APPLICATION OF FRACTURE MECHANICS TO CEMENTITIOUS COMPOSITES

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To apply the classical concept of fracture mechanics, connected with one-parametric stress field characterization, the relation between fracture process zone and singularity dominated zone has to be established. One-parametric solutions hold if singularity dominated zone confines microcracking zone. The extent of microcracking area surrounding crack-tip was evaluated in concrete beams and single-edge-notched specimens by means of photoelastic coating method. Stress field parameters were estimated numerically. The basic assumptions of elastic fracture mechanics are questioned.

INTRODUCTION

In spite of the fact, that basic assumption of Quasi-Elastic Fracture Mechanics in concrete are often called in question, there have been published a number of papers, concerning its application to the description of fracture process in cement-based composites.

As a necessary condition, it was presumed that the size of elements enables to consider them as manufactured of homogeneous, brittle material. The problem of great importance is to determine the range of microcracking zone in the neighborhood of a crack-tip and to match certain geometrical requirements. They form the relation between parameters characterizing the element proportion and the extent of physical nonlinearity zone at the crack-tip area. Applying Finite Elements Method or Dimensional Analysis it was possible to establish the minimal characteristic size of concrete specimen for which QEFM assumptions hold. Theoretical considerations were presented by Bazant (1) and Carpinteri (2).

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The Dimensional Analysis application is motivated by the coexistence of two different structural crises induced by physical factors possessing different physical dimensions: ultimate stress [MPa] and critical stress intensity factor [$MNm^{-1,5}$]. Thus, there is a need to determine conditions and criterions when one of this crises dominates. This paper addresses that need.

LIMITATION OF QEFM IN CONCRETE

It is assumed, that the objective criterion for an application of QEFM in brittle matrix composites is to investigate, directly in the considered elements, the existence of so called "brittle fracture". For concrete-like specimens it is necessary to establish relationship between two areas: microcracking zone (MZ) or fracture process zone (FPZ) and the singularity dominated zone (SDZ). SDZ includes the area in which the stress tensor may be described by one-parametric solution of QEFM, connected with the stress intensity factor. For application of QEFM in cementitious composites SDZ must confine FPZ (Rossmanith (3)).

EXPERIMENTAL PROCEDURE

The experiments were carried out on beams and single-edge-notched specimens. Their dimensions and loading scheme are shown in Figure 1. Elements were manufactured of ordinary concrete with maximal grain size 0.016m. In their midsection an artificial notch of relative length a/W=0.3 was moulded. Three elements of each type were tested. A photoelastic coating 0.002m thick was glued on one lateral surface and a set of electric resistance strain gauges was fixed on the other one. Isochromatic and isoclinic fringe patterns were recorded at loading stages of approximately $0.5P_{max}$ and $0.9P_{max}$.

STRESS-FIELD CHARACTERIZATION

Distortions of the isochromatic fringes caused by irregularities of concrete and boundary effects were described by two Westergaard's type stress functions (Rossmanith (4)) for an isotropic, elastic body. Functions Φ_I and Φ_{II} are connected to the modes I and II of a crack propagation:

$$\Phi_I(r,\theta)=K_I(2\pi r)^{-0.5}(e^{-0.5i\theta}+\gamma_1 re^{0.5i\theta}) \quad \text{..........(1)}$$

$$\Phi_{II}(r,\theta)=K_{II}(2\pi r)^{-0.5}(e^{-0.5i\theta}+\gamma_2 re^{0.5i\theta}) \quad \text{........(2)}$$

The stress tensor is determinated in terms of these functions with addition of an uniform stress field σ_{ox}, parallel to the crack line :

$$\sigma_x = Re\phi_I + 2Im\phi_{II} - y(Im\phi_I{}' - Re\phi_{II}{}') + \sigma_{ox} \quad \text{.............. (3)}$$

$$\sigma_y = Re\phi_I + y(Im\phi_I{}' - Re\phi_{II}{}') \quad \text{......................... (4)}$$

$$\tau_{xy} = Re\phi_{II} - y(Im\phi_{II}{}' + Re\phi_I{}') \quad \text{....................... (5)}$$

