Engineering Fracture Mechanics xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Engineering Fracture Mechanics

journal homepage: www.elsevier.com/locate/engfracmech

Stress analysis of the interaction of a running crack and blasting waves by caustics method

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A R T I C L E I N F O

Article history:
Received 4 January 2017
Received in revised form 11 April 2017
Accepted 30 August 2017
Available online xxxx

Keywords:
Blasting waves
Running crack
Optically geometrical superposition
Caustics
Photoelasticity

A B S T R A C T

The purpose of this work is to investigate the mechanism of crack-wave interaction in blasting engineering. Transient effects of blasting waves on a running crack are evaluated by estimating crack-tip stress field from measurements of distorted shadow spots by caustics method. An optically geometrical superposition of light deflections from the running crack and blasting waves is proposed, considering concave and convex lens effects of waviness of initially flat plane under blasting waves. The stress field near the running crack tip in crack-wave interaction is obtained. Simulations of caustic curves derived from this superposition agree with those from instant records by a high-speed camera, highlighting that this superposition is a powerful way to evaluate the stress field near the crack tip and to extend classical caustics method to the application of unknown transient loadings by blasting waves. At last, similar photoelasticity experiments are made and results from two optical methods are discussed.

1. Introduction

Blasting engineering is still necessary and common in developing countries for constructions of railway tunnels, extractions of natural resources and preventions of geological hazards [1,2]. In practice, rock blasting engineering consists of two main steps, which is, firstly, breaking the rock mass into fragments, and then removing them out safely. We now just consider the first step. When the explosion detonated, internal rock fractures induced by blasting loadings interact with other blasting waves, because generally there are many boreholes in one explosion case. Due to complexity of accurate theoretical calculations and variety of geological situations, blasting designers almost depend on experiences, which possibly results in explosive wastes and abrupt disasters. In order to meet a safe working environment, rock fractures under blasting waves loading or crack-wave interactions in explosion phenomena are necessarily needed to recognize well.

Unfortunately, because rock is a kind of opaque material, both internal rock fractures or cracks and blasting waves cannot be seen directly, let alone interactions between them. In analytical aspects, Sih [3], Freund [4] has achieved much meaningful work involving cracks and stress waves. But in experimental aspects, it is limited perhaps due to limitations in high-speed photography or interpretation of experimental results. Laboratory researches simulated rock blasting processes by using transparent polymers, such as Plexiglass [5], Homalite 100 [6], to pursue qualitative conclusions, even though the actual material differences existed. And Cho et al. [7] reviewed the directional fracture controlled laboratory-scale blasting using

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http://dx.doi.org/10.1016/j.engfracmech.2017.08.037
0013-7944/© 2017 Published by Elsevier Ltd.

Nomenclature

C_l	P wave speed
C_s	S wave speed
V	crack velocity
E_d	dynamic Young's Modulus
υ	Poisson's ratio
c_t	stress-optical constant
z_0	imaging distance between middle plane of the specimen and imaging plane of the high-speed camera
d	thickness of the specimen
f	focal length, positive for the concave lens and negative for the convex lens
$\mathbf{w}_c$	light deflection due to the crack
$\mathbf{w}_w$	light deflection due to blasting waves
$\mathbf{w}$	completed light deflection for superposition of $\mathbf{w}_c$ and $\mathbf{w}_w$
σ_{c1}, σ_{c2}	principle stresses near the crack tip for problem A
σ_{w1}, σ_{w2}	parallel and perpendicular blasting-induced stresses with respect to the crack propagation respectively for problem B
σ_{xx}, σ_{yy}	completed stresses near the crack tip
σ_{t0}	peak tensile stress of the tensile half wave, it is positive
σ_{c0}	peak compressive stress of the compressive half wave, it is negative
K_I^d	mode I stress intensity factor
DSIFs	dynamic stress intensity factors
D_t, D_l	the maximal transverse diameter and longitudinal diameter respectively

the PMMA material. Taking advantage of visibility of full-field stress waves, dynamic photoelasticity [8] has been a powerful method to show the interaction between blasting waves and running cracks. In conjunction with Cranz-Schardin multiple-spark high-speed photoelastic recording system [9], Rossmanith and Shukla [10] studied interaction of stress waves and running cracks, which were subjected to normally, obliquely and tangentially incident blasting waves respectively.

Besides photoelasticity, another well-known optical method in the field of dynamic fracture mechanics is the method of caustics [11]. Compared with photoelasticity, results of caustics experiments avoid sophistical isochromatic fringes, but just the shadow spot in local field occurs around the crack tip. Theocaris and Papadopoulos [12], Kalthoff [13] and Rosakis [14] have extended caustics from static filed to dynamic field. By measurements of caustics patterns in high-speed photographs, many researchers conducted experiments to study fracture parameters as well as relationships between them [15–18]. Involving crack-wave interaction, Ravi-chandar and Knauss [19] studied propagating cracks under stress waves produced by the electromagnetic loading device. To my best knowledge, applications of caustics in the field of explosion are few. Yang et al. [20] has conducted laboratory work involving joint medium made from PMMA model, and Yue et al. [21] used the same material to study crack behaviors under the directional control blasting. However, transient effects from blasting waves were neglected in their work. Stress intensity factors were calculated by formulas for cracks running in a steady state just considering crack velocity, which cannot interpret severely distorted caustics. It is necessary to propose a new way based on basic caustics principles to interpret the distorted caustics under transient effects from blasting waves.

In this paper, dynamic caustics method is employed to study a running crack subjected to blasting waves, especially in consideration of distorted caustics resulting from transient effects. Specimen and experimental set-up for producing interaction processes of a running crack and blast waves are shown in Section 2. In Section 3, an optically geometrical superposition based on caustics principles is first employed. In Section 4, experimental results are analyzed according to the theoretical superposition obtained in Section 3. Finally, we compare caustics results with those from photoelasticity by Rossmanith [10] and us, and discuss advantages of caustics method in the application of blasting fields.

2. Method

2.1. Specimen preparation

Single-edge notched specimens of plane dimension 320 mm × 192 mm shown in Fig. 1(a) are extracted from a 5 mm thickness sheet of the PMMA using a laser cutting machine. Mechanical properties of this material used in our experiments are listed in Table 1. Specimen dimension is designed to ensure that reflected blasting waves from boundaries of the specimen have no interference on the interaction phase between a running crack and normally incident blasting waves. A pre-

Please cite this article in press as: Yue Z et al. Stress analysis of the interaction of a running crack and blasting waves by caustics method. Engng Fract Mech (2017), http://dx.doi.org/10.1016/j.engfracmech.2017.08.037