RECENT RESULTS IN DYNAMIC PHOTOELASTICITY AS APPLIED TO ROCK FRACTURE MECHANICS

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ABSTRACT

Dynamic photoelastic fringe pattern recordings of the interaction between elastic waves and cracks in layered rock provide a suitable means for identification of elementary wave-crack interaction processes. Fringe data analyses of crack-tip fringe patterns allow the evaluation of stress intensity factors at interface crack-tips. Problems of spallation, dynamic layer detachment, and delamination in multilayered rock-type structures are investigated in detail.

INTRODUCTION

During the past decade the scientific branch of rock fracture mechanics has been given increasing attention by researchers and engineers in the field. The subject of rock fracture mechanics serves the purpose of treating fracture problems in rock mechanics. With regard to the rapid exhaustion of known fossil fuel reserves of the world and the completion and extension of infrastructural traffic network in mountainous areas, as well as the growing need for underground storage room, caverns, tunnels etc attention has turned to advanced technologies for treatment of rock. Faster, safer and more efficient procedures for construction and productionof above- and/or underground fractures and excavations with suitable extends and shapes are required. An understanding of the fracture mechanisms of rock is an essential prerequisite for designing mining excavations and civil engineering structures, for developing advanced rock-breaking processes, and for establishing programs to prevent hazardous situations such as rock bursts /1/.

The main process of rock breakage and fragmentation is a complicated interaction of stress waves and crack propagation governed by material and environmental aspects. Dynamic photoelasticity in conjunction with dynamic fracture mechanics is employed to study the role of body and surface waves during their interaction with perfectly and imperfectly bonded adhesive rock layer interfaces /2-4/. Plane photoelastic models fabricated from similar and dissimilar layers with frictional interfaces and imperfect bonds have been loaded in a biaxial load frame and explosively excited for simulation studies /5/. Experimentally recorded dynamic isochromatic fringe patterns not only serve as a visual aid for numerical and analytical studies but also provide qualitative and quantitative results of the interaction process. Particular emphasis has been placed on problems of spallation, layer detachment, and Rayleigh-wave induced delamination /6,7/. Dynamic photoelastic crack-tip fringe pattern recordings provide a means for the evaluation of stress intensity factors and the quantification of energy carried by the stress waves.

PHOTOELASTIC INVESTIGATION OF CRACK-WAVE INTERACTION

When elastic waves are generated and propagated during blasting or an earthquake phenomenon, they interact with geometrical discontinuities or acoustical impedance mismatch zones and are reflected, refracted, and diffracted and often give rise to a high elevation of local stresses. These stress concentrations become severe when the discontinuity is a static or a moving crack or a rough or an imperfectly bonded interface. The presence of highly-energetic surface waves adds to the severity of the stress elevation. These stress amplifications are conductive to initiation and propagation of a fracture.

SPALLATION

Spallation is a direct consequence of elastic wave interference near either a free surface or an interface when incident and reflected sections of one single pulse constructively superimpose. Successful spalling requires the presence of a suitably dense field of micro-cracks or other inhomogeneities to be activated by the stress wave, with a level of activation in excess of the strength of the material. In homogeneous materials a single spall occurs when the stress developed through interference barely exceeds the fracture strength of the material. Multiple spalling, i.e. the development of several juxtaposed fractures, occurs when the wave-induced stress level during superposition becomes more than twice the critical fracture strength. Spalling in laminated materials, such as jointed or layered rock, is highly complex in that joint break-up and layer separation will occur at distinct predefined planes of weakness in the layered structure. Interface cracks may be initiated and extended, and successive layer detachment is often observed.

The position and initiation time of the spall with respect to an interface or a free surface for an incident detonation wave will depend on various parameters, such as angle of incidence of the wave, shape, intensity and form of the wave profil /5/. Very complex situations build up during the interaction of non-planar stress waves with curved interfaces or boundaries.

Oblique stress wave incidence gives rise to superposition of several waves associated with time-varying domains. Figure 1 shows these superposition domains associated with P-wave reflection at a dissimilar media junction at a particular instant of time.

