INTERACTION OF NON-COPLANAR CRACKS APPLICATION TO ROCK FRACTURE

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ABSTRACT

A series of photoelastic experiments was conducted to evaluate both the qualitative and the quantitative static behavior of two non-coplanar approaching or intersecting plane cracks. The stress freezing technique has been employed. Quantitative results have been obtained with a new hybrid data reduction procedure from photoelastic fringe patterns. The tendency of non-coplanar cracks to show crack path instability by rotation and their relation to phenomena observed in rock fracture is discussed.

INTRODUCTION

Increasing interest in hydro-fracturing and rock fracture has been guiding much research and development activity on the many varied aspects of energy reservoir access techniques. One such aspect is the problem of producing stable underground fractures with suitable extents and shapes for economic exploitation of gas and oil resources and dry rock geothermal energy.

The creation and extension of large underground fractures by fluid pressurization - hydraulic fracturing - has been investigated in several long-term research programs, e.g. /1-4/. Explosive generation of large underground fracture is the subject of a study by the University of Maryland Photomechanics Laboratory /5/. Creation of a crack extending from a borehole increases the extracting surface of the fracture and favors diffusion of oil or gas into the crack and flow freely into the well. The relative position of and the interaction between pre-existing cracks and interfaces between rock layers and newly generated fractures is of utmost importance when a fracture is to be propagated successfully within the pay stratum. Successful - path-stable - crack propagation occurs when the fracture extends inside the pay layer and, hence, actually increases the diffusion surface of the fracture. Fracture extension along rock layer interfaces would not be considered optimal. It has been noted in field tests that cracks which propagate in a plane oriented normally to the system of weak interfaces between the rock layers often change their orientation when they approach or intersect an interface.

If the interfaces and the plane of the initiated fracture are not coplanar the problem at hand represents a three-dimensional crack-interaction problem. Piloting theoretical and experimental studies of crack-crack interaction problems that can be reduced to two-dimensional interaction problems may be found in Refs./3,6,7/. The interaction of two coplanar and offset coplanar penny-shaped cracks and their slow extension and coalescence has been investigated by utilizing photoelastic methods /8/.

A research program set up at the Technical University Vienna, Austria, is devoted to the identification of some primary factors associated with their planes of extension rotated at an arbitrary angle. At present a series of static photoelastic experiments was conducted to evaluate both the qualitative as well as the quantitative behavior of two non-coplanar approaching or intersecting plane cracks with included angle equal to 90°. The stress freezing and slicing technique has been employed to obtain the stress intensity factor distributions along the crack front as a function of overlap and normal position of the two crack planes.

THEORETICAL CONSIDERATION

Consider a linear-elastic, homogeneous, isotropic solid weakened by two non-coplanar plane straight-crested cracks as shown in Fig.1. The plane

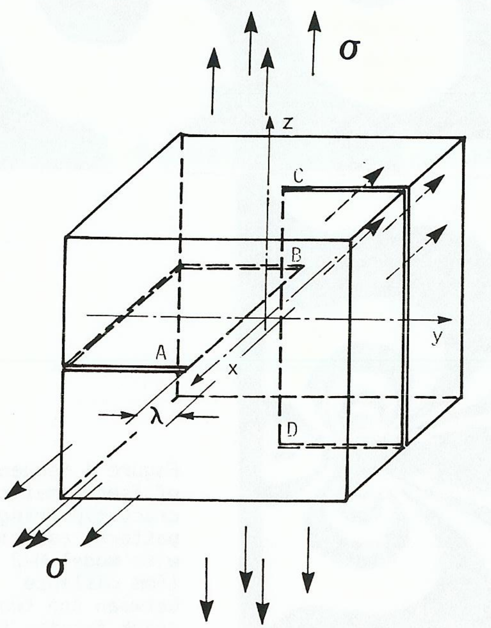

Figure 1 : Geometry and loading configuration of the photoelastic model

of crack AB coincides with the section $(x, y \leq -\lambda/2)$ of the x,y-plane and the plane of crack CD coincides with the section $(y \geq \lambda/2, z)$ of the y,z-plane. The distance, λ, of the crack fronts AB and CD can be positive (distant cracks) or negative (overlapping crossing cracks). For experimental modeling purpose a cube centered at the origin of the coordinate system (x,y,z) and with faces oriented parallel and normal to the crack planes is cut from

the infinite space. Apart from a very thin boundary zone a state of plane strain would prevail along the crack front AB, if there was no crack CD present. The cracked cube is subjected to a uniform biaxial stress field, σ, in directions normal to the crack planes. This kind of exterior tractions causes a relatively complicated distribution of regular stresses that act parallel to the crack fronts. The geometrical and loading configuration of Fig.1 corresponds to a pure mode-1 3D-crack problem.