Parameters γ_1 and γ_2 reflect the influence of specimens' boundary effects and structure irregularities. Utilizing fundamental formulas of photoelastic coating method one can define the function:

$$f_k = (\sigma_x - \sigma_y)^2 + (2\tau_{xy})^2 - [Nf_\sigma E_s^*(1+\nu_c)]^2 [2E_c(1+\nu_s^*)]^{-2} \quad \text{.. (6)}$$

The Young's modulus E_s^* as well as the Poisson's ratio ν_s^* attain their fictitious values in the microcracking region. The fictitious modulus for concrete can be derived analytically provided the strain loci in notch cross-section is known (Stys (5)).

Investigating heterogeneous, brittle material with the aid of photoelastic coating method, the problem of a crack-tip localization has to be solved. For reasons such as crack front curvature, microcracking and stochastic scatter of tough gravel inclusion, the crack-tip in coating does not always coincide with the crack-tip in concrete specimen. An additional correction procedure is introduced for proper crack tip localization. Two independent parameters x_o, y_o are cartesian coordinates of crack-tip refering to the coordinate system which can be easily positioned (for instance: lines of measurement mesh) (Sanford (6)). Finally f function depends on seven parameters: K_I, K_{II}, γ_1, γ_2, σ_{ox}, x_o, y_o.
The unknown parameters were derived numerically. Set of data consisted of thirty points located on isochromatic fringes of orders N_i (5). The Newton-Raphson's procedure and the least-squares minimization process were involved in numerical calculations (6).

Singularity Dominated Zone

Comparing the accuracy of a one-term (K_I -characterization) crack-tip stress components with values obtained from "exact" solution, one can define SDZ. Numerically estimated stress field characteristics describe the stress tensor in a precise way so thereon this solution is called "exact". As the basis for SDZ evaluation stress σ_y , perpendicular to crack line, is commonly used. Limiting condition for SDZ is expressed as a percentage error-q, between "exact" and K_I-solution:

$$q = | (\sigma_y^V - \sigma_y^I)\ (\sigma_y^V)^{-1} | \qquad (7)$$

In case of brittle matrix composite 90% accuracy is quite satisfactory. Formation of SDZ in type I and type II specimen is shown in Figure 3 and Figure 4. For reason of considerable discrepancies between radii of FPZ-r_* and SDZ-r_o , a logarithmic scale was used.

FRACTURE PROCESS ZONE DETERMINATION

The extent of the microcracking zone was defined on the basis of isochromatic fringe patterns employing a relation between optical effect and strains:

$$\varepsilon_{1c} - \varepsilon_{2c} = \varepsilon_{1s} - \varepsilon_{2s} = N f_\varepsilon \qquad (8)$$

Relations given above enable to define the extent of FPZ boundary on the basis of boundary fringe order, derived from equation (8), having assumed strength hypothesis (Jankowski and Stys (7)). It is a matter of convenience to formulate a hypothesis which depends on material characteristics attainable by simple laboratory tests. As the ultimate strain corresponding to initiation of microcracking, a value ε_{TS} =1.1x10 was assumed. For the strength hypothesis expressed in terms of strains:

$$(\varepsilon_{1s}^2 + \varepsilon_{2s}^2)^{0.5} = \varepsilon_{TS} \qquad (9)$$

the value of boundary isochromatic fringe is N =0.12. Exemplary range of FPZ in specimens of type I and type II is given in Figure 2, in logarithmic scale.

CONCLUSIONS

Meaningful differences between SDZ and FPZ illustrate Figures 3 and 4. Particularly in the region above the crack-tip, which is usually examined, the range of FPZ is much more larger than that of SDZ. This was observed in every investigated specimen. Thus, the basic assumption of QEFM are violated. One-parametric stress field characterization should not be used for concrete elements 0.1-0.3m in width, commonly used in laboratory practice.

