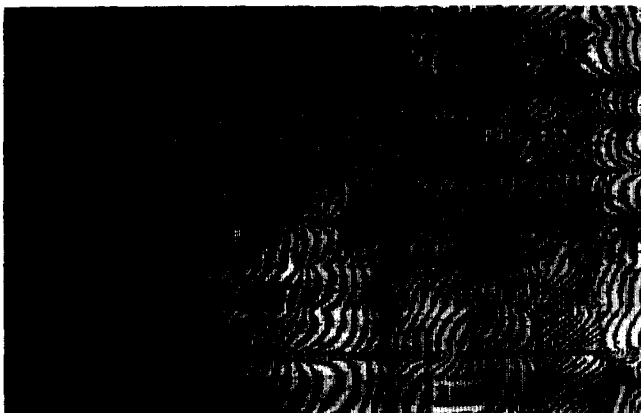


FIGURE 4. Moiré interferometry fringe pattern showing fiber debonding [25].

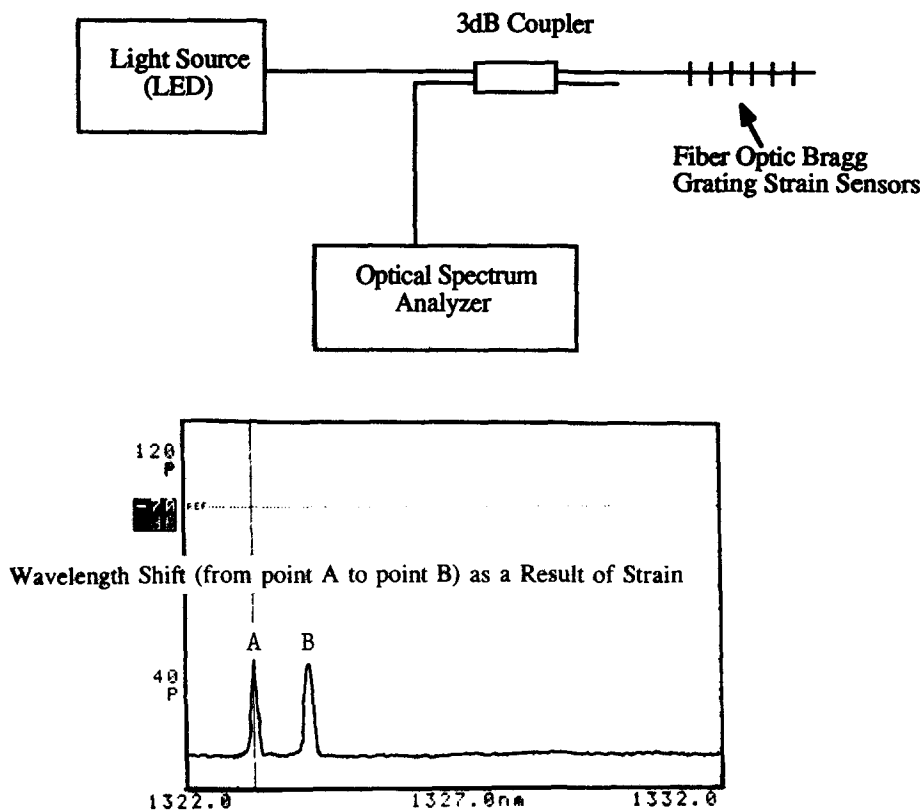


FIGURE 5. Schematic of fiber-optic Bragg grating sensor and output data [31].

tained on the spectrum analyzer. As a material is strained, the spacing on the Bragg diffraction grating changes. This in turn changes the frequency of the output from the optical fibers as shown in the lower diagram.

Huston et al. [32] describes ways of incorporating dynamic measurements in concrete with fiber-optic sensors. They used a distributed multimode fiber-optic vibration sensor embedded and tested in various reinforced concrete members. The sensing technique uses a statistical analysis of the speckle pattern output from an optical fiber undergoing dynamic perturbation. The sensor is referred to as the statistical mode sensor (SMS). The output electrical signal from the sensor is proportional to the dynamic perturbation on the sensor. Frequency response of the sensor varies from 1 Hz to in excess of 10 kHz. Mendez [33] discusses the micromechanical aspects of the fiber-matrix interaction involving cement mortar and silica glass. Significant research has been done in this area due to the efforts to include glass fibers in concrete, long before the advent of fiber-optic applications in civil engineering. Although the detrimental effect of the alkalinity of cement paste on silica fibers is still an important issue, fibers with better environmental resistance are now available. Optical time domain reflectometry (OTDR) was mentioned as the means of determining the exact location of cracks in a structure [33], analogous to ap-

plications of TDR in locating cable flaws by the telecommunications industry.

