A STRESS INTENSITY FACTOR TRACER AND ITS APPLICATION TO TIME DEPENDENT FRACTURE TESTING

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ABSTRACT

An optical method, so called "Stress Intensity Factor Tracer (SIFT)" (Kim, submitted) has been applied for the measurement of the continuous time history of the stress intensity factor $K_I(t)$ of a time-dependent-fracture-testing specimen. This method utilizes the intensity variation of the light impinging on any fixed finite size area Γ, that does not include the focal point, in the focal plane on which initially parallel light rays transmitted through the transparent fracture specimen (or reflected from the surface of an opaque specimen) are focused by a converging lens. The light intensity $I(t)$ is related to the stress intensity factor by $I(t) = B[K_{I(t)}]^{4/3}$ for K_I dominant field, where the constant B is the product of several experimental quantities including a "shape factor" for the sampling area Γ, which is a known function of crack velocity for dynamic K_I field. An important feature of the method is that $I(t)$ is insensitive to the location of the crack in the specimen plane. The relation for SIFT has been checked experimentally for a DCB specimen and applied to the measurement of the stress intensity factor of the DCB specimen under vibrational loading and of a large Homalite 100 specimen subjected to impulsive loading on the crack faces.

KEYWORDS

Stress intensity factor tracer; optical method; time dependent fracture testing; dynamic fracture; fatigue crack.

INTRODUCTION

It is well known that in practical fracture mechanics testing, crack tip loading is characterized by the stress intensity factor when small scale yielding condition prevails. However, there have been difficulties in measuring the continuous time history of stress intensity factor, $K(t)$, for a moving crack using conventional methods such as photoelasticity, optical method of caustics, strain gauges and compliance methods, etc.

Although the compliance method has been well adapted for slow crack growth studies such as in fatigue crack growth and in ductile fracture, it has limitations on real time measurement of K(t) and requires the accurate estimation of crack length. Strain gauges are useful in tests on stationary cracks but they have severe problems when applied to situations involving rapidly moving cracks. Conventional optical techniques have been used in dynamic fracture testing, nonetheless they require high speed photography. Optical techniques have not proved to be very useful in monitoring fatigue crack growth yet.

In this work an optical method so called "Stress Intensity Factor Tracer" (Kim, submitted) is used in order that its usefulness be verified by two experimental demonstrations. The method employes the optical filtering of the deformed state of the specimen similar to those in the Schlieren technique or generalized Fourier filtering based on the focal plane analysis (Kim and Phillips, 1981). Through this optical filtering, the light from the K_I dominant annulus region around the crack tip is collected and the intensity $I(t)$ of the collected light is related to the mode I stress intensity factor $K_I(t)$ by $I(t) = B[K_I(t)]^{4/3}$. The stress intensity factor measured by this technique exhibits the instantaneous spatial average of the deformation around the crack tip. In the experiments described below time histories of SIF, $K_I(t)$, have been measured for a double cantilever beam (DCB) specimen under spring-mass vibrational loading and for a semi-infinite crack in an unbounded medium[1] under impact loading on the crack faces. In the latter experiment, $K_I(t)$ has been recorded during the time period of incubation for dynamic running crack initiation and continuously during dynamic crack propagation up to crack branching. The experimental result shows good agreement with the theoretical predictions based on Freund's work ((Freund, 1974) and (Kim, in preparation)).

