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About a new experimental method of identification of the dynamic toughness of materials

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Summary

A new experimental method has been developed to evaluate dynamic toughness of brittle materials. This approach is based on invariance properties of an integral and is applied to a Kolsky Bar apparatus. This method allows also mixed mode loading to investigate dynamic fracture criteria including mixity. Moreover a technique of dual treatment gives precious information to validate all the assumptions made to analyse the experiments. Some results on PMMA and commercial glass are presented to illustrate this method.

Keywords: Dynamic Fracture, Dynamic Toughness, Stress Intensity Factor, Kolsky Bars

1 Introduction

Dynamic properties of materials are now essential to the designers to compute structures subjected to transient loadings or shocks. These properties are not always well-known because standard procedures are missing and the complexity of existing procedures makes impossible systematic tests on materials. This is the case of the toughness K_{IC} which is assessed in static whereas the dynamic toughness K_{IDC} is still evaluated using various experimental procedures [1] more or less accurate or easy to perform. Some sophisticated techniques are based on optical properties of the material [2] and can not be applied to opaque materials like metals. Recently, we introduced the dynamic H-integral [3] and we used the path-independent property of this integral to relate the dynamic loading on a structure to the evolution of the dynamic stress intensity factor at the crack-tip. This theoretical result has been applied to Kolsky Bars in conjunction with the Compact Compression Specimen (CCS). Knowing precisely the instant of the onset of the crack propagation we evaluate the dynamic toughness as the dynamic stress intensity factors at this instant. We present in this paper results on PMMA and glass. First we recall the principles of the method. Next we discuss the experimental results obtained on these materials.

2 Path-independent H-Integral

The H-integral is a path-independent contour integral which relates forces (F) and displacements (u) applied on the external surface S of a cracked solid (fixed crack length a) to the stress intensity factors K_I^u and K_{II}^u at the crack-tip [3]:

$$H(t) := \frac{1}{2} \int_S \left\{ F * \frac{\partial v}{\partial a} - \frac{\partial T}{\partial a} * u \right\} dS = \frac{1-v^2}{E} \left\{ K_I^u * K_I^v + K_{II}^u * K_{II}^v \right\} \quad (1)$$

This expression stands for 2D linear elastic media in plane deformation. The time dependence of the dynamic effects is explicitly taken into account through the time convolution product $*$. T, v,

K_I^v and K_{II}^v refer to an adjoint dynamic displacement field v which is supposed known (calculated numerically in our case). Practically, $K_I^u(t)$ and $K_{II}^u(t)$ are solution of a linear convolution equation, since the adjoint field has been calculated and H has been estimated from the experimental forces and displacements.

2.1 Separation of mixed modes

H-integral includes combined opening and shearing modes [4] when the loading or the solid are not symmetrical with respect to the initial crack. To get separately $K_I^u(t)$ and $K_{II}^u(t)$ we choose respectively two appropriate adjoint fields: the first one in pure mode I ($K_{II}^v := 0$) and the second one in pure mode II ($K_I^v := 0$).

2.2 Dual analysis

The evaluation of $H(t)$ requires both the knowledge of the forces and the displacements applied to the solid. In fact, if the adjoint field is chosen such that its displacements on S are constant with respect to the crack variation ($\partial v / \partial a := 0$), $K_I^u(t)$ and $K_{II}^u(t)$ depend only on the experimental displacements u . Similarly, we can define an other adjoint field with the applied forces constant with respect to the crack variation ($\partial T / \partial a := 0$). In this case, the dynamic stress intensity factors are evaluated only from the experimental forces and we note them $K_I^F(t)$ and $K_{II}^F(t)$. These two ways to analyse the experimental data give us a precious tool to assess the quality of the experiments and the validation of the theoretical assumptions. If every thing goes right, the stress intensity factors from the displacements are identical to the stress intensity factors from the forces. At the beginning of the crack propagation ($t = t_{frac}$) the two families of stress intensity factors must begin to diverge because the hypothesis of a fixed crack is no longer valid:

$$\begin{aligned}
 t < t_{frac} & \Rightarrow & K_I^u(t) &= K_I^F(t) & \text{and} & & K_{II}^u(t) &= K_{II}^F(t) \\
 t > t_{frac} & \Rightarrow & K_I^u(t) &\neq K_I^F(t) & \text{and} & & K_{II}^u(t) &\neq K_{II}^F(t)
 \end{aligned}$$

This divergence can be used to detect the onset of the crack propagation.