Acoustic Wave-Based Methods Ultrasonics

This is perhaps the most widely used NDE method in many engineering fields. Its applicability in concrete has, however, been limited by the heterogeneous and dispersive nature of concrete. Large-scale structural applications of ultrasonics have been rather successful [34] in determining large flaws or severe internal damage. Applications on the detection of microcracking has been limited due to the need for higher interrogation frequencies that tend to attenuate faster in the heterogeneous media. It is nevertheless possible to measure progressive damage growth during uniaxial or cyclic loading from the attenuation of ultrasonic waves (rather than by using the conventional pulse-echo technique) [35]. Berthaud [36] monitored the progression of internal damage and was able to observe the anisotropic evolution of damage under compression tests. Although these methods are able to measure damage qualitatively, it is not possible to determine the location of damage accurately.

A promising method of determining the depth of a surface crack through the spectral response of transducer's output was shown to hold promise for open cracks (notches) [37]. However, the technique, ultra-

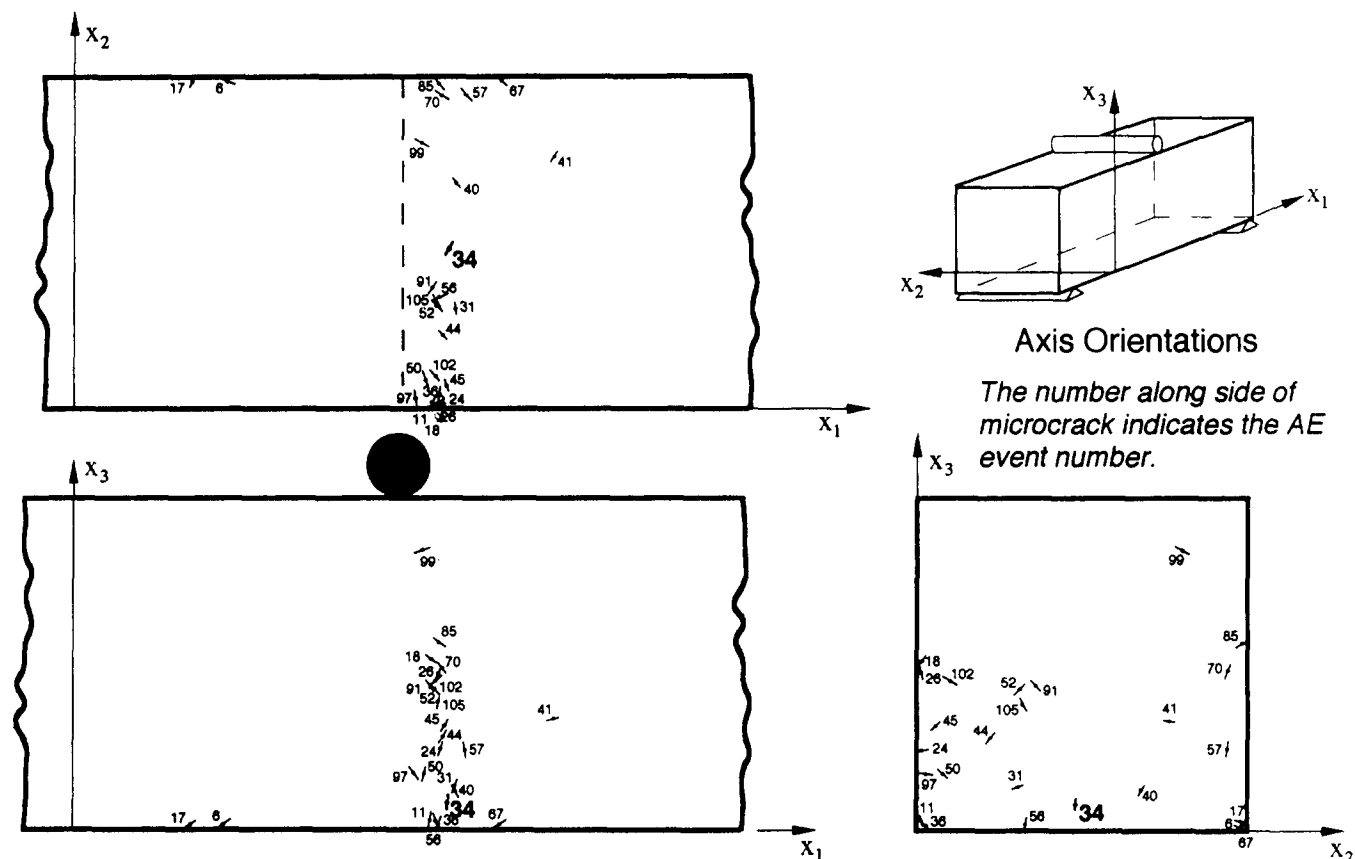


FIGURE 6. Acoustic emission source location and characterization of fracture modes [46].

sonic spectroscopy, is largely empirical and the results depend on test geometry and inherent response of the instrumentation.

