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The Hopkinson pressure bar: an alternative to the instrumented pendulum for Charpy tests

C. RUIZ and R.A.W. MINES *

Department of Engineering Science, Oxford University, Parks Road, Oxford OX1 3PJ, UK

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Abstract

In the instrumented Charpy pendulum, strain gauges mounted on the hammer react to strain waves resulting from the impact against the specimen by providing a jagged strain-time trace. This is electronically filtered to provide a smooth curve taken to represent the variation with time of the load applied to the specimen. The Hopkinson pressure bar (HPB) described here provides an alternative method of testing that does not require electronic filtering and simplifies data collection and interpretation.

1. Introduction

The development of impact tests on notched bars that led to the standard Izod test in 1903 and to the Charpy test in 1916 is traced by Stanton and Batson [1]. Most of the early workers were concerned with the specimen dimensions and the notch shape and with the design of the testing machine but, even with the rudimentary instrumentation then available, they were able to measure the time to fracture and to correlate the impact velocity with fracture toughness. Much of the early interest in the effect of striking velocity and time to fracture seems to have waned by 1960, judging by the contributions to [2], by which time most of the effort was directed towards developing statistical correlations between service experience and transition temperatures [3]. One dissenting voice was that of Schnadt [4] who maintained that fracture toughness could only be assessed at two or more striking velocities in specimens with more severe notch tip conditions than the standard Charpy V. In all cases, the transition temperature was defined by measuring the impact energy absorbed, the percent shear failure or the lateral contraction of the specimen.

Interest in instrumented impact tests revived in the late '60s, as shown by [5,6] and [7] which were amongst the first of a long list of contributions to this subject, whose main conclusions were summarized and discussed at a meeting held by the Electric Power Research Institute in 1981 [8].

2. Derivation of fracture toughness from instrumented Charpy tests

The ASTM proposed standards [8,9] assume that quasi-static equilibrium, with negligible inertial forces prevails in the specimen. Only tests in which the time to failure is sufficient

* At present with the Department of Mechanical Engineering, Liverpool University, Liverpool, UK.

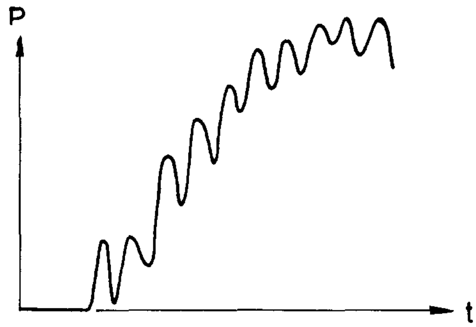

Figure 1. Typical elastic response in an instrumented Charpy test.

to allow multiple stress wave reflections at the supports to take place are considered to yield valid data. It is also required to use instrumentation with a sufficiently fast response and to ensure that the kinetic energy of the hammer is considerably in excess of the energy absorbed by the specimen. When these conditions are satisfied, the dynamic fracture toughness K_{Id} is derived from the static calibration and the estimated load at fracture, P_f. A typical elastic response is given in Fig. 1. It consists of a ramp with decaying inertial oscillations superimposed. A wide variety of forms of response, with varying number of oscillations, is found in the literature. It depends on the mechanics of the test, the impact velocity and the recording instrumentation. In practice, the $P(t)$ trace is considerably more complicated and electronic filtering becomes necessary. Figure 2 gives an example of the unfiltered $P(t)$ trace from a pendulum instrumented Charpy test and Fig. 3 gives the same trace filtered [10]. The specimen yields at A and hence the derivation of a J value may be considered appropriate for this test. (See for example [11].). The question is: are the oscillations in the $P(t)$ trace directly related to the applied load only or a result of the dynamic response of pendulum and instrumentation? Note that once the specimen has