Employing a general fracture criterion in the form

$$\Psi_{analyt} \geq \Psi_{mat} \qquad (1)$$

where the symbol Ψ may be identified e.g. with the stress intensity or the tensile stress, a necessary condition for spallation to occur at point $F(x_F,y_F)$ is the total stress intensity or total stress as obtained from superposition to reach the fracture toughness ($\Psi_{mat}= K_{Ic}$) or the fracture strength ($\Psi_{mat}= \sigma_c$) of the material:

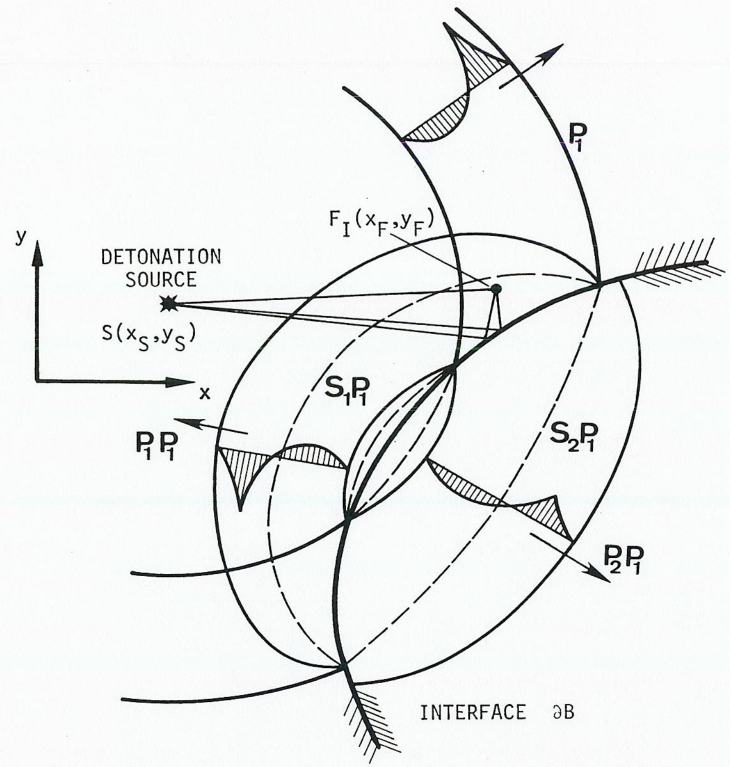

Figure 1 Superposition domains associated with pulse interaction with a dissimilar interface and spallation

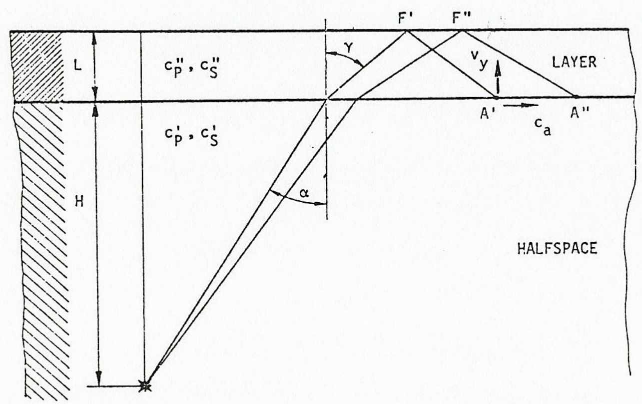

Figure 2 Dynamic layer detachment

$$\Psi_{tot} = \Psi_{refl} + \Psi_{inc} - \Psi_{loc} \Big|_{F,t_F} = \Psi_{mat} \quad , \qquad (2)$$

where Ψ_{loc} corresponds to the static in situ overburden stress at point F and t_F denotes the spall initiation time.

The position of the spall $\{F\} = \{x_F, y_F\}$ with respect to the interface is determined from the relations:

$$\delta\Psi_{tot} \Big|_{F,t_F} = 0 \quad , \qquad \delta^2 \Psi_{tot} \Big|_{F,t_F} < 0 \quad . \qquad (3)$$

The three equations (2) and (3) allow for the determination of the spall site and spall time, $F(x_F, y_F; t_F)$ /4,6/.

DYNAMIC LAYER DETACHMENT IN JOINTED ROCK

In real materials the structure of the material may basically influence the spalling pattern. In rock-type materials individual blocks are separated by planes of weakness and these joints cause a change of crack propagation behavior pattern. If the joint is of lower strength than the base materials, joint-initiated spallation will occur during the wave-interface interaction process. In contrast to the spall process of the preceding section in layered rock the spall locations are often predetermined by the joint distribution (system of bedding and joint planes). Since most joints are not perfectly bonded but show a certain degree of imperfection, bonding may not exist along particular sections with the layers held in position by the confining pressure. With slight modifications equations (2) and (3) hold also for each and every crack-type debond imperfection in the layered structure.

