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OBSERVING THE MULTIPLE CRACKING OF FRC COMPOSITES BY ELECTRONIC SPECKLE PATTERN INTERFEROMETRY

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ABSTRACT

Electronic Speckle Pattern Interferometry technique is used to record the location of crack initiation, sequence of the multiple cracking and recording the cracking stresses of the fiber reinforced cement composites. Microstructural parameters at each crack location are quantified by statistical methods. The size of the fiber free areas are measured and percantage of fiber clumping are calculated at the crack surfaces. Relation between the microstructural parameters and mechanical performance is invesigated. It is found that increase in the size of the fiber free areas in the composite decreases the cracking stresses. It is shown that the toughness of the composite depends on the fiber clumping at the first crack cross-section.

Keywords: extrusion, laser interferometry, fiber dispersion, multiple cracking

INTRODUCTION

Electronic Speckle Pattern Interferometry (ESPI) technique is a highly accurate displacement measurement method, which allows mapping of the crack propagation at the micro-scale. This technique is used to observe the multiple cracking of the fiber reinforced cement composites, and to evaluate the cracking stresses and sequence of the crack formation.

High performance fiber reinforced composites are characterized by enhanced elastic limit, strain hardening response and toughened post-peak response. If the composite is adequately reinforced, the bridging fibers will share the load and transfer it to the other parts of the composite. During the strain hardening response, number of cracks increase and cracks widen very little. Multiple cracking occurs when the subsequent transferred load cracks the matrix again. Hence, the initial flaw size and the fiber dispersion play important role on the initiation of the cracking and toughness (Akkaya et. al. 2000a, and 2000b). This study investigates the effect of fiber dispersion on the multiple cracking behavior of extruded fiber reinforced composites.

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MATERIALS AND EXPERIMENTAL TECHNIQUES

2 mm PVA fibers of 14 microns in diameter are used 3% by volume in the cement based extruded composites. A die with a rectangular cross-section of 25.4 mm x 4 mm is used in extrusion.

Flexural behavior of the composites is studied by closed-loop, Four-point flexure test which is performed by controlling the displacement measured by an LVDT mounted on the specimen. The gauge length was 38.1 mm. Five identical specimens are tested. Flexure tests are followed with ESPI technique to record the location of crack initiation, and sequence of the multiple cracking.

The ESPI experimental setup includes an interferometer, a loading unit, image acquisition and processing units, an analog/digital interface and an image storage and display (Fig. 1).

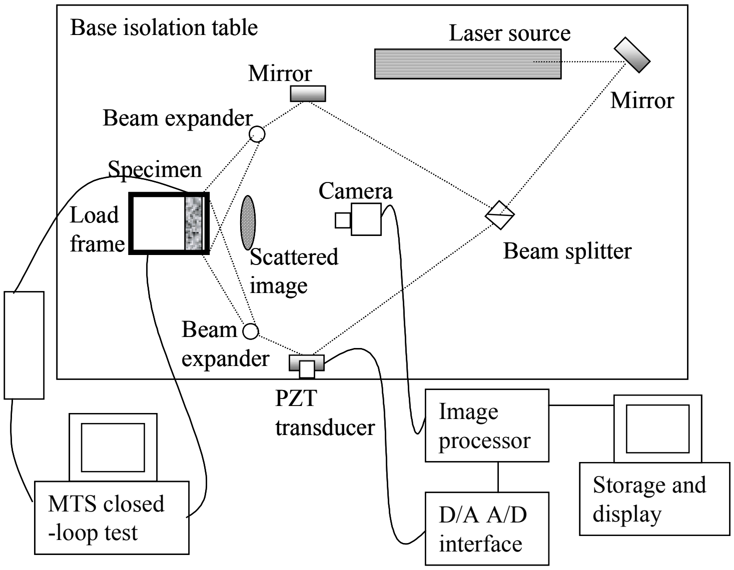

FIG. 1. Test setup

The optical phase-shifts are controlled by piezo-electric transducers. 45 mW Helium-neon laser is used as the light source. The test is followed by a CCD camera to record the speckle patterns. The scattered images of the reference and deformed states of the composite and load – displacement values are recorded. The speckle pattern fringes are formed by the electronic subtraction of reference image and deformed image.

Microstructural observations at the cross-sections of crack locations are made by a Scanning Electron Microscope (S.E.M.), in order to understand the microstructural mechanisms involved in the failure. Crack surfaces are studied in order to evaluate the fiber dispersion and fiber free areas in the composite. Spatial point pattern analysis is employed to quantify the fiber dispersion. The relation between microstructural parameters and the composite cracking is evaluated.

