A methodological improvement of dynamic fracture toughness evaluations using an instrumented Charpy impact tester

T. Lorriot, E. Martin, J. Quenisset, S. Sahraoui, J. Lataillade

To cite this version:

T. Lorriot, E. Martin, J. Quenisset, S. Sahraoui, J. Lataillade. A methodological improvement of dynamic fracture toughness evaluations using an instrumented Charpy impact tester. Journal de Physique IV Colloque, 1994, 04 (C8), pp.C8-125-C8-130. <10.1051/jp4:1994819>. <jpa-00253374>

HAL Id: jpa-00253374
https://hal.archives-ouvertes.fr/jpa-00253374
Submitted on 1 Jan 1994

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L’archive ouverte pluridisciplinaire HAL, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d’enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.
A methodological improvement of dynamic fracture toughness evaluations using an instrumented Charpy impact tester

T. Lorriot, E. Martin, J.M. Quenisset, S. Sahraoui(1) and J.L. Lataillade*

Laboratoire de Génie Mécanique (L.G.M.), Université de Bordeaux I, Institut Universitaire de Technologie "A", Domaine Universitaire, 33405 Talence cedex, France

* Laboratoire Matériaux Endommagement Fiabilité (LAMEF), ENSAM Bordeaux, Esplanade des Arts et Métiers, 33405 Talence cedex, France

Abstract: The study aims at the investigation of a method based on the displacement measurement of a specimen point for the determination of dynamic toughness. Thus, it is possible to avoid the treatment of the force generally recorded through the impactor by a dynamic analysis in order to obtain the true load undergone by the specimen during a CHARPY impact test. Deflection of the impacted specimen is measured with the help of a non contacting displacement transducer. Then, a static calibration is used to derive the fracture toughness from the deflection of the beam at fracture initiation. Characterizing the dynamic fracture toughness of PMMA with this experimental procedure gives rise to a value consistent with results reported in the literature.

1. INTRODUCTION

The exact knowledge of the fracture properties of materials, particularly under conditions of impact loading, is a prerequisite for their reliable use as structural materials. Consequently, instrumented impact tests have been more and more widely used for the determination of dynamic fracture toughness. However, the higher the loading rate of notched specimens, the more difficult the interpretation of the measured load-time curves. Inertial and wave propagation effects imply that the relation between the far field applied load and the stress intensity factor is no longer simple. Furthermore, detecting the critical time when the crack starts to propagate becomes problematic. Although significant progress in the understanding of dynamic responses of specimens has been made, particularly through dynamic models [1-4], there still exists the need to develop simple and reliable testing procedures of dynamic fracture toughness characterization.

It is worthy of note that among different testing methods, the commonly used instrumented CHARPY impact test combines the advantage of low cost and simplicity. However, the interpretation of the load-time curves generally recorded from the instrumented tup is not easy and needs dynamic analyses whose reliability can be questionable depending on material behaviour. The aim of the present contribution is to develop an experimental procedure based on the displacement measurement of a specimen point during a CHARPY impact test in order to deduce a reliable dynamic fracture toughness value. For this purpose, a laser sensor is used to evaluate the deflection of the three point bending specimen during impact test. Then a
quasi-static analysis allows us to determine the dynamic stress intensity factor $K_I$ as a function of the specimen deflection. Assuming that crack initiation is detected by a sudden change in the load time curve, dynamic fracture toughness can be derived for brittle materials.

2 EXPERIMENTAL PROCEDURE

Dynamic three point bending tests are performed with the help of a standard CHARPY testing machine. Initial impact velocities range from 1 m/s to 4 m/s and the maximum capacity of the hammer is 7.5 J. Impact and post-impact velocities are deduced by means of a photocell while the impacting load is measured at the tup by using statically calibrated strain gages. A commercially available transducer using a non contacting measurement method is used to estimate the displacement of the sample during the impact test. As illustrated in Fig. 1, the device focuses a laser beam with an average spot diameter of 185 μm on a point located near the notch of the specimen. The value of the 3 dB frequency response of the optical transducer is 16 kHz and consequently allows dynamic measurements. A mechanical system is added to stop the hammer after impacting the specimen in order to avoid any damage of the sensor. Force and displacement signals are recorded as a function of time with the help of a numerical oscilloscope connected to a personal computer in order to perform data processing.

