# EVALUATION OF COHESIVE CRACK MODELS USING HOLOGRAPHICALLY MEASURED STRAIN FIELDS

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The cohesive crack model assumes that fracture in concrete can be modeled as a discrete crack with a closing pressure applied to the crack faces. However, there is no clearly defined method of determining the closing pressure and several authors have proposed widely varying closing pressures. This paper uses laser holographic interferometry to accurately measure crack openings and surface strain fields in a center cracked mortar specimen. These experimental results are then compared to crack openings and strain fields obtained from finite element studies using the cohesive crack model. With this method, it is possible to find a bilinear closing pressure for the type of mortar used and to explore which parameters are needed to define the closing pressure.

## INTRODUCTION

One proposed model for fracture in concrete and mortar is the Hillerborg or cohesive crack model (1). In this method, a crack is modeled as discrete crack in a finite element mesh and a closing pressure is applied to the faces of the crack. This closing pressure is supposed to represent the effects of the fracture process zone, shielding, aggregate interlock and bridging. However, the original model assumed that the closing pressure was a function only of the crack opening displacement, w, the tensile strength, $f'_t$, and the fracture energy release rate, $G_f$ and that the stress intensity factor, $K_I = 0$. The

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original model also proposed a linear relationship (1). Several other authors (2) (3) (4) (5) (6) have proposed closing pressure relationships and/or modifications to the original model, but there is no consensus on which closing pressure relationship is correct or what factors are important in determining the closing pressure relationship.

## USE OF HOLOGRAPHIC INTERFEROMETRY

A holographic interferogram is formed by making a hologram of an object in two different states of deformation and then combining the holograms. The result is an image of the object covered with fringes. These fringes represent the difference in displacement of the object surface which occurred between the making of the two holograms. A discussion of the holographic method for determining displacements can be found in references (7) and (8).

Using the holographic method, it is possible to determine the displacement between any two points on the object surface to an accuracy of 0.5 $\mu$m. This is done by counting the number of fringes between the two points and applying the proper equation (see references (7) and (8)). These displacements can then be converted to crack opening displacements or strains.

## ANALYSIS OF CLOSING PRESSURES

The specimen used was a center notched plate specimen made of mortar with a maximum aggregate size of 3 mm and a w/c ratio of 0.65. Five specimens were tested. One of the five specimens had a 25 mm diameter circular piece of limestone, simulating an aggregate, embedded 25 mm from the notch tip (Figure 1). Crack opening measurements for approximately 10 different crack lengths in each specimen were made using the holographic method. Strain fields were measured in the "aggregate" specimen and one of the other specimens.

The measured crack profiles in the specimens without the "aggregate" were used to evaluate some closing pressures given in literature: linear (2), trilinear (3), exponential (4), and bilinear (5). While some of these closing pressures were able to match the measured load vs. notch tip opening displacement (NTOD) curve, none of the closing pressures studied were able to match the entire crack profile (Figure 2). However, some of the proposed closing pressures preformed better than others, and closing pressures which were the closest to matching the measured profiles were those developed for concrete with similar aggregate sizes. The fit was also improved by taking crack length into account. This was done using the method proposed by Cook, et. al. (6) which proposed that some part of the crack should be permanently traction free. It therefore appears that aggregate size and crack length are important parameters for the closing pressure relationship.

Using the measured crack profiles it was possible to back calculate the required closing pressure for each crack length. These back calculated closing pressures were then optimized to a single bilinear closing pressure for each specimen (Figures 3 and 4). As expected, the optimized closing pressures provided and excellent fit, but the fit was again improved by using the method of Cook et. al. (6) to account for crack length effect. If the corrected closing pressure is used to calculate the value of the stress intensity factor, $K_I$, the calculated value is almost constant at 15 MPa $\sqrt{}$mm. However, assuming $K_I = 0$ does alters the results only slightly as long as the $K_I = 0$ crack length is calculated, not assumed.

## ANALYSIS OF STRAIN FIELDS

Another critical test for the cohesive crack model is to see if the model can predict the behavior of the entire specimen. Using the holographic method, it was possible to measure the strain fields across the entire specimen. (Figure 5). Note that a small, elliptical zone of concentrated strain forms at the crack tip. However, this strain is not as high as predicted by a linear elastic (LEFM) solution. Figure 6 shows the results if the holographic strain field is subtracted from the LEFM strain field. The areas enclosed by the contours in Figure 6 are areas where the difference in strain is either greater than 60 $\mu\epsilon$ or less than -60 $\mu\epsilon$. It can be seen that there is a zone of constant size formed in front of the crack where the strains are lower than the LEFM solution. This may indicate a fracture process zone of constant size. Behind the crack is a zone where the measured strain is higher than the LEFM solution. This appears to be a wake and it grows larger as the crack propagates.

Using the calculated bilinear closing pressure (Figure 3) and a finite element program, a predicted strain field for the cohesive crack model was calculated (Figure 7). These strain fields were consistent with the measured strain fields, indicating that the cohesive crack model can predict the whole field behavior of a specimen.