An instructive example of dynamic layer detachment is illustrated in Figure 2, where an explosion is ignited at depth H below the surface of a half-space covered by a loose dissimilar top-layer of thickness L (generalized Pekeris-problem /6/). From simple geometrical ray construction the speed of dynamic layer detachment c_a is given by

$$c_a/c_p' = \sin^{-1}\alpha \left\{1 + \frac{c_p''}{c_p'}\frac{2L}{H}\frac{\cos^3\alpha}{\cos^3\gamma}\right\} / \left\{1 + \frac{c_p'}{c_p''}\frac{\cos^3\alpha}{\cos^3\gamma}\right\} \qquad (4)$$

with

$$\sin\alpha / \sin\gamma = c_p'/c_p'' \quad , \qquad (5)$$

and is shown in Figure 3. c_p' and c_p'' denote longitudinal wave speeds in the dissimilar adherends. Layer separation occurs due to momentum trapping in the receptor layer. The relative amount of momentum transferred to the receptor layer is given by

$$M = \iint (c_s'' v_{y,S_2P_1} + c_p'' v_{y,P_2P_1})\, dt\, ds \quad , \qquad (6)$$

where v_{y,S_2P_1} and v_{y,P_2P_1} are the particle velocities in the transmitted shear and longitudinal waves with wave speeds c_s'' and c_p'', respectively. Notice, that the particle velocities depend on the reflection and transmission coefficients and their varying distribution determines the locus of detachment arrest.

In practice, rock joints in limestone quarries range from open mud-filled cracks to very tightly bonded calcite joints with properties similar to the adjoining rock masses.

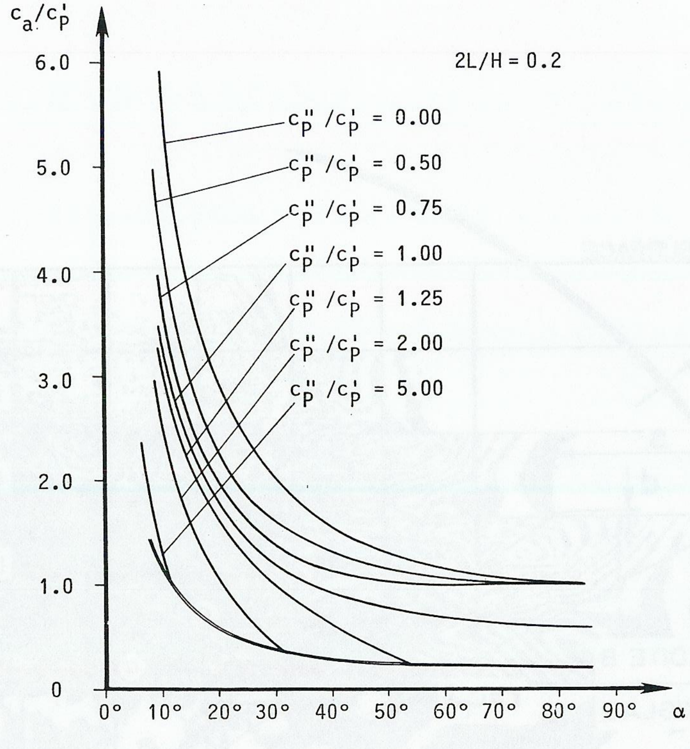

Figure 3 Layer detachment speed versus angle of wave incidence

The special case of a multilayered structure dynamically excited by a buried detonation pulse is shown in Figure 4, where high speed stress optics has been utilized to record the dynamic photoelastic fringe pattern taken at time 94 μsec after detonation. The characteristic feature of the pattern is the staggered lag of the wave front when passing through the stack of layers. Because of the loose (no overburden stress) frictional junctions between the individual layers delay times will be induced by mechanically closing the surface-roughness-generated gaps of width d between any two adjacent layer surfaces. Delay times may be determined by measuring appropriate lengths s_j from equations

$$d = \frac{1}{\rho c} \int_0^{\Delta t^*} \sigma_n(t) \cos\alpha' \, dt \qquad (7)$$

$$s_j = c_p' \, t' \left\{ \sqrt{(1+\Delta t^*/t')^2 - \cos^2\alpha'} - \sqrt{1-\cos^2\alpha'} \right\} , \qquad (8)$$

where the wave impinges at time t' at an angle α', and Δt* is the time interval to close the gap of width d; $\sigma_n(t)$ is the stress wave profile of the detonation pulse. Imperfectly bonded dissimilar multilayer rock structures comprise combinations of the two basic phenomena spallation and layer detachment. The interaction process between elastic waves and