Although no analytic investigation and results of problems of this kind could be found in the literature, some preliminary aspects of the problem may be discussed by reflecting on earlier work on arbitrarily loaded semi-infinite plane cracks /7/. Consider the special case of a pair of equal and opposite concentrated normal forces P applied to the surface of a semi-infinite crack AB at $(x=0,\ y=-a,\ z=0^{\pm};\ a > \lambda/2)$. The distribution of the stress intensity factor $K_1 = \lim \sigma_z(x,\eta,0)\sqrt{2\pi\eta}$ with $\eta = y+\lambda \to 0$ along the crack front AB is given by

$$K_1(x) = P\sqrt{2\pi a}\,/\{\pi^2(a^2+x^2)\}\ , \qquad (1)$$

with its peak $K_{1,max} = \sqrt{2}\,P(a\pi)^{-3/2}$ for x=0. The K-distribution drops off very rapidly with increasing distance from the peak. In addition, it flattens out with increasing distance of the load application point. Peak flattening is also achieved by spreading the load P over an increasingly larger symmetrical load application area. The regular stress σ_x acting parallel to the crack front AB shows a tensile peak at the mid-plane (x=0).

EXPERIMENTAL PROCEDURE

A series of four photoelastic models of the cracked cube was fabricated from a photoelastic material, epoxy-resin Araldite B. The first model M-1 was weakened by one crack only and served for reference purpose. A special sandwich technique has been developed in order to improve the fabrication of large 3D-photoelastic models and to eliminate disturbing residual stresses due to inhomogeneous polymerization by bonding together a stack of identical layers of size 150x150x16 mm^3. Cracks were band-saw cut (width 0.8mm) to varying depths yielding various overlaps wanted: $\lambda=\infty$ for M-1; $\lambda=$ 5mm for M-2; $\lambda=0$ for M-3; and $\lambda=-5$mm for M-4 (see Fig.1). Particular attention has been focussed on layer delamination during the heating phase. Hence, a bonding agent (a mixture of Araldite AV138M with hardener HV 997) with an ultimate strength slightly higher than that of Araldite B at freezing temperature (T=140°C) was given preference.

Surface tractions were applied by means of a balancing lever-system as is illustrated in Figure 2. The load level was monitored by strain-gages in semi-bridge arrangement. The complete experimental set-up is shown in Figure 3. Upon loading the model-load-system was subjected to a heating-stress freezing-cooling process with rate of temperature changes as follows:

Room temperature	to	80°C	∿	3°/hour
80°C	to	105°C	∿	2°/hour
105°C	to	140°C	∿	1°/hour.

This very low temperature to time ratio provides photoelastic models that are free of thermal stresses. Upon cooling the model with stresses locked-in was multi-sliced (up to 13 slices per model) parallel to the layer faces with net slice thickness of 5 mm.

RESULTS AND DISCUSSION

The distribution of stress intensity factors were determined by utilizing an advanced version of a multi-parameter-multi-point overdeterministic