Strain fields were also measured in the specimens with aggregates (Figure 8). These specimens also show a concentration of strain near the crack tip. However, once the crack tip begins to propagate around the aggregate, there is also a strain reversal (to compressive stress) at the point where the crack first meets the aggregate. At the present time, analysis of this specimen is continuing.

## CONCLUSIONS

The cohesive crack model (Hillerborg model) can predict the fracture behavior and entire strain field for a concrete specimen. However, great care must be taken to select the correct closing pressure relationship. The current model, which only uses crack opening, tensile strength and fracture energy is not adequate. Maximum aggregate size and crack length are also important parameters. The assumption in the original model that $K_I = 0$ is acceptable as long as the $K_I = 0$ crack length is calculated, not assumed.

Analysis of the measured strain fields show an elliptical zone of high strain in front of the crack tip which becomes larger as the crack grows. However, if the difference between the measured strain fields and the predicted linear elastic fields (LEFM) is taken, the fracture process zone is seen as a zone of constant size in front of the crack. There is also evidence of a zone of waking behind the crack.

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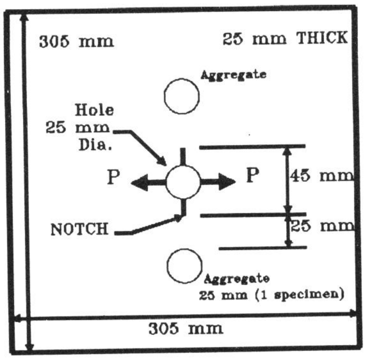


Figure 1 - Specimen

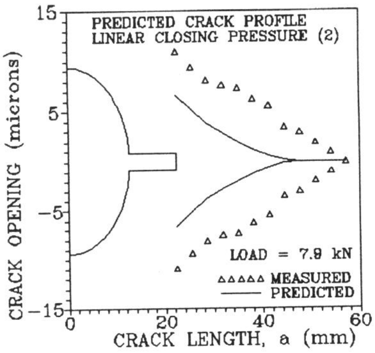


Figure 2 - Measured vs. predicted profile - linear cp

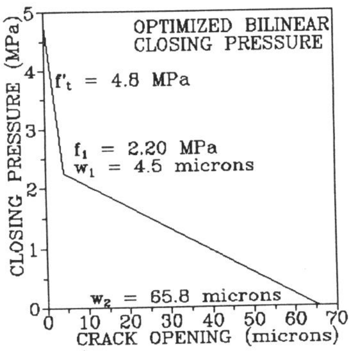


Figure 3 - Optimized bilinear cp

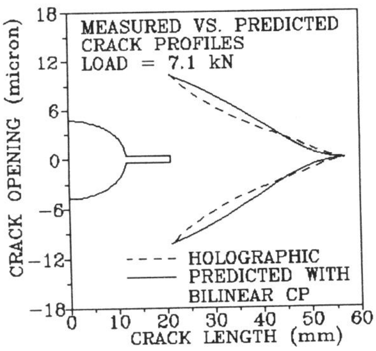


Figure 4 - Measured vs. predicted profile - bilinear cp

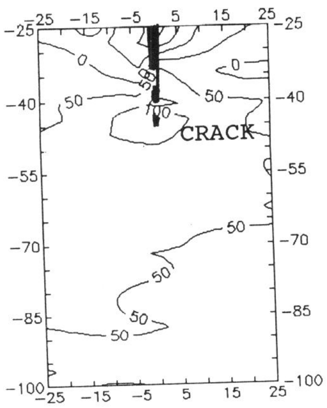


Figure 5 - Holographically measured strain fields (contours in $\mu\epsilon$, mm grid)

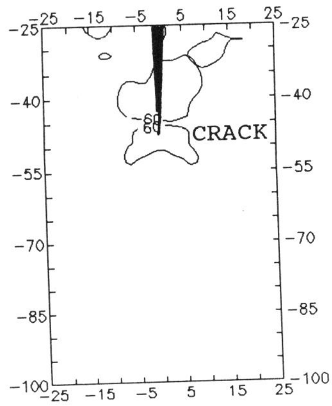


Figure 6 - Difference between LEFM and measured strain fields ($\mu\epsilon$ contours, mm grid)

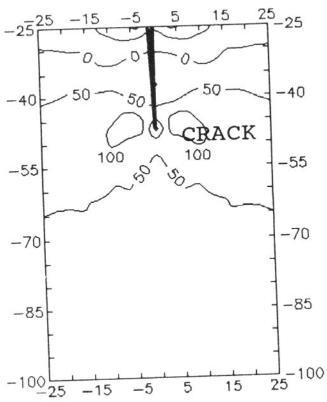


Figure 7 - Predicted strain field with closing pressure ($\mu\epsilon$ contour, mm grid)

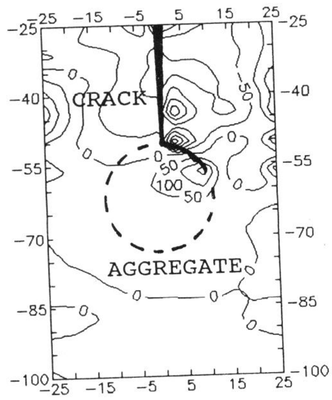


Figure 8 - Strain field in aggregate specimen ($\mu\epsilon$ contours, mm grid)