3 Experimental setup

We implement the preceding theoretical results to the Kolsky Bar apparatus. This device provides a mean to apply dynamic impact and to measure forces and displacements at the interface between the bars and a specimen. We designed the special specimen CCS to be inserted between the bars without extra devices to turn compression into tension at the crack-tip (fig. 1).

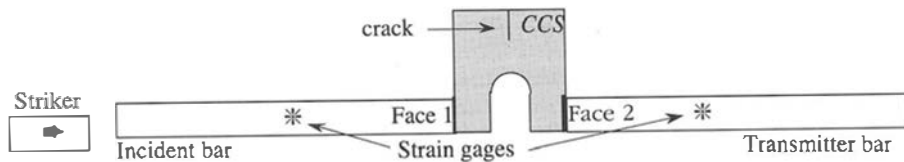


Fig.1: Experimental setup. The CCS is inserted between two instrumented bars (Kolsky Bars). Transient signals are recorded on two strain gages. Forces and displacements are determined at the specimen interfaces.

It can be noted that the geometry of the CCS is symmetrical, but loads are applied on one side only. Consequently, both mode I and mode II are present but it is obvious that the opening mode should be predominant. Kolsky apparatus giving the resultant forces (F_1 and F_2) and the mean displacements (u_1 and u_2) at the interfaces, H-integral at the boundary reduces to the sum of four convolution products between scalar quantities:

$$H(t) := \frac{1}{2} \left\{ F_1 * \frac{\partial v_1}{\partial a} - \frac{\partial T_1}{\partial a} * u_1 + F_2 * \frac{\partial v_2}{\partial a} - \frac{\partial T_2}{\partial a} * u_2 \right\} \quad (2)$$

For a given series of experiments on a material, one has to generate four adjoint fields corresponding to the mixed mode and dual analysis. Since the set of adjoint fields must be calculated once, a large sample size can easily be tested.

4 Experimental results

Tests were performed on 16.5 mm diameter Kolsky Bars. Acquisition sampling was carried out at 1 MHz. Furthermore, a single wire fracture gage was glued at the vicinity of the notch tip to detect the onset of the crack propagation at the surface.

4.1 PMMA dynamic toughness

The present result concerns commercial PMMA whose properties are listed in table 1.

Young's modulus E [GPa]	Poisson ratio ν	Density ρ [kg m^{-3}]
static: 3.70 dynamic: 5.76	0.42	1182

table 1: mechanical properties of the PMMA used in this study

Due to the viscosity of the PMMA, a dynamic modulus was determined by the time required for waves to travel in a rod specimen. The initial notches were machined mechanically with an average root radius 0.2 mm. Typical experimental signals (incident, transmitter pulses) are shown in fig. 2.