SIFT FOR K_I FIELD[2]

In order to understand the SIFT system, consider the optical set up shown in Fig. 1(a). A light beam initially collimated parallel is transmitted through (or reflected from) a flat transparent (or opaque) fracture specimen and focused by a converging lens. In this arrangement the light ray from a generic point (x,y) on the specimen plane[3] (with the origin of the axis at the crack tip) will be mapped onto a point (x',y') on the focal plane which is parallel to the specimen plane and has its origin at the focal point of the converging lens. Then the mapping $[x'(x,y),y'(x,y)]$ due to K_I field, is identical to the deflection vector in the optical method of caustics. The mapping, then, provides the expression of the distribution of the light intensity on the focal plane in terms of $\Omega(x,y)$ the distribution of the transmitted (or reflected) light intensity on the specimen plane.
If a uniform intensity of light ($\Omega(x,y)$ = constant) is incident on the specimen, the total light intensity 'I' collected in a finite area Γ of the focal plane, excluding the focal point, is expressed as (Kim, submitted)

$$I = [\, \frac{4}{9}\, \Omega D(cfd/\sqrt{2\pi})^{4/3}]\, K_I^{4/3} \tag{1}$$

where c is the shadow optical constant (Beinert and Kalthoff, 1981) of the specimen, f is the focal length of the converging lens, d is the thickness of the specimen and K_I is the opening mode stress intensity factor. D is a shape factor which depends only on the shape of the light collecting aperture and it is a function of the speed of the crack "v" as

$$D = \beta(v)\ [\int_{\Gamma^+ + 2\Gamma^-} \{(x')^2 + (y')^2/\alpha_1^2\}^{-5/3} dS'] \ , \tag{2}$$

$$\beta(v) = [(1+\alpha_2^2)\ (\alpha_1^2 - \alpha_2^2)/\{4\alpha_1\alpha_2 - (1+\alpha_2^2)^2\}]^{4/3}/\alpha_1^2 \ ,$$

$$\alpha_1 = (1 - v^2/c_\ell^2)^{1/2} \ , \qquad \alpha_2 = (1 - v^2/c_s^2)^{1/2} \tag{3}$$

where c_ℓ and c_s are the longitudinal and the transverse wave speeds respectively. Γ^+ is the part of Γ for which $x' > 0$ and Γ^- is the other part of Γ for which $x' < 0$. For a stationary crack (v = 0), $\beta(0)$, α_1 and α_2 all become unity respectively.

In a laboratory experiment, the distribution of light intensity Ω can be made relatively uniform on a chosen (simply connected) area S_o of the specimen plane containing the crack tip, by using an aperture of illumination for an expanded and collimated laser beam. Then eqn. (1) can be normalized as

$$I(t)/I_o = [K_I(t)/K_n]^{4/3} \ , \tag{4}$$

$$K_n = (3\sqrt{3\pi}\ S_o^{3/4})/(2D^{3/4} cfd) \ , \tag{5}$$

where I_o is the total intensity of light transmitted through (or reflected from) the area S_o of the specimen plane. For the given range of $K_I(t)$ the sensitivity of $I(t)/I_o$ can be controlled by the normalizing parameter K_n the dimension of which is equal to that of stress intensity factor.

The SIFT is essentially an amplitude modulation of light with the time variation of stress intensity factor. In the signal processing point of view, frequency modulation gives better signal to noise ratio and the extraction of stress intensity factor variation from the phase variation of the light on the focal plane is also possible with an interferometry. The phase variation of light on the focal plane is analyzed in the reference by Kim (Kim, submitted).

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[1] The condition of unbounded medium is created by measuring the stress intensity factor before any reflected wave arrives at the crack tip from the outer boundary of the specimen.

[2] The detail analysis is given in the reference by Kim (submitted).

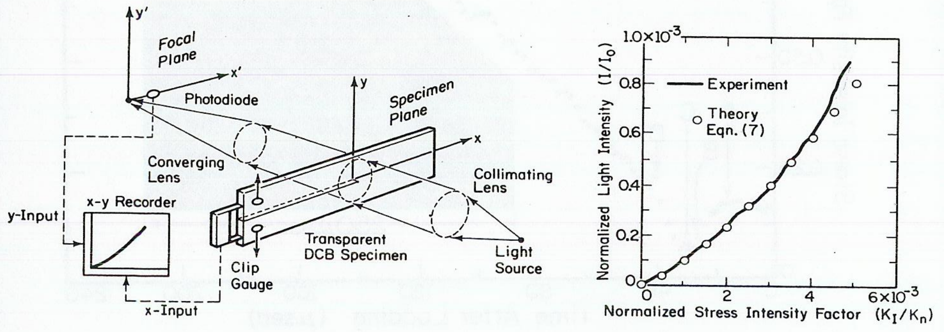
[3] Since the thickness of the specimen is much smaller than the focal length of the lens, specimen mid-plane can be considered as the specimen plane for transparent specimen.