Acoustic Emission

Acoustic emission (AE) involves listening to acoustic events (ultrasonic waves) generated through cracking, friction, and other energy dissipative phenomena in concrete. The technique is very well developed in monitoring pressure vessels and other mechanical parts. Its applications to concrete started in the late 1950s, and various aspects of concrete fracture were studied involving parameter estimation and source location of AE events [38]. Over the past decade, the applications of AE techniques have increased. Research efforts have moved away from parameter estimation (empirical measures of AE waveform characteristics such as pulse count, rise time, etc.) and have focused more on the ability to locate the sources of AE events and, thereby, to locate the occurrence of microcracking. Developments in theoretical formulations and data processing capabilities have also allowed the AE events to be characterized at their source, rather than on the basis of the transducer's response.

The location of the source of AE events can be determined from the time taken by the same AE event to reach a number of transducers (time-of-arrival studies). A number of researchers used this method to detect the location of microcracking in concrete. The ability to locate microcracks as they occur allowed researchers to study crack propagation and crack-arrest mechanisms under various loading conditions [39–42]. Various two-dimensional and three-dimensional source location algorithms were used in the research. Accurate location of the AE source also required a more critical investigation of the AE signals to distinguish between the AE events and spurious noise. As a result, the concrete community became more aware of the specific nature of AE technology as applicable to concrete and geomaterials, as opposed to AE technology in other fields where AE technology was well established.

In the latter part of the 1980s, researchers started extending source location techniques further by evaluating the AE event on the basis of the source function rather than at the transducer's output. This technique of source characterization was already developing in other applications of AE [43] and depended on the proper modeling of the specimen and the transducer's

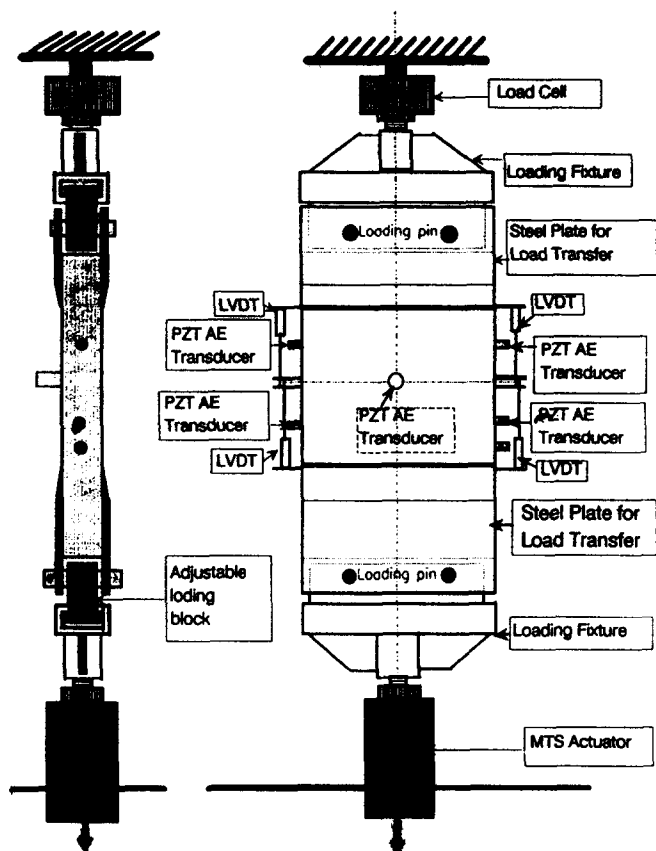


FIGURE 7. Feedback control system with acoustic emission input for unnotched beam tests [48].

response characteristics (transfer function). One objective of source characterization was to remove the subjectivity of using conventional AE parameters (such as rise time, pulse count, etc.), which were based only on the transducer's output. The other use of source characterization was to differentiate between the fracture modes at a microscopic level. A number of investigations were carried out, based on various levels of complexity. Calibration of transducers against known re-

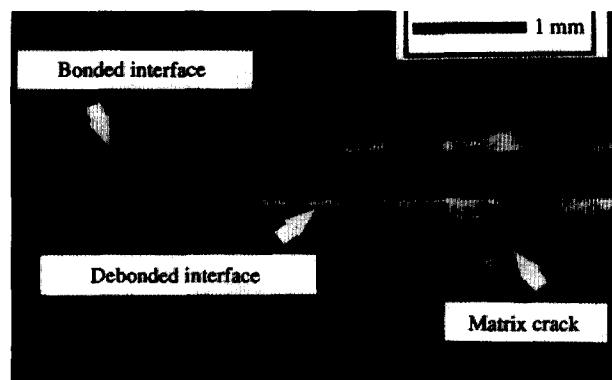


FIGURE 8. Optical fluorescence microscopy of fiber reinforced concrete [51].