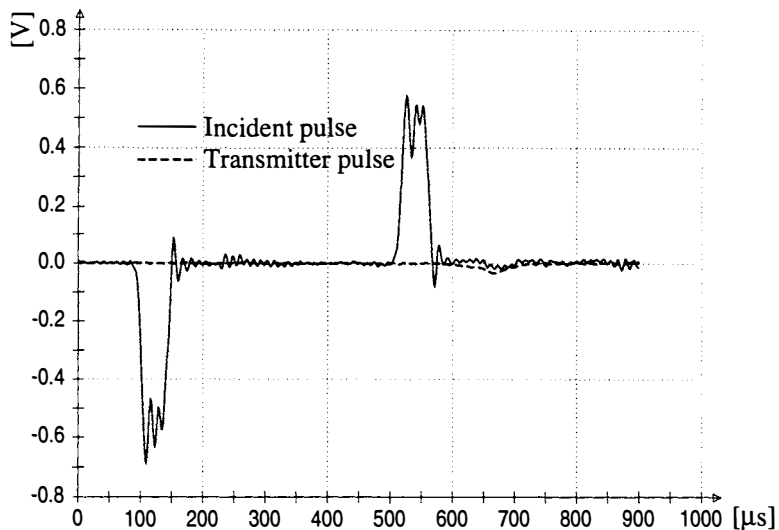


Fig.2: Typical incident and transmitter pulses

For this example this incident pulse is $70\mu\text{s}$ long. One can see that the transmitter signal is very small because of the very short time needed to fracture the whole specimen. After treatment of these gages signals, we get the interfacial forces and velocities applied to the specimen (fig. 3).

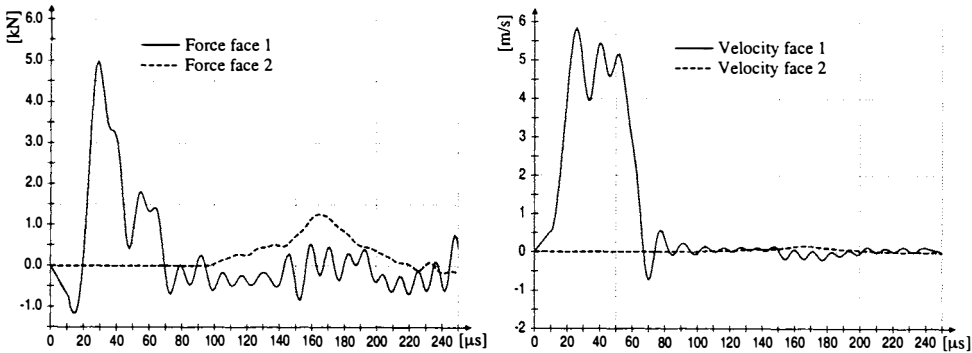


Fig.3: Interfacial forces and velocities applied on the CCS. Note that the forces are not in equilibrium.

Following equation (2), we then calculated the four H-integral with the four adjoint fields. By deconvolution we obtain four evolutions of stress intensity factors (three of them are shown fig. 4).

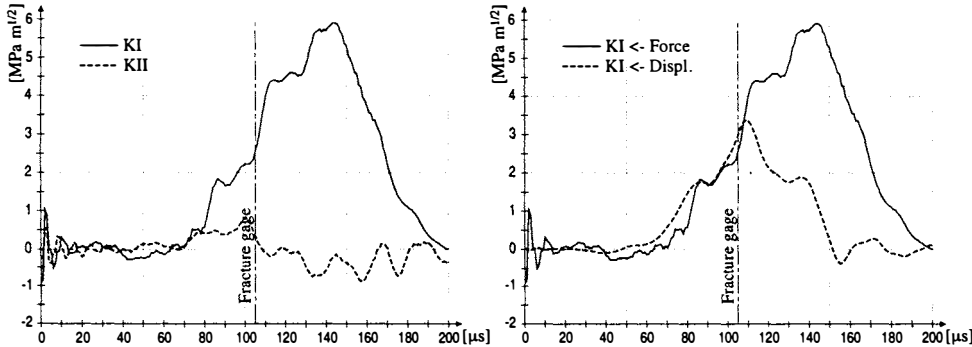


Fig.4: Dynamic stress intensity factor evolutions. The time of fracture given by the fracture gage glued on surface is also reported.

Signals take typically $60\mu\text{s}$ to reach the crack and force its opening. Fracture occurs soon after. Mode II exists because of the non symmetrical loading but very soon the mode I is dominant. This predominance of the opening is confirm by the observation of the broken specimen (fig.5). The crack path is not straight but the begining of the propagation is along the direction of the initial notch. The dual analysis gives identical evolutions until $110\mu\text{s}$ which is nearly the instant given by the fracture gage. We suppose that the crack propagation begins at this time and we obtain a critical stress intensity factor of $2.4 \text{ MPa m}^{1/2}$.