EXPERIMENTS

Calibration

A calibration experiment was carried out. The schematic of the experiment is shown in Fig. 1 (a). The Homalite 100 DCB specimen was loaded in the opening mode. The shadow optic constant 'c' of the specimen was 1.1×10^{-10} m^2/N. The specimen had dimensions of 63 mm x 254 mm, 11.2 mm thick with 150 mm crack loaded 138 mm away from the crack tip. A 3 mW He-Ne laser was used as the light source. The laser beam was expanded, collimated and cut by a 50 mm diameter aperture of illumination. Since the expanded beam has Gaussian distribution of light intensity the aperture was arranged to pass the only central portion of the expanded beam, so that uniformity of the light intensity was within ±3% variation. Then the transmitted beam was focused by a converging lens of 3m focal length. On the focal plane a photo detector with a circular aperture of 2.5 mm dia was located at $x' = 3.0$ mm.

The crack opening displacement was measured by a clip gauge extensometer attached to the end faces of the two arms of the specimen. The gauge output of crack opening displacement which is proportional to the stress intensity factor was connected to the X input of an X-Y chart recorder, while the SIFT photodetector output was connected to the Y input of the recorder. The result of the calibration experiment is shown in Fig. 1(b), together with the theoretical predictions of equation (4). The result shows excellent agreement between experiment and theory for $K_I/K_n < 0.4 \times 10^{-2}$. As K_I/K_n grows above $K_I/K_n > 0.4 \times 10^{-2}$ the experimental curve increasingly deviates from theory because the filtering system collects the light from a larger area on the specimen plane, where the boundary effect becomes important so that the deformation field is no longer represented by the K_I field. However the experimental calibration curve can be used for $I(t) - K_I(t)$ relation of SIFT, while the theoretical formula can be used by maintaining $K_I(t)/K_n < 0.4 \times 10^{-2}$. This ratio can be controlled by selecting K_n for the expected range of $K_I(t)$.



(a) (b)

Fig. 1 Calibration Experiment for SIFT with a DCB specimen.

Vibrational Loading

For the first application of SIFT, the DCB specimen used in calibration experiment was loaded by a spring-mass in a free vibration mode. The schematic of the experiment is shown in Fig. 2(a). The upper grip point of the specimen was held fixed while the lower grip point was connnected to a freely hanging mass of 1.8 Kg by a linear spring of 3.5 N/cm spring constant. In this case the arms of the DCB specimen also have inertia and compliances, so that the time history of the crack mouth opening displacement is no longer a unique measure of stress intensity factor. The real time stress intensity factor was measured by SIFT directly for the crack tip and the result is shown in Fig. 2(b). The result shows a double beat of frequencies on the time trace of the stress intensity factor (to 4/3 power) due to three different but close frequencies. The three fundamental modes arise due to the upper and the lower arms of the specimen, and the spring of the loading system. Damping is also noticed on the continuous time trace of stress intensity factor (to 4/3 power).

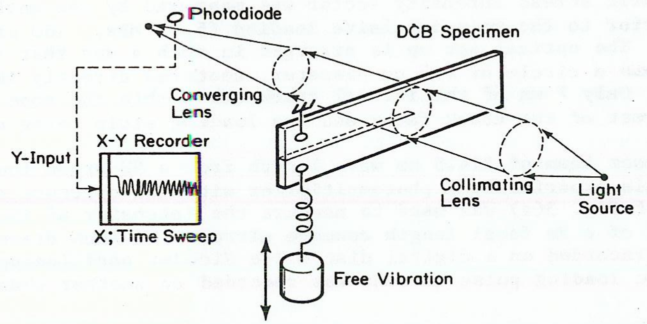


Fig. 2(a) Schematic of Vibration Experiment with SIFT.