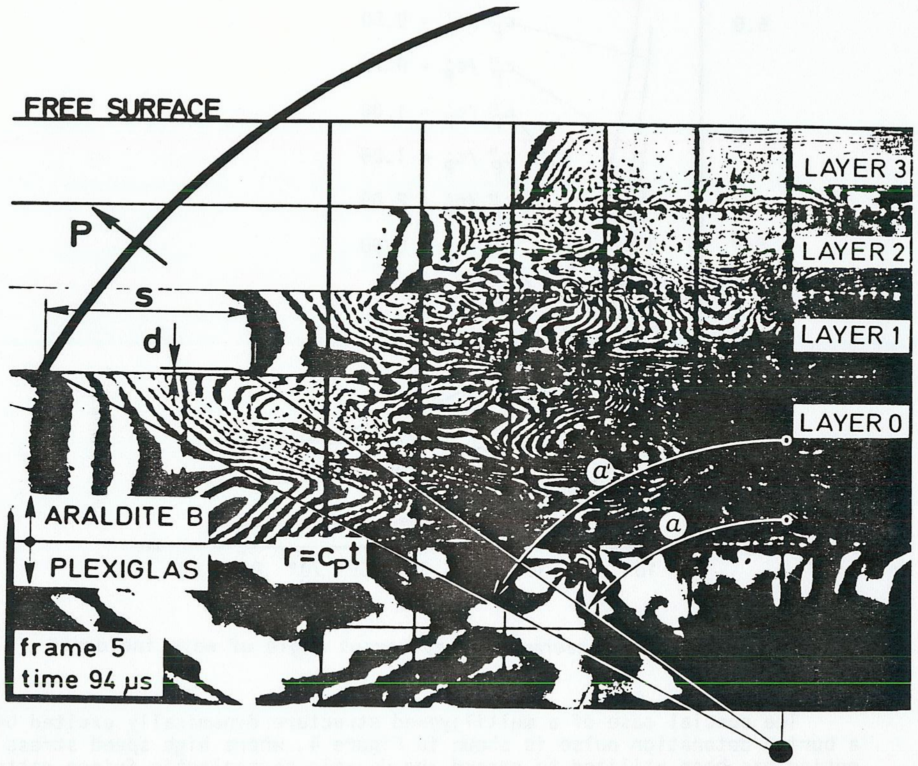

Figure 4 Dynamic layer detachment in a multi-layered model stratum by a buried detonation pulse (Ref./6/)

cracked interfaces becomes extremely complicated. When the elastic wave front during oblique passage of the cracked interface impinges on a bond-debond junction (crack) the stress intensity is raised due to wave diffraction and the detachment phase may come to an arrest (c_a=0) or changes for a delamination phase associated with delamination speed $c_d < c_a$. The instantaneous stress intensity factor K_d can be determined from photoelastic crack-tip fringe pattern recordings /2,3/ and the delamination speed may be measured from a time-sequence of consecutive fringe patterns.

CONCLUSIONS

An extensive research program covering the interaction of detonation-induced stress waves with structural discontinuities has demonstrated the major role that joints and bedding planes play in the wave-structure interaction process as well as in the fragmentation process. It has been observed that detachment, spallation, and delamination may occur either from the outgoing P-wave or possibly from a combination of the tensile P-wave tail and the reflected PP- and/or SP-waves. In multilayered rock this process is further complicated by the possibility of partial load transmission and transmission delay due to gap closure and joint contact formation. Stress intensity factors or strain energy release rates associated with interface cracks may be evaluated from dynamic elastic fringe pattern recordings by utilizing well-known data reduction procedures.

ACKNOWLEDGEMENT

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REFERENCES

/1/ First Intern.Symposium on "Rock Fragmentation by Blasting", LULEA, Sweden, August(1983)
/2/ Rock Fracture Mechanics (Ed.H.P.Rossmanith), Springer-Verlag/CISM, Vienna-Udine, CISM-Publ. No 275, (1983).
/3/ Fourney W.F. et al.: University of Maryland Photomechanics Laboratory Research Reports (1975-1983)
/4/ Rinehart J.S.: Stress Transients in Solids, Hyperdynamics, Santa Fe (1975)
/5/ K.R.Y.Simha et al.: Model studies on explosively driven cracks under confining in-site stresses; Vol.I., 183-198, Ref./1/ (1983)
/6/ Rossmanith H.P. and R.Knasmillner: Spallation, break-up and separation of layers by oblique stress-wave incidence; Vol.I, 149-168, Ref./1/(1983)
/7/ Rossmanith H.P.: Photoelastic investigation of Rayleigh-wave induced layer delamination (to be published, 1983).