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A NEW METHOD FOR DYNAMIC FRACTURE TOUGHNESS TESTING

D. Rittel[1], H. Maigre[1], H.D. Bui[1,2]
[1]Laboratoire de Mécanique des Solides, URA 317 - CNRS
Ecole Polytechnique, F-91128 Palaiseau Cedex, France
[2]Electricité de France, D.E.R.-I.M.A.-M.M.N.
F-92141 Clamart Cedex, France

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Introduction

The dynamic fracture toughness of a material K_{Id} is a key property when dynamic loading is involved. Yet, by contrast with the static case, there is no standard method to determine K_{Id} and one currently relies on two different approaches. The first, which is empirical, attempts to relate K_{Id} with various material properties such as yield strength and reduction of area (see *e.g.* [1, 2]). In the other approach, the tip of the propagating crack is monitored and the dynamic stress intensity factor is assessed using optical methods (for a review, see *e.g.* [3]).

Recently, Bui *et al.* developed a novel experimental approach to the determination of the *dynamic stress intensity factor*. With dynamic effects fully taken into account, the history of $K_{Id}(t)$ can be determined using an exact theoretical framework [4, 5, 6].

In this paper we describe our experimental method for the determination of $K_{Id}(t)$ with emphasis on the *dynamic toughness* K^c_{Id} at the onset of crack propagation.

Determination of $K_{Id}(t)$

Theoretical

We first recall briefly the principle of the method exposed in detail in [4, 5, 6]. Consider a body S containing a crack a. Let $\mathbf{u}$ be the displacement field in S to which a dynamic load $\mathbf{T}[\mathbf{u}, t]$ is associated (boldface symbols denote field quantities). Let $\mathbf{v}$ be a reference field. Define $K^{\mathbf{u}}_{Id}$ and $K^{\mathbf{v}}_{Id}$ as the stress intensity factors associated with $\mathbf{u}$ and $\mathbf{v}$ respectively. $\mathbf{u}$ and $\mathbf{T}$ are determined *experimentally*. $\mathbf{v}$ and $K^{\mathbf{v}}_{Id}$ are determined *numerically* (FEM). For a *linear-elastic* material, the following results is established:

$$H := \frac{1}{2}\int_S \mathbf{T}[\mathbf{u}] * \frac{\partial \mathbf{v}}{\partial a}\, dS = \frac{1-\nu^2}{E} K^{\mathbf{u}}_{Id} * K^{\mathbf{v}}_{Id}$$

where $*$ indicates time convolution product. H is a path-independent functional. It can therefore be evaluated along selected paths among which the specimen's outer boundaries (path 1) and the close vicinity of the crack-tip (path 2). The expression for H contains *explicitly*:

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- on the l.h.s. of the equal sign global mechanical parameters (forces & displacements) - measured experimentally (path 1);
- on the r.h.s. of the equal sign a convolution product between two factors - one of which $K_{Id}^{\mathbf{u}}$ is for determination (path 2).

The approach relies practically on:

- a specially devised experimental setup, to be described next, by means of which $\mathbf{u}$ and $\mathbf{T}[\mathbf{u}]$ are determined;
- efficient elastodynamic finite element modelling to generate reference data, $\partial\mathbf{v}/\partial a$ and $K_{Id}^{\mathbf{v}}$. This is done once and for all for a given specimen geometry and for any combination of load and crack length bounded by a and $a + da$;
- finally, a reliable algorithm for the quick and accurate solution of the linear convolution equation leading to $K_{Id}^{\mathbf{u}} = K_{Id}$.

Experimental procedure and results

The split Hopkinson bar (SHB) apparatus provides a convenient means to apply controlled dynamic loads on the faces of a specimen while measuring interfacial stresses and displacements (see *e.g.* [7, 8]). As shown in figure 1, the *Compact Compression Specimen* (CCS) was designed to be inserted between the Hopkinson bars without special fixtures. Due the special geometry of the CCS, the crack opens up during impact loading and the interfacial stresses and displacements $\mathbf{T}[\mathbf{u}]$ are determined the usual way from the gage recordings. To assess the dynamic fracture toughness, the time at which the crack starts to propagate must be known, that is $K_{Id}^{c} = K_{Id}(t = t_{frac})$.