ELECTRONIC SPECKLE PATTERN INTERFEROMETRY TECHNIQUE

ESPI technique is a highly accurate displacement measurement method, which allows mapping of the crack propagation at the micro-scale. The sensitivity of the technique is in the order of a fraction of wavelength of the monochromatic light. Speckle effect forms when a rough object is illuminated with a laser light. The scattered light from the object presents a granular appearance. Each point on the object surface absorbs and re-emits the light as a source of spherical waves. The complex amplitude of the scattered light at any point in space is given by the sum of the amplitudes of the contribution from each point on the object surface. Since the surface roughness is typically random, the intensity of the scattered light at any point also varies randomly, leading to the speckle effect. The random speckle pattern contains information about the surface shape of the object. Speckle interferometry utilizes this phenomenon to obtain the relative deformation due to loading of a structure. This is done by comparing (correlating) the random speckle pattern at two different loaded states of the object. If the random variation in phase and amplitude of the speckle patterns are not too drastic, the speckle patterns in the original and displaced states are correlated and can be processed to obtain correlation fringes (Fig. 2). Excessive displacement can be a source of de-correlation. To overcome this effect, the displacement process was segmented into intervals and a significant change in the random phase and amplitude of the speckle pattern were prevented. Details about the technique and fringe formation can be found in Ghandehari et.al.1999 and Ghandehari et.al.2000.

FIBER DISPERSION ANALYSIS

Fiber dispersion is important in the initiation and sequence of the cracking. As the fibers clump and the size and number of matrix areas which are not supported by fibers increase, the initiation of a crack requires less energy and once the crack forms, it can advance easily through the fiber free areas in the matrix. Point process statistics are calculated in order to quantify the dispersion of fibers. The procedure is described in detail elsewhere Akkaya et. al. 2000c.

Two statistical functions are calculated to quantitatively describe the fiber dispersion. The K-function is a standard measure of the expected number of fibers within a certain distance of a given fiber location. The K-function is calculated to describe the tendency of fibers to clump. Percentage of clumping in the composite can be calculated by comparing the K-function of the composite with the random dispersion. The F-function is the distribution of distances between arbitrary points to the nearest fiber. The largest of these arbitrary point-nearest fiber distances is the radius of the maximum fiber free area. The compliment of this function would also indicate the fraction of the total fiber free area

LINEAR ELASTIC FRACTURE MECHANICS

Fiber reinforced cement composites contain preexisting flaws and defects. It is the size of these flaws that determines the critical load required for crack initiation. Far-field stresses, well away from the location of the flaw, will be equal to the applied stress. However, the presence of the flaw along the cross-section perpendicular to the applied load would cause stress concentration at the tip of the flaw. Here, the flaw is considered to be in an infinite plane, traction-free and subjected to uniaxial tensile stress. According to the principles of linear elastic fracture mechanics, stresses at the flaw tip are proportional to a factor called the Stress Intensity Factor, K_I, which can be derived by basic principles of elasticity. K_I increases proportionally with the applied load and at a critical value, K_{IC}, the failure occurs. LEFM is applicable as long as the initial flaw size can be considered unchanged. In this study, LEFM is used to calculate the fracture toughness at the crack initiation. K_I solution for an edge cracked plate subjected to pure bending is given in Anderson, 1995. Fracture toughness K_{IC} can be calculated by using the moment and flaw size at which the composite cracking occurs.

RESULTS AND CONCLUSION

Crack locations are identified by discontinuities in the fringes of ESPI pictures (Fig. 2).

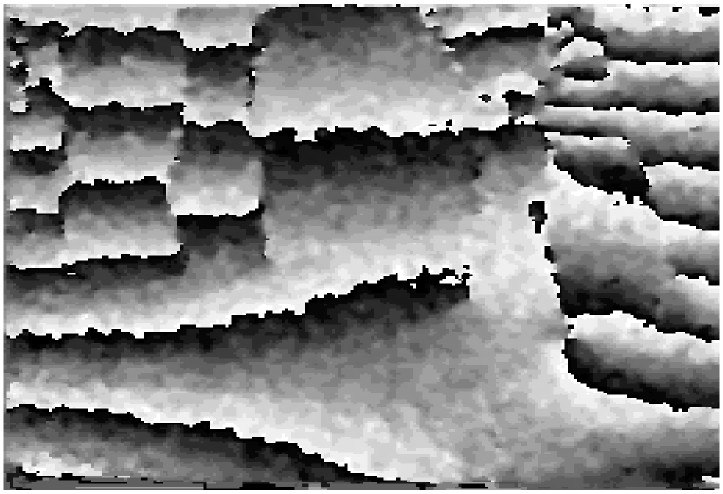

FİG. 2. Crack locations identified by the discontinuities in the fringes.

Later, each specimen is separated from the main crack location, polished and SEM picture of the cross-section is taken. Then the distances between fiber pairs and the point process statistics are calculated.

It is found that first, second and third crack cross-sections have higher K-function values, meaning more number of fibers can be found around any given fiber. Cross-sections with a higher degree of fiber clumping would crack before cross-sections with evenly dispersed fibers. Fourth, fifth and sixth cracks exhibited fiber dispersions similar to the random dispersion.