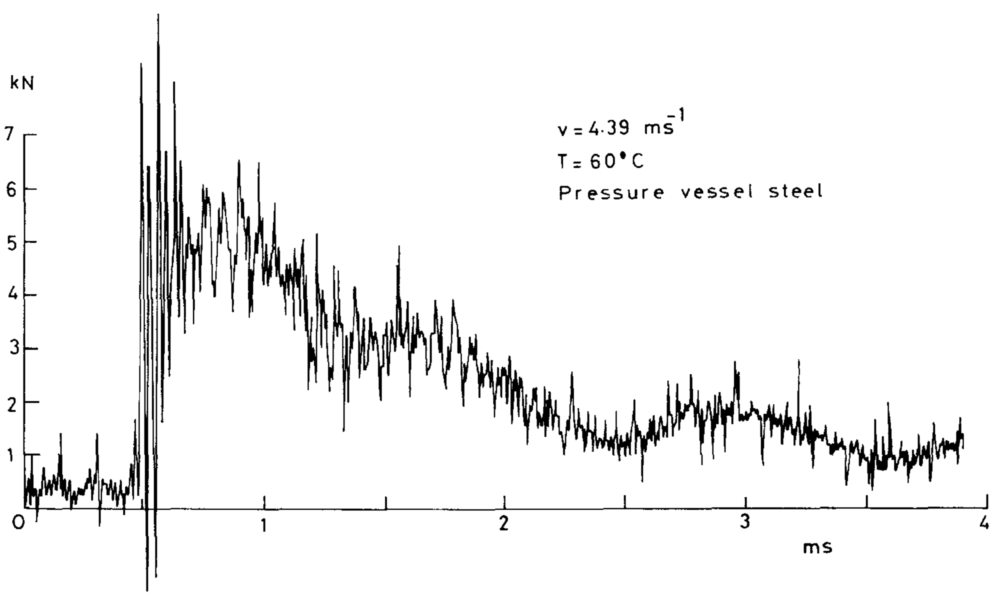

Figure 2. Unfiltered $P(t)$ trace from instrumented Charpy test.

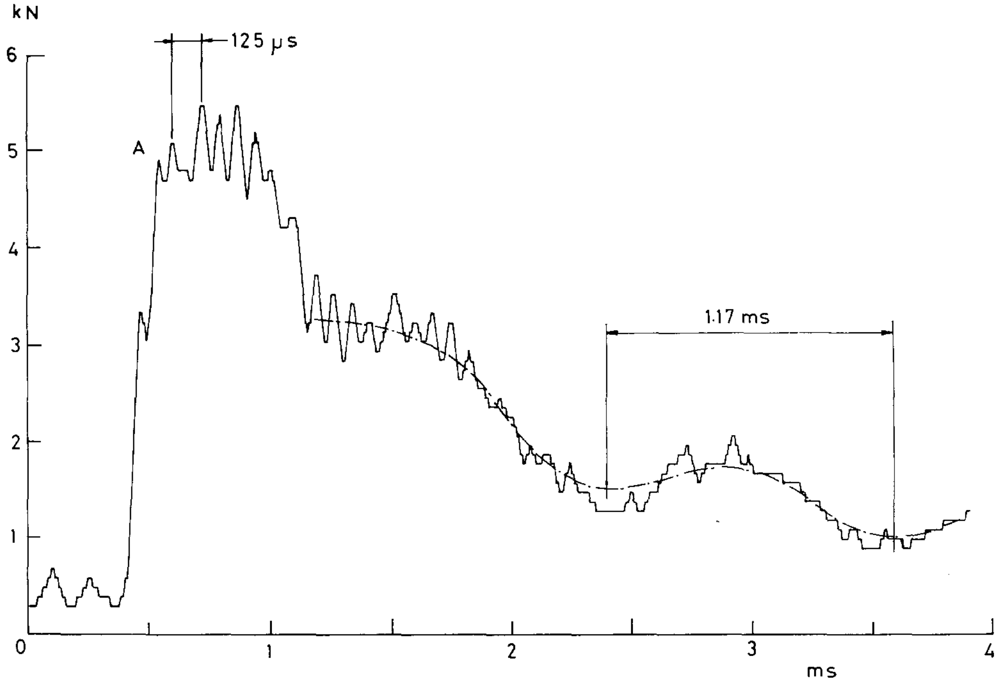

Figure 3. Filtered $P(t)$ trace from instrumented Charpy test.