Fig. 1: Measurement of the deflection of the specimen during impact test.

Evaluation of the dynamic fracture toughness can be derived from the load and deflection time curves provided by the previously described experimental system with the help of the following assumptions:

(1) the fracture initiation time is detected by the sudden change in the load response of the specimen. This is assumed to be all the more realistic as the behaviour of the tested material is brittle,

(2) the stress distribution in the specimen before fracture initiation is similar to that of a statically loaded specimen. Photoelastic study and numerical work both confirm the predominance of the quasistatic mode before fracture initiation although this situation does not prevail during the first specimen oscillations [5,6],

(3) the displacement of a specimen point measured near the notch tip before fracture is equivalent to the deflection of the specimen at midspan. This assumption is confirmed by a finite element computation which has demonstrated that under static conditions the relative difference between the displacements of the relative two points is less than 0.1%.
Consequently, the critical dynamic stress intensity factor $K_{Id}$ can be expressed by the following equation:

$$K_{Id} = \frac{3}{2} \frac{S}{B} W^2 \sqrt{\alpha} \frac{Y(a/W)}{C(a/W)} \delta_c$$

(1)

where $S$, $B$, $W$, and $a$ are respectively the span, the thickness, the width and the notch length of the specimen as defined in Fig. 2, $\delta_c$ the specimen deflection measured at fracture initiation, $Y(a/W)$ the geometrical factor and $C(a/W)$ the specimen compliance.

The geometrical factor $Y(x)$ is given by the following equation for $S/W = 4$, where $x = a/W$ [7]:

$$Y(x) = \left[ \frac{1.99 - x (1 - x)}{1 + 2x} \right] \frac{1}{(1 - x)^{3/2}}$$

(2)

The specimen compliance $C(a/W)$ can be expressed as [8]:

$$C_E B = C_0 E B + \frac{9}{2} \left( 1 - v^2 \right) \left( \frac{S}{W} \right)^2 \int_0^{a/W} x Y^2(x) \, dx$$

(3)

where $E$, $v$ are respectively Young's modulus and Poisson's ratio and $C_0$ the compliance of an unnotched specimen under three point bending, given by [9]:

$$C_0 E B = \frac{S^3}{4 W^3} \left[ 1 + 2.85 \left( \frac{W}{S} \right)^2 - 0.84 \left( \frac{W}{S} \right)^3 \right]$$

(4)

To take into account the shearing effect related to a short bending specimen, the Young's modulus $E$ is replaced by the effective Young's modulus $E_{eff}$ which is introduced by the following equation [10] where $G$ is the shear modulus ($G = \frac{E}{2(1+v)}$ for isotropic material):

$$\frac{1}{E_{eff}} = \frac{1}{E} + \frac{1.2}{G} \left( \frac{W}{S} \right)^2 \left( 1 - \frac{a}{W} \right)^2$$

(5)

and, finally, equation (3) becomes:

$$C_{eff} = C_{0eff} + \frac{9}{2} \left( 1 - v^2 \right) \left( \frac{S}{W} \right)^2 \int_0^{a/W} \left[ 1 + 1.2 \frac{E}{G} \left( \frac{W}{S} \right)^2 (1 - x)^2 \right] x Y^2(x) \, dx$$

(6)

where $C_{0eff}$ is the compliance of the unnotched specimen calculated with the effective Young's modulus $E_{eff}$. 
3 RESULTS

PMMA was selected as an example of brittle material to assess the capability of the procedure previously described. The dimensions of the tested specimens are depicted in Fig. 2. Notches were machined with a milling cutter so that $a/W$ ratios were chosen in the range of 0.28-0.6. Young's modulus and Poisson's ratio are taken to be $E=5.2$ GPa and $v=0.34$ [11]. The PMMA samples were tested with an initial impact velocity of 1 m/s.

Fig. 3 shows typical load and deflection signals versus time. The load-time curve exhibits oscillations which can be interpreted as a consequence of a complex interaction between anvil, tup, and specimen during the fracture process. In contrast, the specimen deflection versus time remains quasi linear. The first peak of the load curve is the inertial peak resulting from the rigid body acceleration of the specimen and is generally distinguished from the following oscillations [12]. Loss of contact between the tup and the specimen may occur at the end of the inertial peak. Thereafter, the tup regains contact and the applied load increases. This is confirmed in Fig. 3 which indicates that the specimen deflection begins to increase at the end of the inertial peak.