Several experiments, one of which involved monitored crack propagation, were carried out on 1035 (HRB 65)-16.5 mm thick steel CCS's (figure 2). In this fractured specimen $a = 18.33mm$ and $a/w = 0.52$ with a root radius of approximatively 0.17 mm (diamond wire cut). The fracture gage (timing wire - less than 400 micron wide) was painted using conductive silver paint very close to the crack-tip. The fracture gage was connected to a clock triggered on by the incident pulse and turned off as the wire was fractured by the propagating crack. The clock runtime was recorded on a digital oscilloscope as the time to fracture. For metallic specimens, a thin electrically insulating backing (about 300 micron thick) was laid on the CCS. We found that commercial epoxy (metallographic grade) has an excellent chemical compatibility with the silver paint. Also it is hard enough to fracture neatly rather than deform so that satisfactory accuracy is reached with this single-wire technique.

For the specimen of figure 2, fracture occurred 57 microseconds after the incident pulse reached the incident bar-specimen interface. As shown in figure 3, fracture occured significantly after the peak interfacial force was reached. The evolution of $K_{Id}(t)$ was thus determined from the experimental information using appropriate references for this material and crack length ($a = 18.0 \pm 0.5mm$). The corresponding value of K_{Id}^{c} is $\approx 180MPa\sqrt{m}$ at $\dot{K}_{Id} \approx 10^{6}MPa\sqrt{m}/s$.

To validate these results, a complete 2D-FEM elastodynamic simulation of the SHB-CCS setup was carried out, assuming perfect interfacial bonding and no fracture. The pulse recorded on the incident gage was applied to the model incident bar and interfacial velocities were calculated. As shown in figure 4, numerical and experimental evolutions of the interfacial velocities are quite similar until the onset of fracture. This suggests that crack-tip plasticity in this specimen developed well after the crack took off. The crack opening displacement (COD) was also determined and the corresponding stress intensity factor was calculated using the well known formula:

$$COD(r, \theta = \pi) = K_I \frac{8(1-\nu^2)}{E} \sqrt{\frac{r}{2\pi}}$$

In figure 5 are shown results for $K_{Id}(t)$ obtained by our approach (linear deconvolution) and by numerical simulation of the experimental COD. An excellent agreement is noted between both methods.

Discussion

The CCS is not loaded symmetrically so that mixed I-II crack opening mode occurs due to specimen inertia. Yet, the combined loading mode and specimen geometry ensure that mode I is the predominant crack opening mode. Furthermore, the reported results include "filtering out" of the mode II component through the choice of appropriate reference fields [4].

The CCS is quite convenient since it is used *without* special fixtures to turn a compressive load into a tensile load to open the crack. Such fixtures interfere with the loading pulse and add unnecessary complexity to the numerical modelling.

The present results thus show that K_{Id}^c can be reliably assessed using a relatively simple procedure. Here, $K_{Id}(t)$ is determined from the onset of the impact until fracture by contrast with other methods in which continuous crack-tip monitoring is required and K_{Id}^c is obtained by extrapolating to zero crack extension. In addition, numerical calculation requirements (generation of reference data) are kept to a minimum and they only involve *nonpropagating* cracks. There is absolutely no need for a complete FEM simulation of the setup except for comparison purposes or planning of future experiments.

Finally, the determined value of $180 MPa\sqrt{m}$ provides only an order of magnitude since the crack-tip was relatively blunt compared to a sharp fatigue crack and this raises the apparent fracture toughness of the material [9] and makes it difficult to establish a comparison with values reported in the literature.

Conclusions

The new method is ideally suited for linear elastic and/or small scale yielding materials. It should thus provide new interesting insights into the dynamic fracture of engineering materials such as ceramics, intermetallics etc. for which K_{Id}^c is difficult to measure by existing methods.