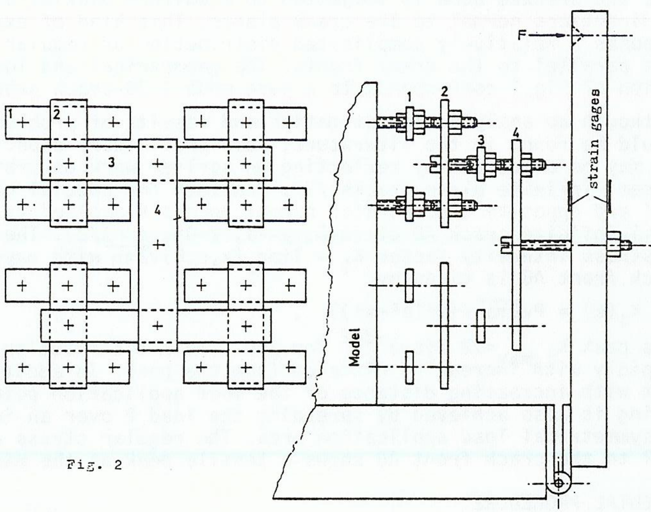

Fig. 2

Figure 2 Balanced lever-system for uniform load application

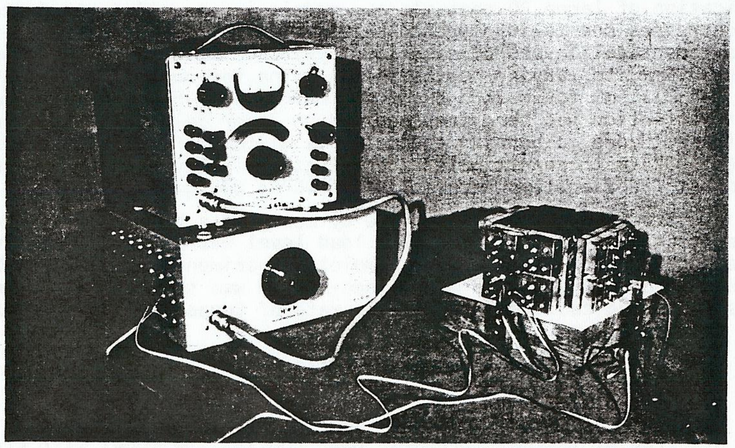

Figure 3 Experimental set-up showing the multi-layer photoelastic model with loading device and strain gage monitor system

K-evaluation procedure /9/ where initial estimates of K_1 followed from Irwin's classical engineering procedure /10/. The sequence of isochromatic crack tip fringe patterns shown in Figure 4 associated with a 9-slice model (slice 1 = surface slice; slice 5 = midsection slice) is representative for experimental K-determination.

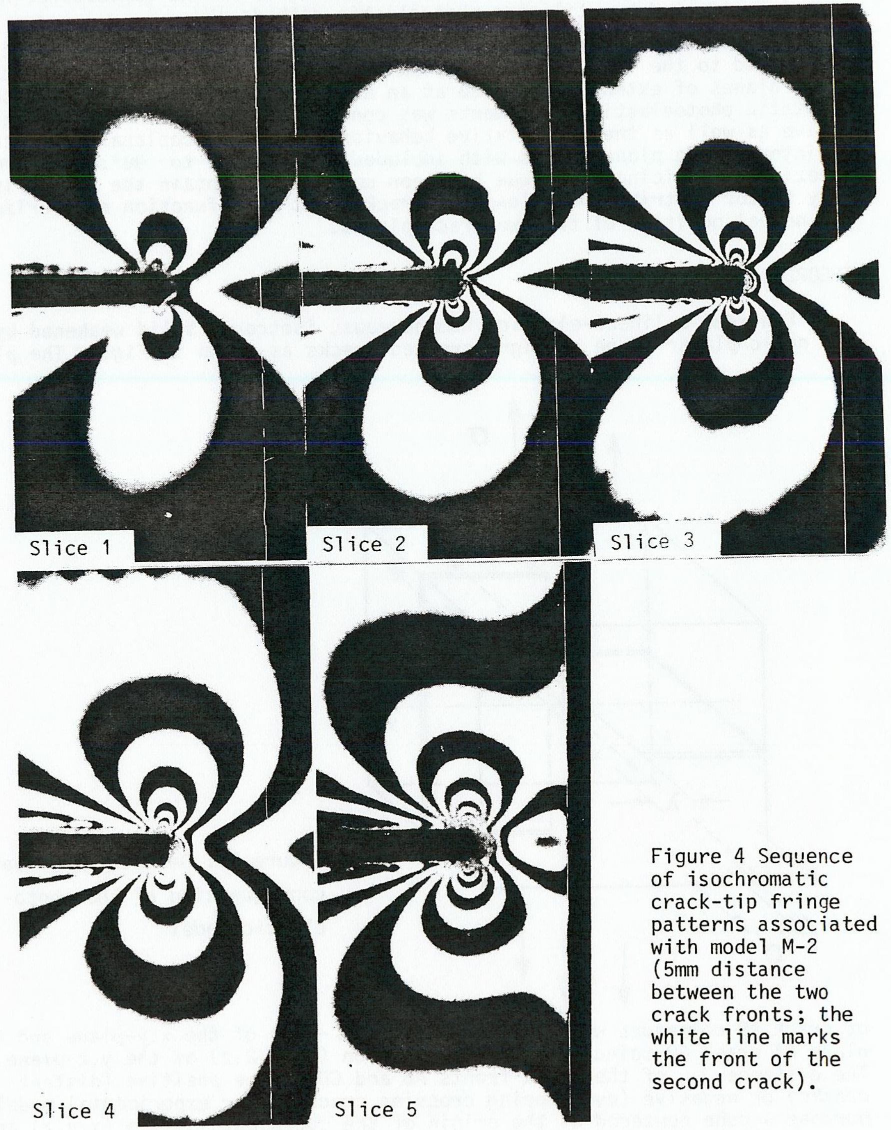

Figure 4 Sequence of isochromatic crack-tip fringe patterns associated with model M-2 (5mm distance between the two crack fronts; the white line marks the front of the second crack).