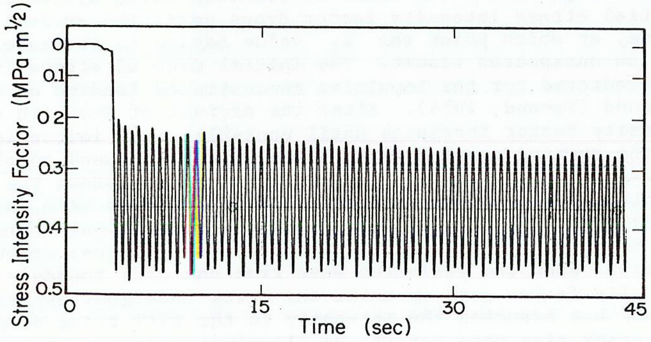


Fig. 2(b) Time Trace of SIF for DCB Vibration Experiment.

Dynamic Fracture

In the experiment of vibrational loading the time trace of stress intensity factor was measured only for a stationary crack. However in this section SIFT is applied to a fast moving crack initiated under dynamic loading (Kim, in preparation). The loading condition is in the form of a time step on the faces of a semi-infinite crack in an unbounded elastic two dimensional medium. The condition is simulated experimentally by applying on the crack faces electromagnetic forces induced by a nearly-square pulse of high electric current flowing in opposite directions through a double-up thin copper strip (0.48 mm thick). This strip, the legs of which are separated by a Mylar insulator 125 µm thick, is inserted into the crack of a large Homalite 100 specimen plate (30 x 60 cm and 4.7 mm thick). The schematic of the loading is shown in Fig. 3(a).

A sharp initial crack tip was prepared by applying a low pressure loading pulse (0.179 MPa, 160 µsec duration) to make a dynamic crack extension from a blunt crack tip. The crack was extended by 32 mm from the end of the loading strip and the arrested sharp crack had nonzero stress intensity factor because of the crack opening made by the copper strip inserted. The initial static stress intensity factor was measured by the method of optical caustics prior to the main impulsive loading (5.85 MPa, 160 µsec pulse duration). The optical set up is arranged in such a way that the illumination area was a circle of 7.5 cm diameter, centered directly ahead of the crack tip. Only 7 mm of the initial crack was within the zone of illumination, the rest of the crack faces and the loading strip being excluded.

A 200 mW laser beam of 514.5 nm wave length from a 5W argon ion laser was used for this experiment. A photomultiplier with the aperture shown in the insertion of Fig. 3(a) was used to measure the intensity of the light on the focal plane of a 3m focal length concave mirror of 6 inch diameter. The signal was recorded on a digital disc drive Nicolet oscilloscope while the shape of the loading pulse current was recorded on another channel of the scope.

The oscilloscope trace of SIFT is shown in the insertion of the Fig. 3(b) and the stress intensity factor variation from the loading time to dynamic branching is plotted on the figure. An interesting result is that when the precursors of longitudinal and shear diffraction waves arrive at the crack tip the initial stress intensity factor drops until the arrival of the Rayleigh wave, at which point the K_I value begins to increase. However this is not an unexpected result. The initial drop of stress intensity factor was predicted for the impulsive concentrated loading on the crack faces by Freund (Freund, 1974). After the arrival of Rayleigh wave the stress intensity factor increases until unstable crack initiation. For the portion of the running crack dynamic shape factor was used to plot the dynamic stress intensity factor. The SIFT trace also shows the fluctuation of stress intensity factor in the mist and hackle zones (Kim, Dickerson and Knauss, 1983) that occur during dynamic crack propagation. This fluctuation is believed to be due to the irregular microcrack (tongue) growth around the main crack tip. When the reflected wave from the side boundary arrives the stress intensity factor goes up until the crack undergoes dynamic branching. Once the crack has branched the intensity in the SIFT trace drops until finally the crack tips move out of the illumination zone. Detailed analysis of the dynamic experiments is reported in reference (Kim, in preparation).