Generally, SDZ and FPZ are better correlated for single-edge-notched specimens. In both types of specimens there exists an area, in which SDZ confines FPZ and classical solutions of fracture mechanics are correct. Unfortunately, these regions are located below a crack-tip.

SYMBOLS USED

γ_1, γ_2	= higher order terms of stress functions
f_ε, f_σ	= photoelastic constants (N^{-1}, MPa/N)
N	= fringe order
E_s^*, E_c	= Young's modulus for concrete and coating (MPa)
ν_s^*, ν_c	= Poisson's ratio as above
x_o, y_o	= crack-tip coordinates (m)
σ_y^I, σ_y^V	= one and five-parametrics stress characterization (MPa)
ε_{1c}, ε_{2c}, ε_{1s} ε_{2s}	= principal strains in coating and specimen
ε_{TS}	= ultimate tensile strain
r_*, r_o	= radii of FPZ and SDZ ($\ln(m\times10^4)$)

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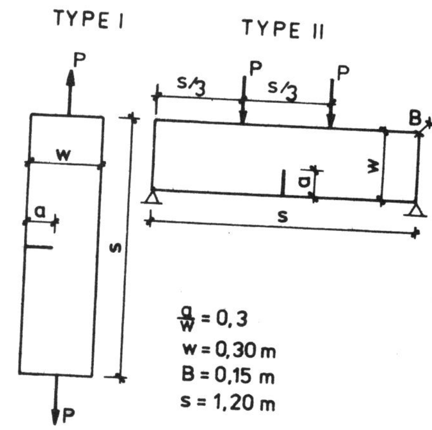

Figure 1 Geometry and dimensions of specimens

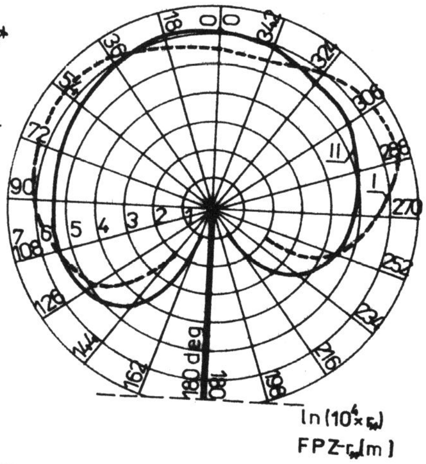

Figure 2 Range of FPZ in specimens of type I and II

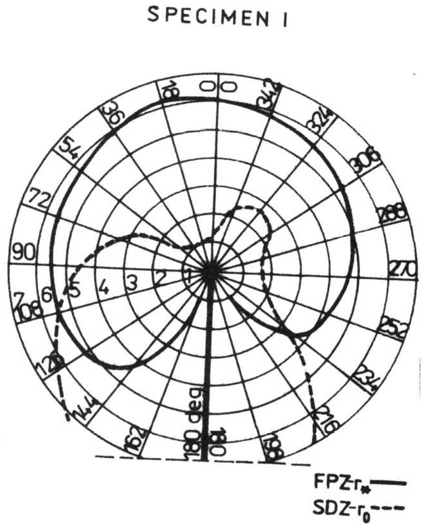

Figure 3 Formation of FPZ and SDZ in type I specimen

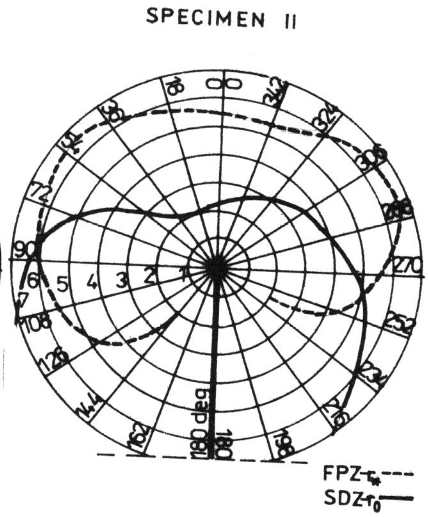

Figure 4 Formation of FPZ and SDZ in type II specimen