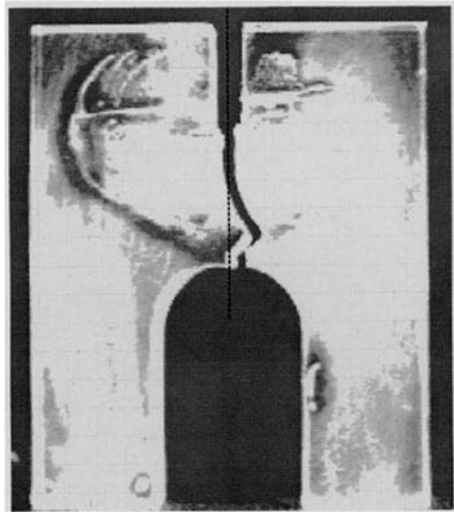


Fig.5: PMMA CCS after dynamic loading. The crack does not deviate at the onset of the propagation which confirms the existence of dominant mode I at this time.

Using this technique on 16 specimens we have shown that for this material the fracture toughness increases markedly with stress intensity rate [5] and this was already observed [6]. This variation correlates qualitatively with the visual aspect of the fracture surfaces. Indeed at higher rates some hackles can be observed in the vicinity of the crack-tip whereas a mirror aspect is observed at lower rates.

4.2 Glass dynamic toughness

We have also tested glass with this technique combining Kolsky Bars and Compact Compression Specimen. The material properties of the studied glass are listed in table 2.

Young's modulus E [GPa]	Poisson ratio ν	Density ρ [kg m^{-3}]
dynamic: 80	0.23	2503

table 2: mechanical property of the glass used in this study

We prepared 10 specimens. The initial notches were machined mechanically with an average root radius 1.0 mm. Four adjoint fields have been also calculated. We do not present again the experimental signals and the interfacial loads which are very similar to those on PMMA. We present directly after deconvolution results of a typical experiments (fig. 6). Like PMMA, the non-symmetrical loading does not generate significant mode II. There is also a good agreement between the analysis from forces and the analysis from displacements until $90\mu\text{s}$ which the time given by the fracture gages glued on both side of the specimen. What is more surprising is the very high value of the toughness around $12 \text{ MPa m}^{1/2}$ which is 10 times much higher than the static value $1 \text{ MPa m}^{1/2}$. In fact we have to observe the specimen after testing (fig. 7).

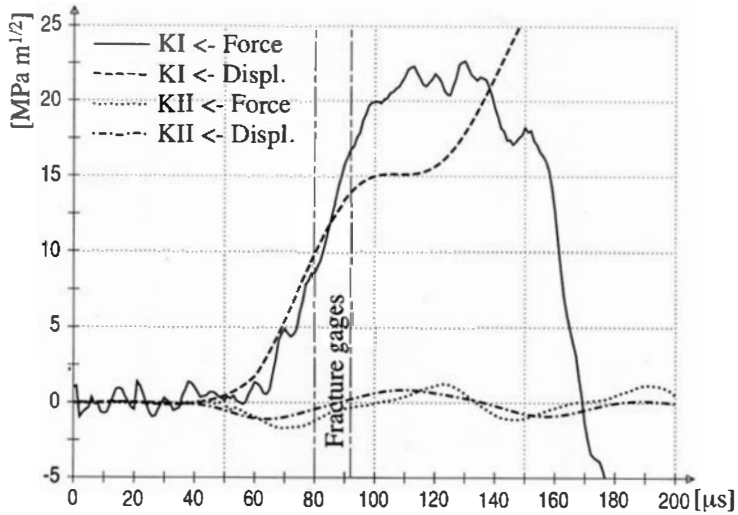


Fig.6 : Evolutions of the dynamic stress intensity factors for glass. Mode I is soon predominant. Analysis from experimental forces or displacements are very similar until the time of fracture recorded on the faces of the specimen.

