The Dynamic Punch Test in Isotropic and Composite Materials *

C. Rubio-Gonzalez[1] †and J. J. Mason[2]
[1]Centro de Ingenieria y Desarrollo Industrial
Pie de la Cuesta 702, Desarrollo San Pablo
76130 Queretaro, Qro., Mexico

[2]Department of Aerospace and Mechanical Engineering
University of Notre Dame. Notre Dame, IN 46556. U.S.A.

Abstract

An experimental investigation is conducted on the two-dimensional punch problem for isotropic and unidirectional fiber-reinforced composite materials under quasi-static and impact loading. Singular estresses are generated in the especimen near the punch corners and the stress intensity factor K_I is introduced to describe such singular stress field. Laser interferometry was used to measure in-plane stresses (transmission mode) and out-of-plane displacements (reflection mode), and then estimate the stress intensity factor. In the dynamic case, a high speed photography technique was employed to capture the transient response of the specimen and measure $K_I(t)$ just after the impact. In all the cases a good agreement between the measurements of K_I and the theoretical predictions was found.
Keywords: stress intensity factor, dynamic fracture, coposite materials, punch test.

1 Introduction

The potential use of composite materials in the construction of defense structures makes it necessary to understand the initiation of damage in the composite as caused by impacting fragments. Typically, this kind of damage initiation is simulated in the laboratory by the punch test. In such a test, fiber-reinforced epoxy matrix composites will develop a limited amount of plasticity before failure occurs. This fact suggests an elastic solution of the stress field will play an important role in understanding and predicting the behavior of composites under punch test, impact conditions.

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†e-mail: crubio@cidesi.mx, Ph:+(52)4211-9838

Like in fracture mechanics, a stress intensity factor K_I is introduced in this work to characterize the behavior of the singular stresses around the punch corners. This parameter is measured experimentally using laser inteferometry and then compared with theoretical predictions. The experimental investigation is conducted on the quasi-static and dynamic punch test for isotropic and orthotropic materials. A rigid punch impacts (in the dynamic case) one side of the specimen, figure 1. The lateral shearing interferometer of coherent gradient sensing (CGS), in conjunction with high speed photography will be used to obtain real time interferograms of the singular stress field generated near the corner of the punch.

The application of the CGS method in the punch test is new. Here, results for isotropic as well as for composite materials are reported. In the isotropic case, the material selected was PMMA (polymethyl methacrylate) a transparent acrylic for which the CGS method in transmission mode is suitable. For the orthotropic case, the material chosen was a unidirectional graphite-epoxy composite with fiber volume density of 0.65. In this case the CGS method in reflection mode was used.

The CGS method has been applied successfully in dynamic fracture experimentation of isotropic materials (Tippur, Krishnaswamy & Rosakis 1991, Mason, Lambros & Rosakis 1992) and fiber reinforced composite materials (Lambros & Rosakis 1997*a*, Lambros & Rosakis 1997*b*).

In the quasi-static test, K_I is compared successfully with known solutions of the punch problem for isotropic and orthotropic materials. In the dynamic case, each photograph taken by the high speed camera is digitized and $K_I(t)$ is then measured. The time evolution of K_I agrees very well with the theoretical predictions for the dynamic punch problem developed in Rubio-Gonzalez (1999).

A detailed explanation of the analysis and results for the dynamic test is included in the following sections.

2 Elastodynamic Analysis of the Finite Punch Problem

The punch problem is of great importance in solid mechanics for its multiple technical applications including ballistic impact, metal forming and manufacturing operations such as punching and blanking.

The problem of a *finite*, rigid and flat punch impacting an orthotropic half-plane has been analyzed by Rubio-Gonzalez (1999) using integral transforms and the Wiener-Hopf technique. A solution for the dynamic stress intensity factor $K_I(t)$ was developed which is valid while the dilatational wave travels the punch width $(2l)$ twice. That is

$$K_I(t) = \begin{cases} K_I^{(0)}(t) & \text{for} \quad 0 < t < 2l/c_d \\ K_I^{(0)}(t) + K_I^{(1)}(t) & \text{for} \quad 2l/c_d < t < 4l/c_d \end{cases} \tag{1}$$

where $K_I^{(0)}(t)$ and $K_I^{(1)}(t)$ may be called contributions of zero and first orders respectively.

For isotropic materials, the zero order contribution is (Freund 1990)

$$K_I(t) = 2\sigma_0 \frac{\sqrt{c_d(1-2\nu)/\pi}}{(1-\nu)}\sqrt{t}. \tag{2}$$

which coincides with the dynamic stress intensity factor for a semi-infinite crack under uniform impact load, σ_0, applied on the crack faces in mode I.