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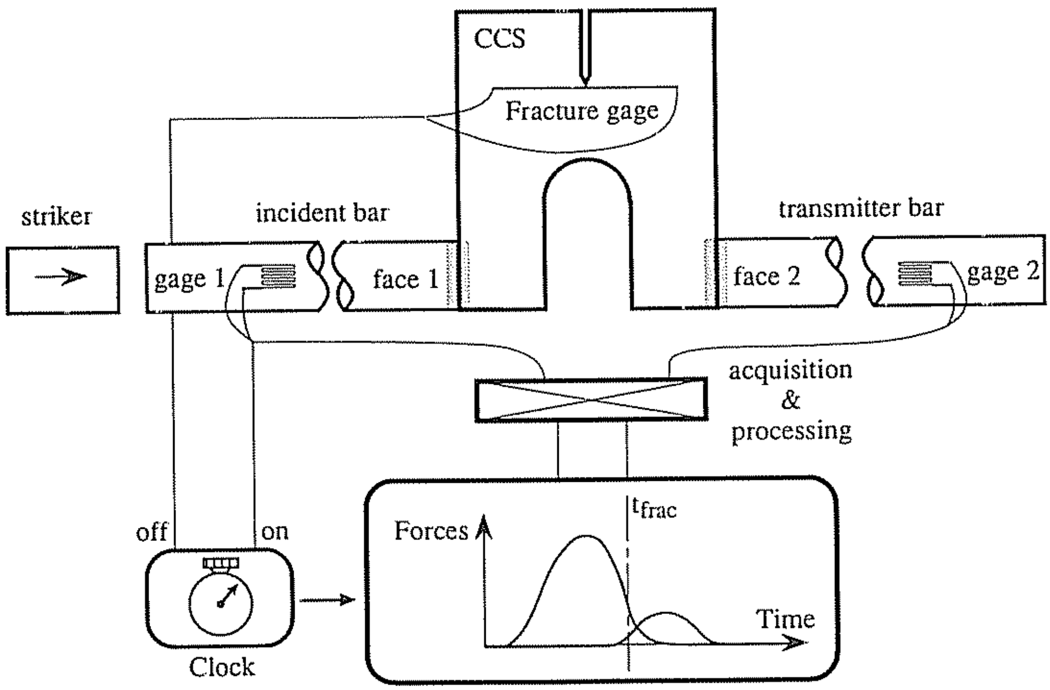

Figure 1: Schematic representation of the experimental setup

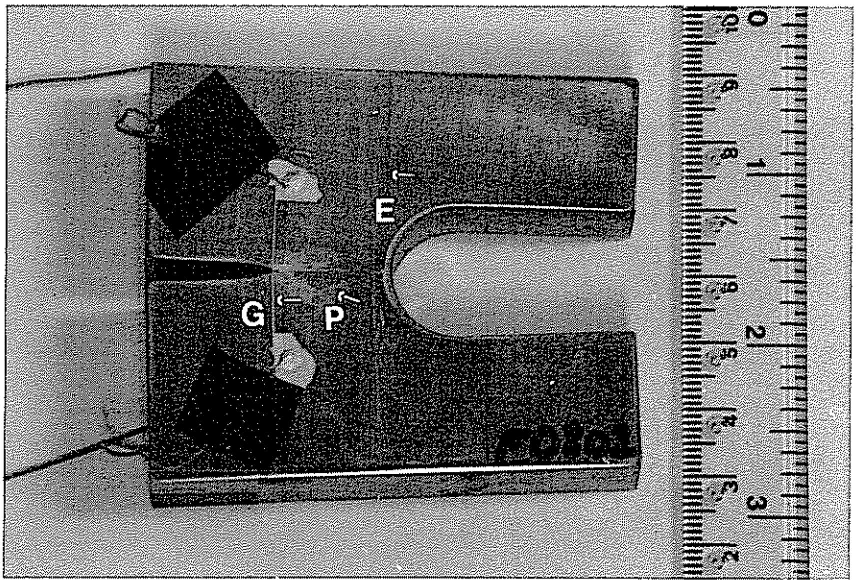

Figure 2: Fractured mild steel CCS with fracture gage G and epoxy backing E. P points to the plastic zone in the backing.