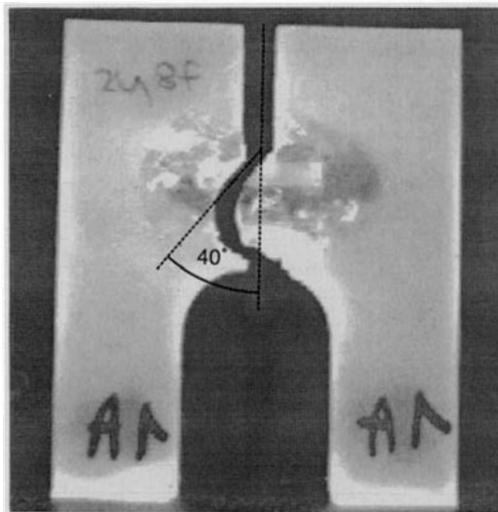


Fig.7 : Glass specimen after dynamic testing. Note the 40° kink of the crack at the beginning of the propagation.

The initial deviation of the crack around 40° from the axis of the notch is not compatible with a fracture occurring during dominant mode I. A possible explanation is that fracture initiates much earlier than supposed until now when mode II is similar to mode I. On fig. 8 we plot the evolutions

of mode I and mode II stress intensity factors until $80\mu\text{s}$. We present only the results obtained from experimental displacements because of the noise on those from forces.

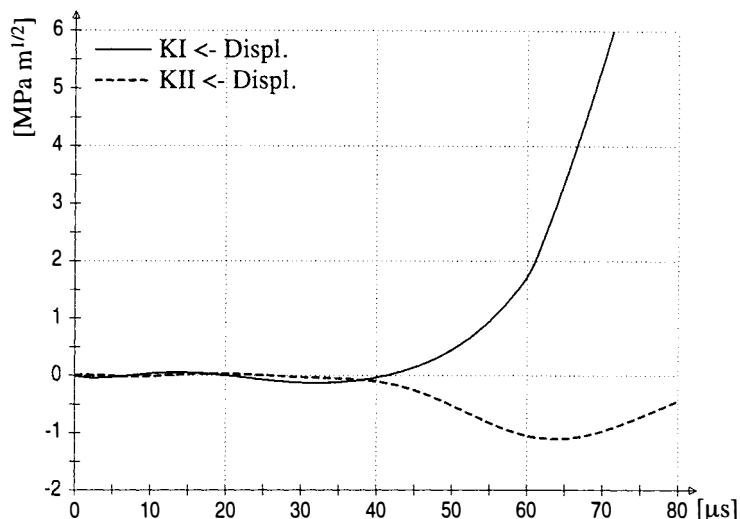


Fig. 8: Dynamic stress intensity factors at the very beginning of the sollicitation at the crack-tip.

Until $65\mu\text{s}$ mode II is equivalent to mode I. During this time stress intensity factors do not exceed $2\text{ MPa m}^{1/2}$ which is closer to the static value. So it seems that fracture occurs very soon and it can not be detected either by the fracture gages or the separation in the dual analysis. Defining a criteria including mode I, mode II and the angle of kinking one can imagine to find when the fracture initiates.

5 Conclusions

We have presented a new convenient method to evaluate dynamic toughness of brittle materials. It is based on the H-integral and it is applied to Split Hopkinson Bars with CCS specimens. This method allows identification of mode I and mode II contributions. The dual analysis using independently experimental forces or displacements gives indications about the quality of the experiments and can also be used to detect the crack initiation. Experiments on PMMA have shown the good applicability of this method. Moreover, the results have confirmed the already observed increase of toughness with the the loading rate. Experiments on glass work as well but it seems much more difficult to detect the exact instant of the crack initiation. Experiments on very brittle materials have to be done very carefully and the use of the observed kink angle could provide a mean to reveal the initiation and the mode of fracture.

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