At the first crack location, number of fiber free areas observed are more than the subsequent cracks (Fig. 3). These fiber free areas act as defects in the composite and decrease the mechanical performance. The largest fiber free area is found at the first crack location.

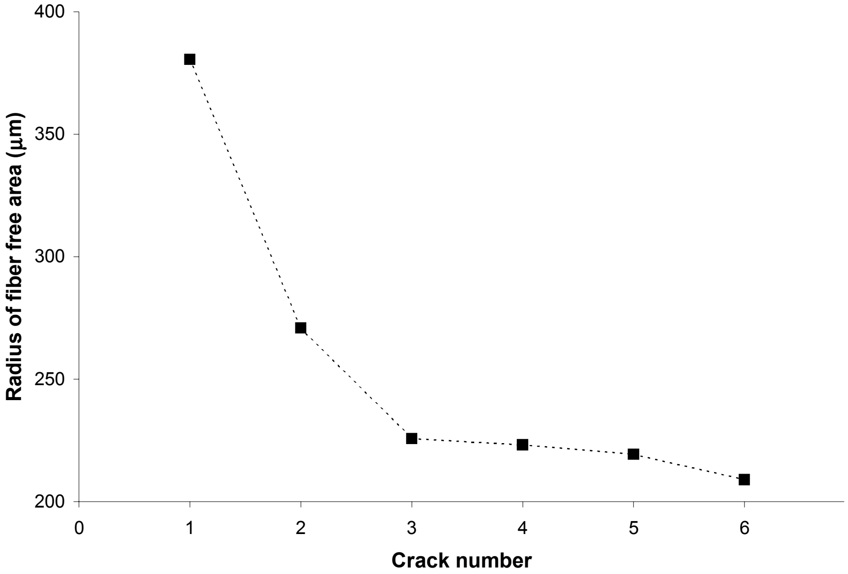

FIG. 3. Fiber-free areas in the crack sequence.

Experimental values of cracking loads are used to calculate the moments and the radius of the fiber free areas are used as the flaw size in order to calculate K_{IC} values of the cement composites. The average K_{IC} value is calculated as 26 MPa $mm^{1/2}$, in accordance with literature (Mobasher, B. et. al. 1991, and Ouyang C. and Shah, S.P., 1992**.**). Detailed statistical analysis of this comparison can be found in Akkaya et. al. 2001. From these results, it is reasonable to conclude that the procedure used to measure the size of the fiber free areas is reasonably accurate and that the linear elastic fracture mechanics assumptions are a good approximation for the cracking process.

A variation in toughness is seen among the identical specimens. Microstructural parameters are used to explain the different behavior among the samples. A close relationship between the fiber dispersion at the first crack location and composite toughness is seen in Fig. 4. An efficient fiber bridging and transfer of the load to the other parts of the composite can be achieved if there is a better fiber dispersion and less fiber clumps at the first crack location. Better fiber dispersion, in turn, increases the toughness of the composite.

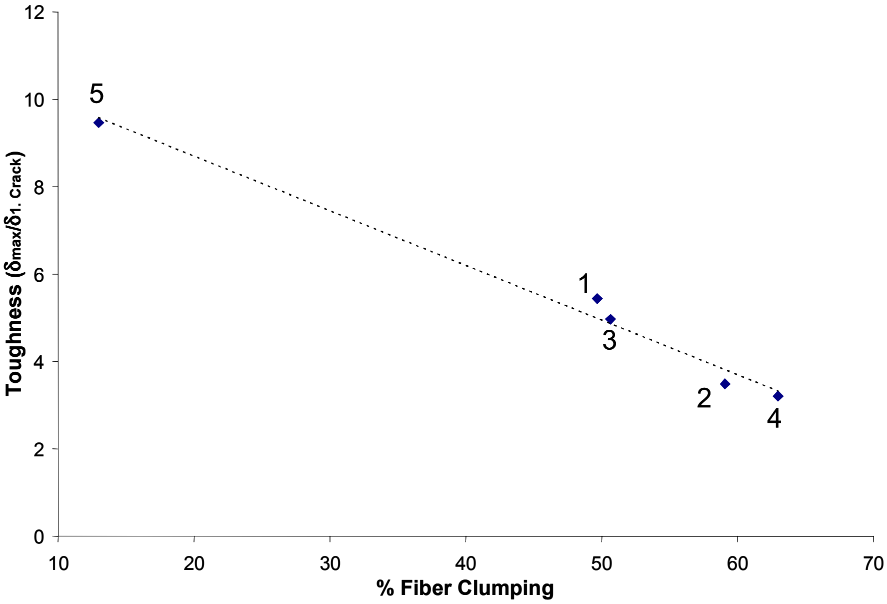

FIG. 4. Relation between toughness and fiber clumping at the crack location

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