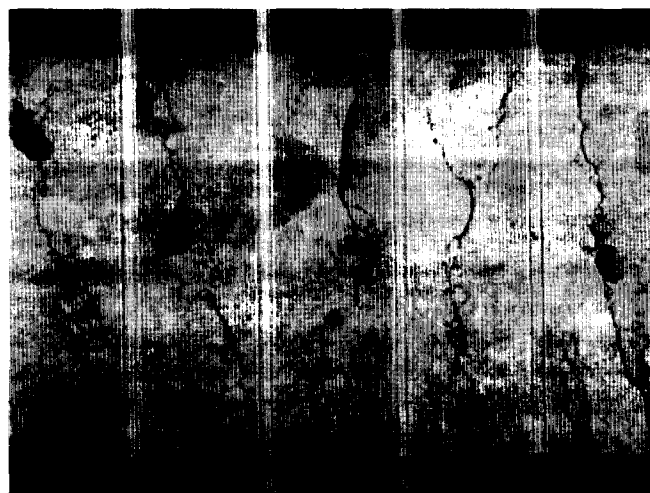


FIGURE 9. Crack pattern resolved with a liquid penetrant method [53].

sponses provided their transfer functions. Specimen response Green's functions were determined from elastodynamic wave propagation theory with various simplifying assumptions. It was possible to determine the orientation (relative movement of the crack faces) of each microcracking event that caused an AE wave and the associated energy dissipation [44-46]. The direction of the arrows in Figure 6 designate the orientation of each microcrack AE event located during a flexure test [46]. The more recent works [46] have involved considerable cross-checking, accurate modeling, and sophisticated deconvolution algorithms. Nevertheless, one aspect of source characterization that is both an asset and a drawback at present is the inability to verify the results independently with other methods, because no other method yields the character of the microcrack source.

Other interesting applications of AE have emerged such as the ability to monitor freeze-thaw induced damage much earlier than possible with any other method [47]. It is difficult to control uniaxial tensile test of concrete without using crack-opening displacement as the feedback control signal. At the same time, it is impossible to know where a crack will form in an unnotched specimen. Using the location of AE events, Li et al. [48] were able to select the proper LVDT (displacement transducer) to use as the feedback control, and they obtained stable postpeak tension behavior (Figure 7) of unnotched specimens.

Other Techniques

A number of other disparate methods have been used on concrete. In the context of smaller flaws, the detection of bubbles in grouted bridge cable stays have been addressed with a number of NDE techniques (ultra-

sonic, X-ray, and neutron radiography) [49]. The progression of internal microcracking can be observed with neutron radiography [50] by inspecting sections of the concrete specimen at different loading stages. Although the neutron radiography technique itself is noninvasive, the process of slicing the samples is obviously not.

Optical fluorescence microscopy has proven to be an effective means of studying matrix and interface cracks in fiber reinforced concrete [51] (Figure 8). In an article on various means of detecting the fracture process zone, Mindess [52] discusses other techniques such as the use of liquid penetrants (Figure 9) [53,54] and infrared vibro-thermography, which have been used to a lesser extent. It is also possible to add short well-dispersed carbon fibers to concrete to increase its electrical conductivity. Subsequently, cracking can be detected by degradation in the conductivity in this smart material [55].

Because the applications of NDE at the structural level were not the focus of this paper, some of the pertinent literature on structural testing is worth mentioning. A detailed description of many techniques for both laboratory and field applications is in the CRC handbook [56]. CANMET [57] prepared an annotated bibliography on various NDE methods used on concrete both at the materials and at the structural level. Other relevant literature consists of the proceedings of various national and international conferences on NDE of concrete [58-60].

Conclusion

The number of available NDE techniques and their sophistication has increased in recent years. This trend is expected to continue with the advances in data processing and sensor technology. The primary issue is therefore the culmination of the research into better design and maintenance of concrete and in better structural and material inspection tools and standards.

Acknowledgment

The author's research in this field is supported by the National Science Foundation (grant No. MSS 9212733, administered by Dr. K.P. Chong).

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