broken there is "ringing" in the pendulum of a period approximately equal to 125 μs. The natural vibration period of the specimen, from Ireland's equation [12] is 45 μs. Thus, the coupling between the mechanical and electronic constituents of the system cannot be discounted in this case. The performance of the entire measurement system needs to be fully defined but even then the strain gauge on the impacting weight will only give a quasi-static load and any inertial or stress wave effects in the weight will influence results.

In any test it is assumed that the reduction in the velocity of the hammer is less than 20% to ensure that the response approaches that of a constant rate of deflection test. This is ensured by hitting the specimen with considerably more energy than the one absorbed in fracture.

Given the above criteria, it is assumed that the specimen fractures at the maximum load. Kalthoff et al. [13] have shown that this is not necessarily the case, particularly for a very brittle material under high rate of loading.

Having defined the load at which the specimen fractures, it has to be related to the stress intensity at fracture. This is achieved by using a static compliance calibration function. Note that the load may still be oscillating at fracture – see Figs. 1, 3 – and hence the specimen is not exactly in a state of static equilibrium. The decay in the inertial oscillations is due to material damping, structural damping between surfaces in contact and possible non-linear effects in the system. Such a quasi-static analysis restricts the impact velocity and hence compromises the high strain rate that should be used to achieve brittle fracture in notch-tough materials.

3. The use of the Hopkinson pressure bar (HPB) in instrumented impact testing

Some of the difficulties that have been mentioned are avoided by means of the Hopkinson pressure bar apparatus, described in the schematic diagram of Fig. 4(a).

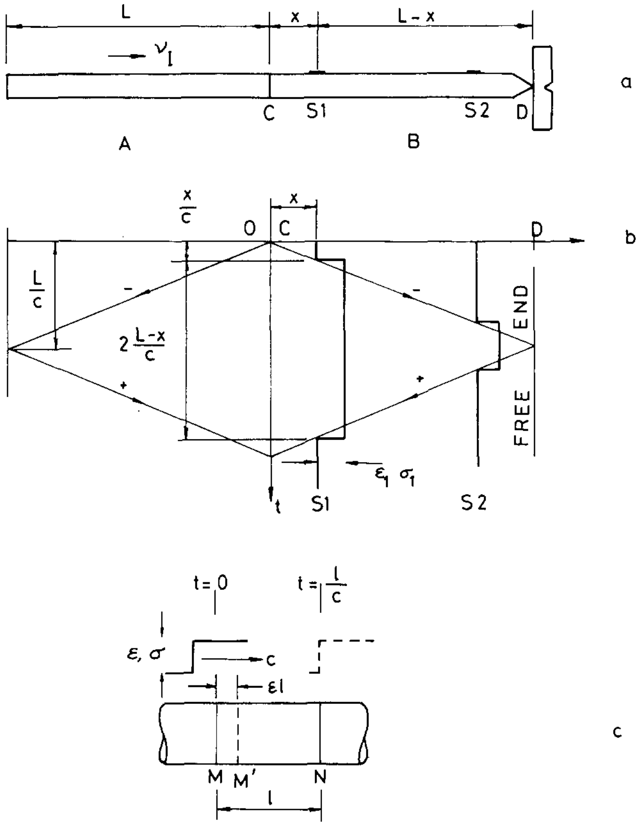

Figure 4. Diagram of the Hopkinson pressure bar apparatus, (a); Stress wave diagram, (b); Relationship between velocity (wave and particle) and stress or strain pulse amplitude, (c).