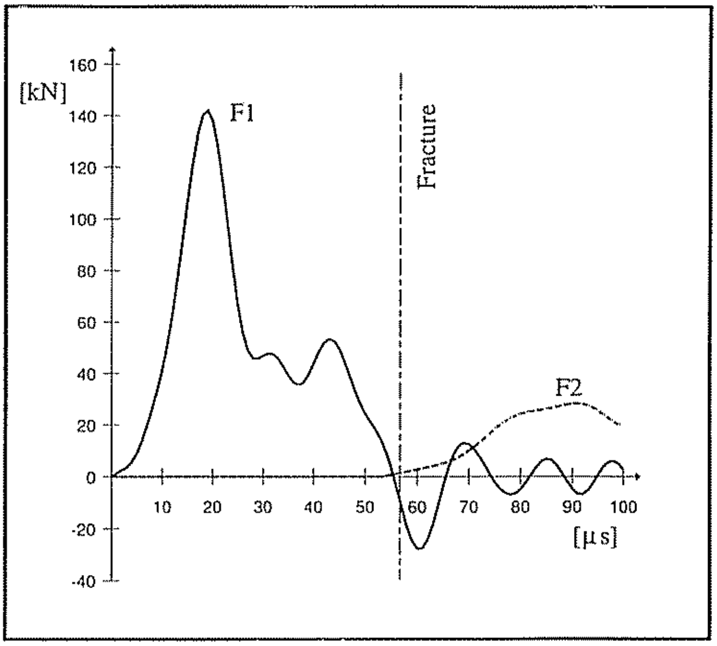

Figure 3: Incident (F1) and transmitted (F2) bar-specimen interfacial forces and time to fracture. Note that fracture occurs way beyond the peak force at $t_{frac} = 57\mu s$.

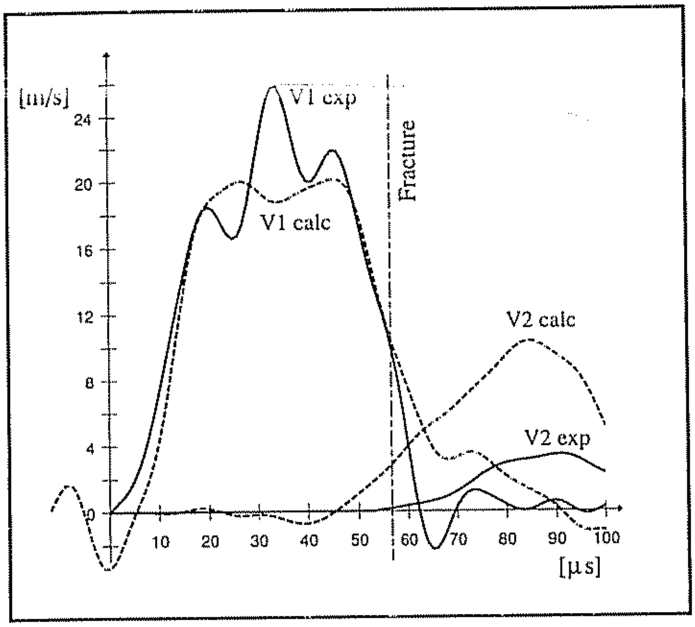

Figure 4: Experimental and calculated interfacial velocities. Note the excellent agreement until fracture.

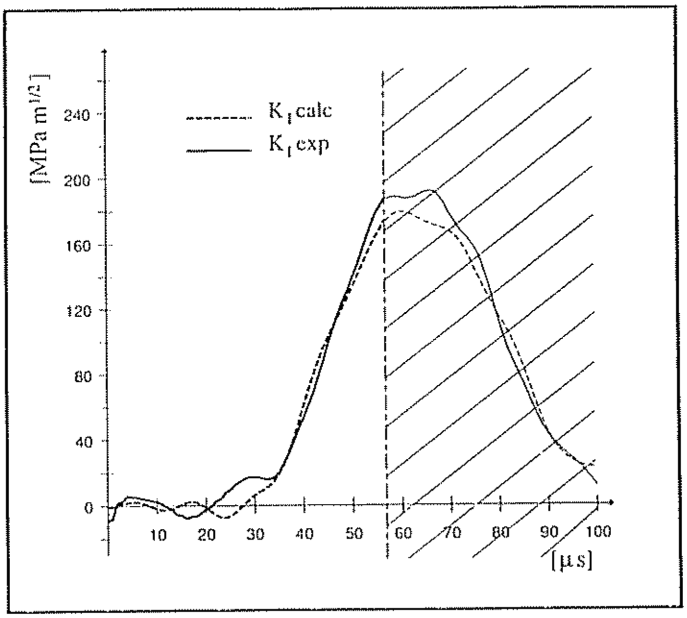

Figure 5: Evolution of the stress intensity factor determined by FEM calculation and by linear deconvolution. The results are not valid past fracture time, $t_{frac} = 57\mu s$.