Fig. 3: Load and deflection curves versus time ($a/W = 0.28$) recorded during impact testing of a PMMA sample with an impact velocity of 1 m/s.

Evaluation of the stress intensity factor requires the value of the specimen compliance. In Table I values of PMMA specimen compliance estimated with equations (3) and (6) are tabulated for various values of $a/W$.

As is made clear in Table 1, ignoring the shearing effect leads to underestimate the compliance of the specimens. This is confirmed by the evaluation of compliance with the help of force-deflection curves recorded during low blow tests as plotted in Fig. 4; the value of the related compliance is greater than that given by Eq. (3).
Table 1: Values of PMMA specimen compliance.

<table>
<thead>
<tr>
<th>a/W</th>
<th>0</th>
<th>0.1</th>
<th>0.2</th>
<th>0.3</th>
<th>0.4</th>
<th>0.5</th>
<th>0.6</th>
<th>0.7</th>
</tr>
</thead>
<tbody>
<tr>
<td>C *10^{-9} (m/N)</td>
<td>448</td>
<td>473.2</td>
<td>544.6</td>
<td>667.8</td>
<td>874.6</td>
<td>1263.3</td>
<td>1925.6</td>
<td>3445</td>
</tr>
<tr>
<td>C_{eff} *10^{-9} (m/N)</td>
<td>538.2</td>
<td>568.5</td>
<td>649.4</td>
<td>786.4</td>
<td>1010.5</td>
<td>1394</td>
<td>2110.7</td>
<td>3666.3</td>
</tr>
<tr>
<td>E_{eff} (GPa)</td>
<td>4.33</td>
<td>4.47</td>
<td>4.61</td>
<td>4.73</td>
<td>4.85</td>
<td>4.95</td>
<td>5.04</td>
<td>5.11</td>
</tr>
</tbody>
</table>

**Fig. 4**: Determination of a PMMA specimen compliance by low blow test. The slope of the curve provides the specimen compliance: \( C = 768 \times 10^{-9} \text{ m/N} \)

Lastly, Fig. 5 depicts graphically the critical deflections and the corresponding critical values of dynamic fracture toughness for various ratios \( a/W \). As expected, the parameter \( K_{Id} \) remains approximately constant versus the initial crack length. The evaluated dynamic fracture toughness of PMMA is \( 3 \pm 0.25 \text{ MPa} \cdot \text{m} \) which is in agreement with results reported elsewhere (between 2 and 3 MPa \cdot m) \([8, 11, 13, 14]\). In contrast, using a similar static calibration and the maximum of the load signal recorded by the instrumented tup leads to an overestimated value of \( K_{Id} \): equation (7) gives \( K_{Id} = 4.10 \text{ MPa} \cdot \text{m} \) for the test presented in Fig. 3 since equation (1) gives \( K_{Id} = 2.8 \text{ MPa} \cdot \text{m} \).

\[
K_{Id} = \frac{3}{2} \frac{S}{B} \frac{v^{-\frac{2}{3}}}{W} Y_{W} \frac{\alpha}{W} F_{\text{max}}
\]

(7)

4. CONCLUSION

The experimental procedure that is being developed uses a CHARPY instrumented tester to determine the dynamic fracture toughness. Deflection of the specimens during testing is evaluated with the help of a non-contacting displacement transducer. Such deflection-time curves are linear and do not exhibit the oscillating behaviour of the load-time curves recorded by the gage instrumented tup. Deflection at fracture initiation is detected by the sudden change of the load-time response of the specimen and a static calibration allows the determination of the fracture toughness. Experimental results obtained with PMMA samples show that the approach is reliable and simple. Nevertheless, it must be pointed out that the quasi-static
analysis restricts the impact velocity. Test method for the determination of fracture toughness of brittle materials at high strain rates of loading has still to be established.

Fig. 5: Critical deflection and toughness values for PMMA samples under dynamic loading (initial impact velocity: 1 m/s)

ACKNOWLEDGEMENTS

The authors wish to thank J-M. Robert for his technical assistance in the design and realisation of the experimental system.

REFERENCES