Impact bar A collides with bar B which is held stationary and in contact with the specimen. A one-dimensional system of compression waves emanates from the point of contact between the bars, C. In the absence of a specimen, the stress wave behaviour is illustrated in Fig. 4(b) in which "time" is represented along the vertical axis and "position" along the horizontal. A strain gauge S1 detects the arrival of a compression wave, travelling at,

$$c = \sqrt{\frac{E}{\rho}} \tag{1}$$

after

$$t_1 = \frac{x}{c}. \tag{2}$$

In the absence of a specimen, D is entirely free and the compression wave is reflected as a tension wave with the same amplitude and travelling from D to C at the same velocity as c. This wave will reach the strain gauge after,

$$t_2 = 2\frac{L-x}{c} \tag{3}$$

bringing the strain gauge signal back to zero. Strain gauge S2 will behave similarly.

Consider two positions M and N on one of the bars, Fig. 4(c). A stress pulse of amplitude σ, corresponding to a strain $\epsilon = \sigma/E$, travels with a wave velocity c past M at

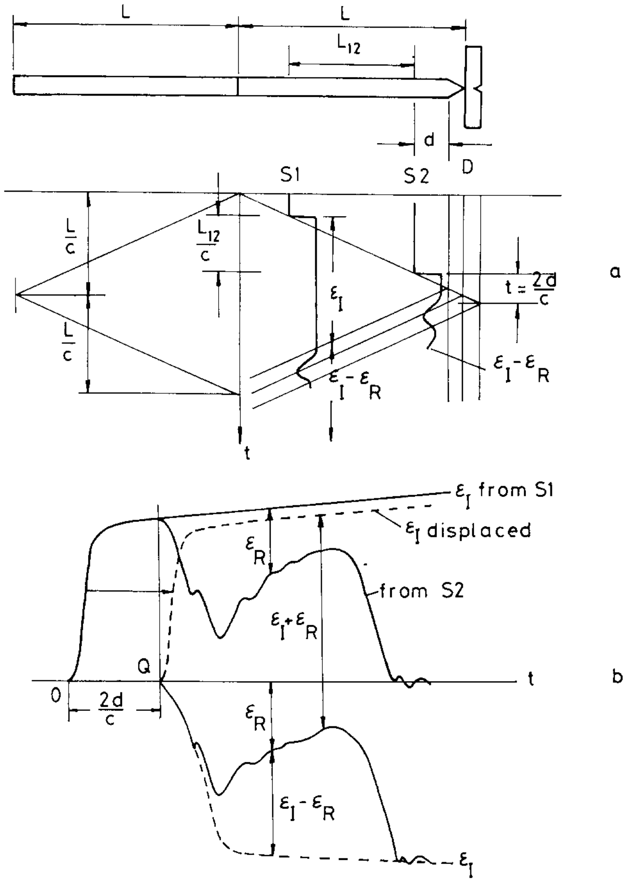

Figure 5. Stress wave diagram of HPB with specimen, (a); Construction of $P(t)$ and $\nu(t)$ curves, (b).

time $t = 0$, reaching N at $t = 1/c$. At that instant MN is under uniform compression σ, and M will have moved to M′ where,

$$MM' = \epsilon l$$

The velocity of M (particle velocity) is therefore,

$$\nu = \frac{\epsilon}{1/c} = \epsilon c \tag{4}$$

or, from (1)

$$\sigma = E\epsilon = \rho c \nu. \tag{5}$$

Equation (5) gives the relationship between stress or strain amplitude, wave velocity and particle velocity. At point C, the particle velocity upon impact is 1/2 of the impacting velocity, ν_I.

When the end of bar B is in contact with the specimen, Fig. 5(a), the stress wave passes S1 and S2 giving an incident signal ϵ_I as before, with a particle velocity ν_I. Strain gauge S2 then unloads due to the wave reflected not by the free end D, but by the specimen itself, and the reading of S2 becomes a combination of the incident pulse ϵ_I and of the reflected pulse ϵ_R. Thus, after a time

$$t = \frac{2d}{c}$$

where d is the distance from S2 to the conical transition of the loading bar, strain gauge S2 gives $(\epsilon_I + \epsilon_R)$ while S1 is still giving only ϵ_I. The reflected pulse ϵ_R can then be obtained by subtracting the two signals, (S2 − S1), displacing S1 by (L_{12}/c) to make it coincide with S2. The procedure is then as follows:

1. store traces S1 and S2 in transient recorders.
2. displace S1 by (L_{12}/c). The difference between the two traces is ϵ_R.
3. displace S1 by an additional $(2d/c)$, so that its origin coincides with Q. and invert the trace. This permits the determination of the particle velocity at D and of the force applied to the specimen, $P(t)$, since,

$$P(t) = AE(\epsilon_I - \epsilon_R)$$

$$v = c(\epsilon_I + \epsilon_R).$$

Integrating $v(t)$ one obtains the specimen deflection $\delta(t)$.

The above assumes one-dimensional wave behaviour. This breaks down over the tapering part of the pointer, which has a length of 25 mm equivalent to a time error of 10 μs. Values of $P(t)$ and $v(t)$ are therefore suspect below that limit.

4. Results using the HPB apparatus and comparison with instrumented pendulum

Figure 6 reproduces raw data – signals from strain gauges S1 and S2 – for the same pressure vessel steel of Figs. 2 and 3, tested at the same temperature, in a HPB of $L = 1$ m. The jagged peaks that appear in the unfiltered trace – Fig. 2 – are absent in Fig. 6, although no electronic filtering has been introduced in the HPB instrumentation consisting of:

Strain gauges −120 ohm, epoxy backed foil.

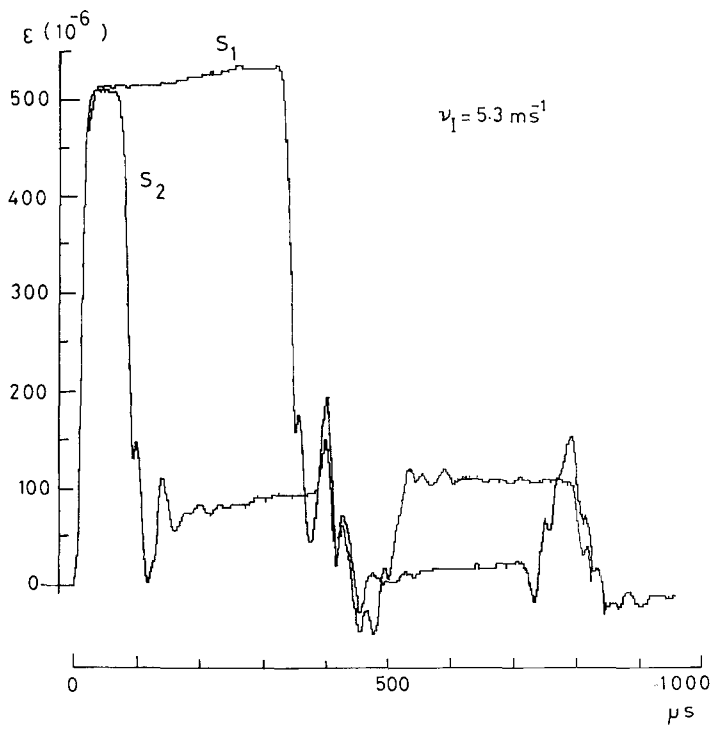

Figure 6. Raw data from strain gauges S1 and S2 in 1 m. long HPB apparatus.