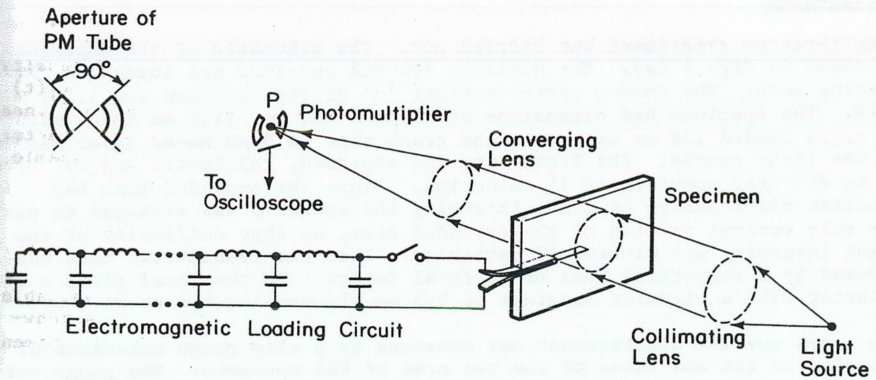


Fig. 3(a) Schematic of Dynamic Fracture Experiment with SIFT.

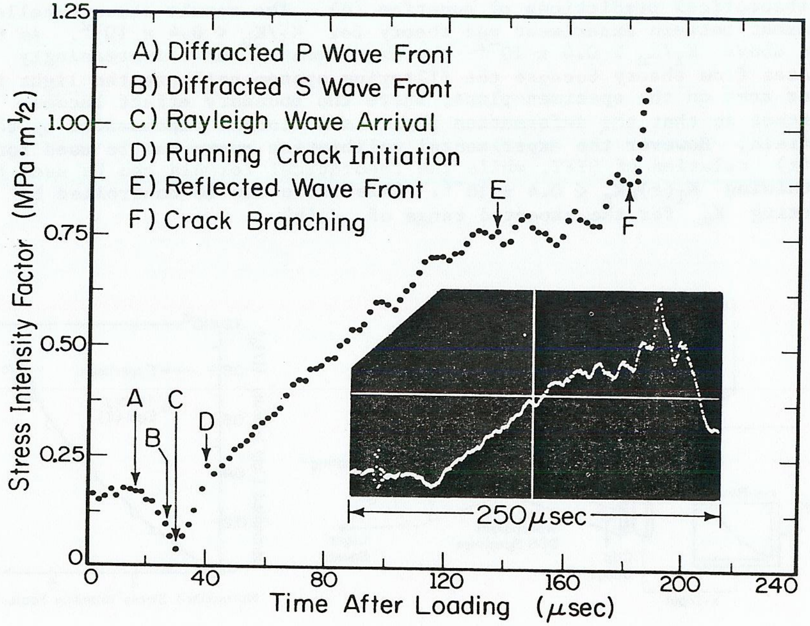


Fig. 3(b) Time Trace of SIF for Dynamic Fracture Experiment.

CONCLUSION

An optical technique, the "Stress Intensity Factor Tracer (SIFT)" (Kim, submitted) is applied for two experiments of time dependent fracture testing. The SIFT gives a continuous analog time trace of stress intensity factor regardless of crack motion. The theoretical result of $I(t) - K_I(t)$ relation shows good agreement with the experimental results. The usefulness of SIFT is expected to be extended to other types of time dependent fracture tests such as in fatigue crack growth monitoring and especially in dynamic toughness testing with finite size specimens.

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