The expression $K_I^{(0)}(t)$ for orthotropic materials has been developed by Rubio-Gonzalez & Mason (2000)

$$K_I(t) = 2\sigma_0\sqrt{\frac{2c_s\xi}{\pi\sqrt{c_{22}}}}\,\sqrt{t}. \tag{3}$$

In both cases, the velocity $c_d = \sqrt{c_{11}}c_s$ represents the dilatational wave speed along the $x-$axis. The constant ξ is given by

$$\xi = \frac{\beta\sqrt{\frac{c_{22}}{c_{11}}}}{\sqrt{\beta - 2\frac{c_{12}}{c_{22}} + 2\sqrt{\frac{c_{11}}{c_{22}}}}}, \qquad \text{with} \quad \beta = \frac{c_{11}c_{22} - c_{12}^2}{c_{22}} \tag{4}$$

and $c_s = \sqrt{\mu_{12}/\rho}$ represents the velocity of the in-plane shear wave propagating along the the principal material axes and ρ is the mass density. The non-dimensional constants c_{ij} may be written in terms of engineering constants see (Rubio-Gonzalez & Mason 2000)

3 Dynamic Punch Test

The specimen was impacted on one side by a rigid projectile made of hardened steel as shown schematically on figure 1.

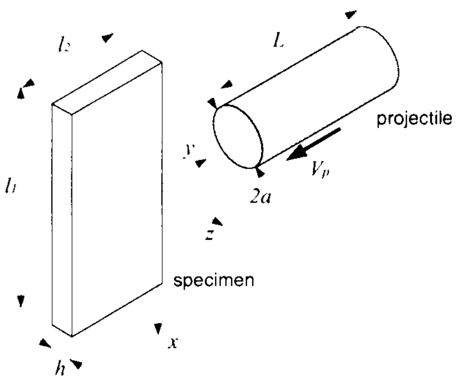
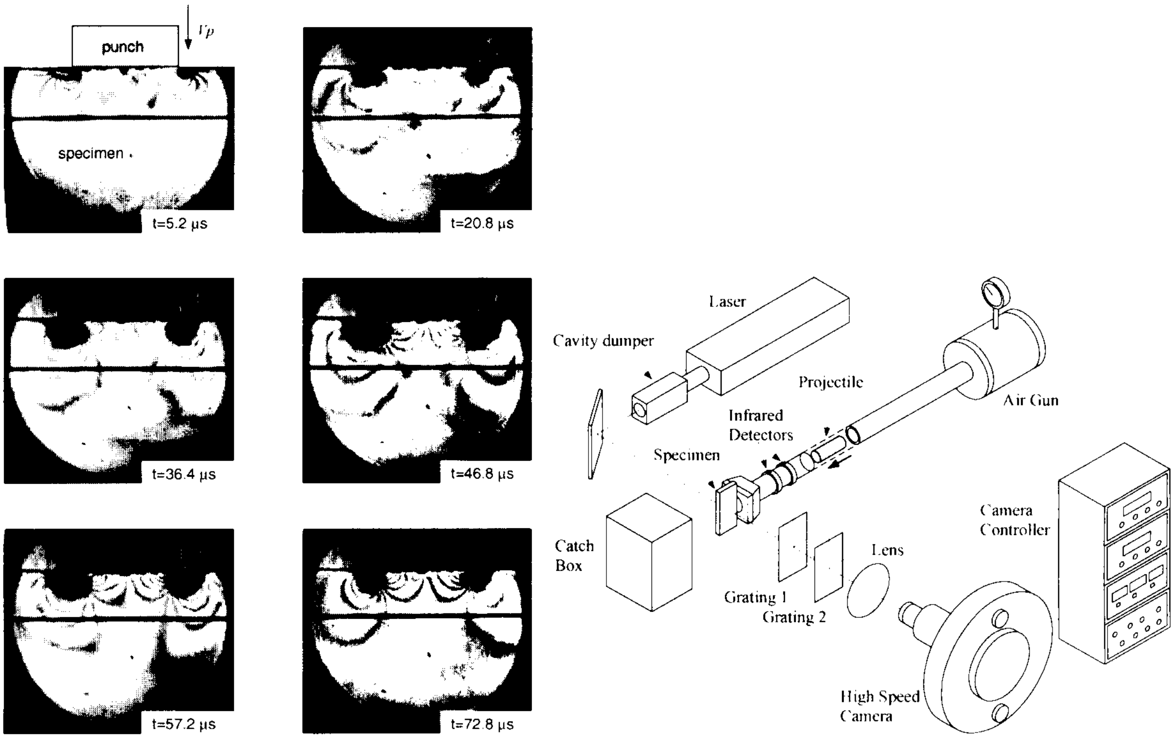


Figure 1: Specimen and projectile geometry in the dynamic punch test.

3.1 Isotropic Materials

The projectile is shot by an air gun as shown schematically in figure 2(b). The apparatus consists primarily of an air gun, a Cordin 330 high speed camera and a coherent argon-ion laser pulsed for 10ns. Once the projectile is launched it travels along the barrel and activates two infrared detectors, this signal is used to trigger the camera and laser controllers and to determine the projectile velocity, V_p. The speed of the camera was set to 5.2μs between pictures or 192,300 frames/sec. The specimen dimensions were 127x50x6.3mm, the grating pitch was $p = 0.0254$ mm and the distance between gratings was Δ =30 mm. A 50 mm-diameter collimated laser beam was used. The projectile length was L =145 mm and $2a$ =25.4 mm, the velocity V_p =16 m/s.