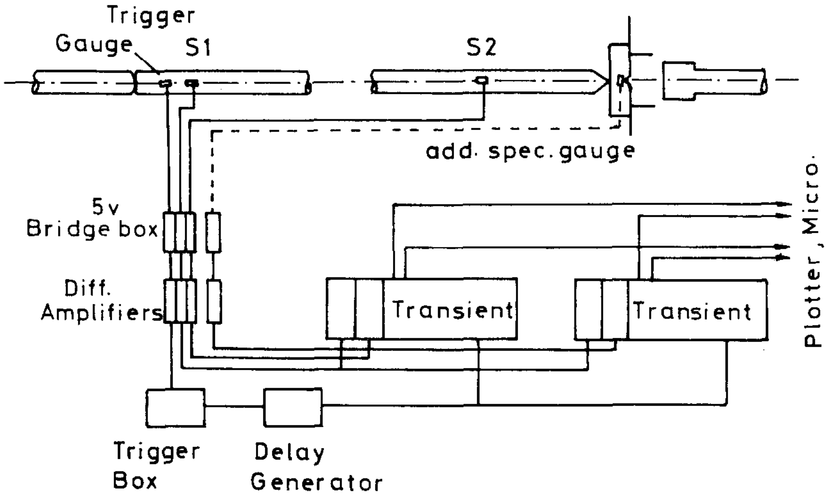

Figure 7. Diagram of HPB apparatus and instrumentation.

Amplifier - gain of ×100, frequency response 100 kHz, unfiltered.
Transient recorder - frequency response 6 MHz, 20 MHz conversion rate analogue to digital.

The apparatus and instrumentation are described in the diagram of Fig. 7.

The complex interaction between hammer, specimen and supports in the instrumented pendulum has been studied by Kalthoff [13] amongst others. The specimen response depends on the testing conditions and the dynamic characteristics of the system as a whole and results may be affected by bouncing of specimen against supports. In a conventional pendulum testing machine, the strain gauges, mounted in the hammer, near to the striking edge, respond to the complex stress waves set up on impact as well as to the load applied to the specimen. The jagged appearance of the trace in Fig. 2 is thus not only due to electronic noise but also to the changing stress wave pattern in the hammer. In contrast, the HPB apparatus delivers a clean blow and the results can be easily processed to give both the load and the specimen deflection at any given time.

To comply with the ASTM proposal, the frequency response of the electronic instrumentation should be sufficient to ensure that the time to failure exceeds the response time of the instrumentation by at least 10%. That response time, T_R, is defined from the equation,

$$T_R = 0.35/f_{0.915}$$

where $f_{0.915}$ is the frequency at 0.915 dB (10% attenuation). For the system used in the HPB, T_R was found to be in the order of 10 μs.

The processing of the raw data of Fig. 6 is best done by microcomputer. Figures 8(a) and (b) show how it can also be done following the graphical construction described in Fig. 6. In the HPB used, the cross sectional area of the loading bar was 283 mm^2 and with Young's modulus equal to 210 GPa and a density 7850 kg m^{-3},

$$P = 59.5 \times 10^3(\epsilon_I - \epsilon_R) \text{ kN}$$

$$V = 5.1 \times 10^3(\epsilon_I + \epsilon_R) \text{ ms}^{-1}.$$

It is interesting to note that the $P(t)$ trace peaks as the $v(t)$ dips and vice versa. For comparison with the instrumented pendulum, the trace from Fig. 3 has been superimposed on the HPB result. The first and last peaks are smoothed out by filtering the instrumented