For reference purpose consider the one-crack model M-1. The uniform external traction σ is acting parallel to the z-direction normally to the crack line AB. Apart from the plane-stress boundary layer zone the stress intensity factor K_{M-1} distribution is constant along the crack front (Fig. 5, line M-1). Addition of an external stress σ acting in the x-direction parallel to the crack line would not influence the K_{M-1}-value if this stress was homogeneous and their was no further crack present. If, however, a second crack CD is introduced the stress pattern suffers severe disturbance due to the change of boundary conditions along (x=0, $y \geq \lambda/2$,z), σ_x=0 on CD. This disturbance influences also the K-distribution along the crack front AB. Likewise, the presence of crack AB represents a disturbance to the stress field of crack CD and since the external stress fields are of the same magnitude the two K-distributions along the crack fronts AB and CD are identical provided the crack depths in the cube are the same.

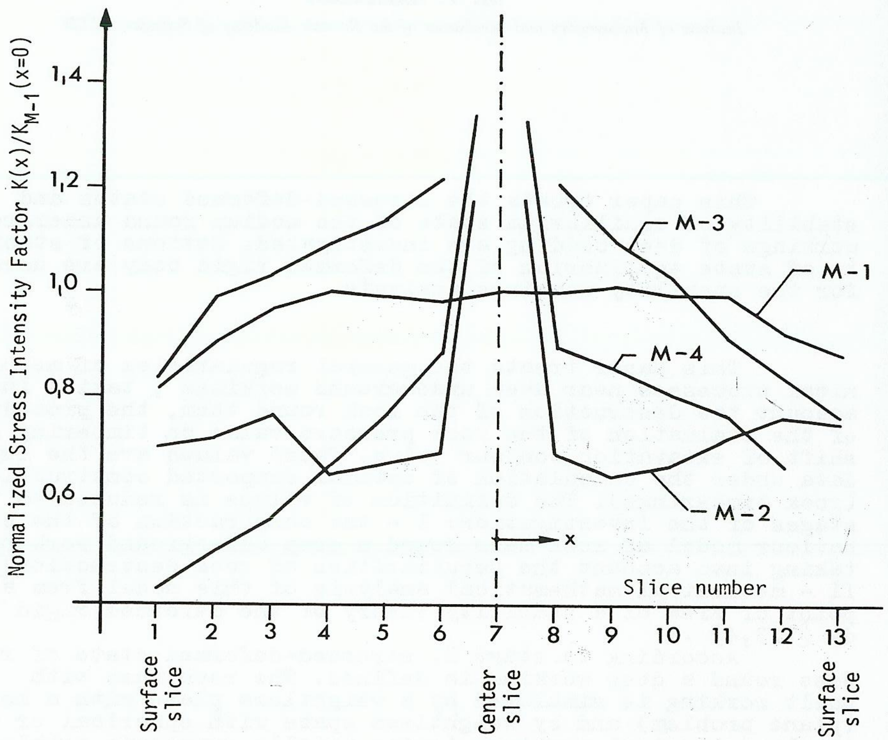

Figure 5 Distributions of stress intensity factors along crack fronts for approaching and overlapping normal crack planes.

Distributions of normalized stress intensity factors along the crack fronts for models M-2 to M-4 that pertain to various distances of crack fronts are shown in Figure 5. Results show the expected drop-off of the stress intensity with increasing distance from the point of interaction.

Numerical procedures for evaluation of the K-distribution may be set-up on the basis of suitable finite element programs or a generalisation of the alternating stress removal technique to three-dimensional problems. Both techniques are currently under investigation. Moreover, the distribution of the stresses σ_x and σ_z acting parallel to the crack fronts AB and CD, respectively, could not be determined from the photoelastic experiment to any acceptable degree of accuracy; this, however, would be necessary in order to investigate the problem of crack-path stability and crack-plane rotation. The second part of the research project is devoted to these open problems.

ACKNOWLEDGEMENT

The first author was sponsored in this research project by the Austrian Science Foundation under contract number FWF P4532.

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