Figure 2(a) shows a series of some CGS interferograms for the dynamic test. Note that the size of the lobes increases and then decreases with time. Such a behavior is expected for the stress intensity factor as well. An analysis of each photograph leads to the determination of the time evolution of the stress intensity factor $K_I(t)$ for the punch test.



(a) (b)

Figure 2: (a) Sequence of CGS interferograms for the dynamic punch test. Transmission mode, isotropic materials, (b) Schematic illustration of CGS set-up in transmission mode for use in the dynamic punch test.

Figure 3(a) shows the dynamic stress intensity factor for the dynamic punch test. Note a good agreement in the loading zone between experimental results and the theoretical prediction for the semi-infinite punch.

3.2 Orthotropic Materials

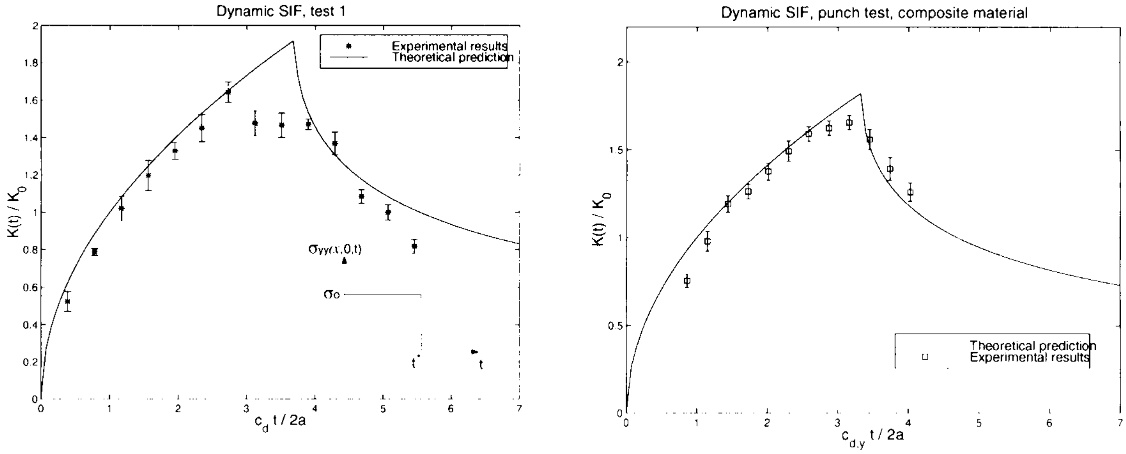
The dynamic punch test was conducted on graphite-epoxy composite material using the CGS method in reflection. For a detailed explanation of specimen preparation and characterization see (Rubio-Gonzalez & Mason 1999). The fiber orientation of the specimen was along the $x-$axis. The $x-$gradient was considered, e.i., $\partial w/\partial x$ was measured. The projectile impacted the specimen (with dimensions 101x50x6.5mm) at the velocity V_p = 11.5m/s. The grating pitch was $p = 0.0254$mm and the distance between gratings was $\Delta = 36$mm. The speed of the camera was set to 4μs between pictures or 250,000 frames/sec.

The normalized dynamic stress intensity factor for the punch test is shown in figure 3(b). The normalization factor is $K_0 = \sigma_0 C_I \sqrt{2a/c_{d,y}}$, where $\sigma_0 = \rho c_{d,y} V_p$, being $c_{d,y}$ the dilatational wave speed for wave propagation along the $y-$axis. An increase in $K_I(t)$ is noted and then a decrease occurs when the dilatational wave reflected from the opposite side of the specimen arrives at the punch corners. The solid line corresponds to the stress intensity factor for the semi-infinite punch problem under impact load $\sigma_0 H(t)$ applied during a time interval $0 < t < t^*$

$$K_I(t) = \sigma_0 C_I \left[\sqrt{t} H(t) - \sqrt{t - t^*} H(t - t^*) \right] \tag{5}$$

where C_I is a material dependent parameter derived in Rubio-Gonzalez & Mason (2000) and given by

$$C_I = 2\sqrt{\frac{2c_s \xi}{\pi \sqrt{c_{22}}}}. \tag{6}$$



(a) (b)

Figure 3: Normalized dynamic stress intensity factor for the punch test. (a) Isotropic materials, (b) Composite materials

4 Conclusions

Like in fracture mechanics, the stress intensity factor K_I has been introduced to characterize the severity of the singular stresses around the punch corners in the punch test. Quasi-static and dynamic punch tests were performed on PMMA and unidirectional graphite-epoxy composites to measure K_I. Laser interferometry was used to measure in-plane stresses (transmission mode) and out-of-plane displacements (reflection mode), and then estimate the stress intensity factor. In the dynamic case, a high speed photography technique was employed to capture the transient response of the specimen and measure $K(t)$ just after the impact. Each photograph of the CGS fringe pattern was digitized. A fitting procedure based on the least squares method was used to estimate K_I from the fringe pattern. In all the cases a good agreement between the measurements of K_I and the theoretical predictions was found. The theoretical prediction for the dynamic case on composites is just an extension of the solutions developed in Rubio-Gonzalez (1999) and Rubio-Gonzalez & Mason (2000) for orthotropic materials.

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