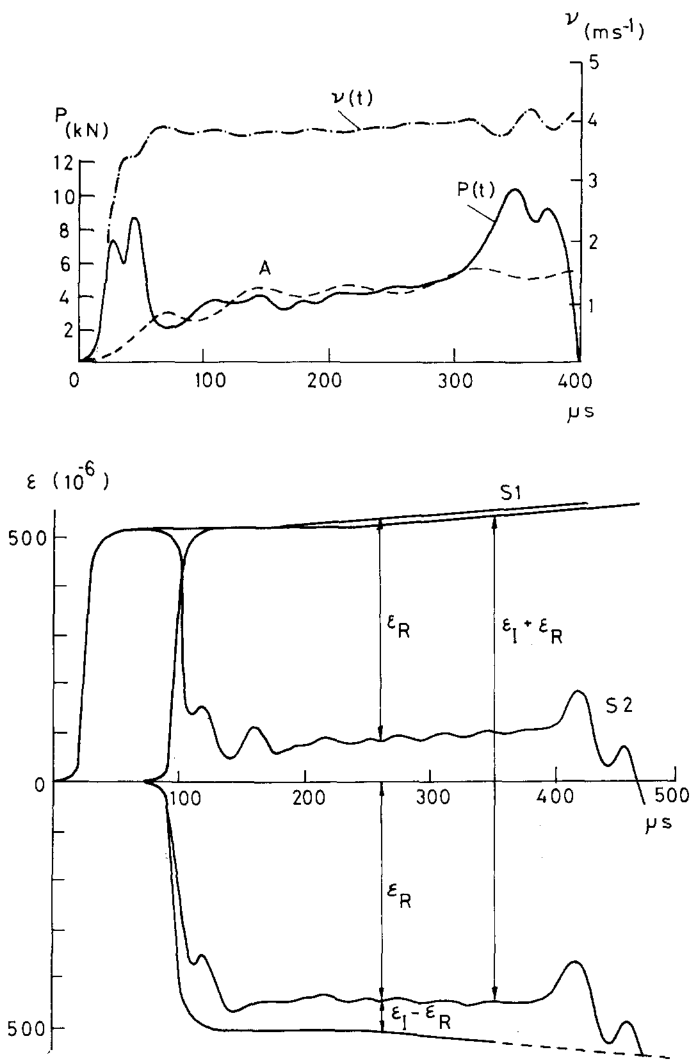

Figure 8. Application of graphical construction to the interpretation of the raw data of Fig. 6, (a) strain curves; (b) resulting $P(r)$ and $\nu(t)$.

pendulum, thus missing potentially valuable information. The first peak occurs very shortly after impact, before flexural stress wave action has time to fully transfer the impact load to the ends of the specimen [14]. The compression stress waves set upon impact are reflected on the back face of the specimen and diffracted at the crack tip within a few microseconds. A dynamic calibration is necessary to determine stress intensities from the $P(t)$ trace before stationary waves set in, i.e., within the first 50–100 μs after impact. At point A in Figs. 3 and 8(b) it may be possible to use the static calibration with adequate accuracy.

5. Conclusions

The assessment of fracture toughness from Charpy specimens, precracked or not, presents a problem that remains unresolved in spite of its obvious industrial interest. In an instrumented pendulum, the strain gauge used to provide a measure of the force applied to the specimen responds to complex strain waves giving a jagged strain-time trace that requires electronic filtering before it can be interpreted in terms of force-time. The amount of filtering has to be carefully balanced to smooth the signal without losing those peaks that may be important in determining the true load felt by the specimen. A further problem rises when relating the load to the stress intensity at the tip of the notch or the crack in precracked Charpy specimens, in that the static calibration that is normally used is only valid when the load is applied as a slowly rising ramp and the time to fracture is long, in comparison with the time taken for flexural waves to travel from the point of impact to the end supports. The HPB apparatus overcomes the first practical difficulty and, by providing a well defined implusive load it facilitates the interpretation of the experimental results. Its main advantages are:

- the load $P(t)$ is applied to the specimen for a duration of 350 μs, depending on the length of the two bars. It is accurately measured by the strain gauges.
- fracture occurs before the stress waves are reflected at the free ends of the bars and therefore a simple one-dimensional wave analysis is sufficient to characterise the dynamic behaviour of the system.
- the specimen deflection can be derived. It is therefore possible to obtain the energy absorbed at any given time more accurately than with the conventional pendulum.
- since the load is maintained over a time exceeding the time to fracture, there is no bouncing of the specimen on its anvil thus eliminating a source of non-linear behaviour.

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Résumé

Dans un mouton pendule Charpy instrumenté, les jauges de contrainte disposées sur le marteau réagissent à l'onde de déformation provenant de l'impact sur l'éprouvette en produisant une trace irrégulière sur un graphe déformation/temps. Un filtrage électronique permet d'obtenir une courbe régulière, que l'on adopte pour représenter la variation dans le temps ou la charge appliquée à l'éprouvette. Le dispositif HPB présenté dans l'étude constitue une autre méthode d'essai, qui ne nécessite pas de filtrage électronique, et qui simplifie la collecte et l'interprétation des données expérimentales.