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AN EVALUATION OF THE RELIABILITY OF INSTRUMENTED CHARPY TEST RE--ETC(U)
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TECHNICAL NOTE

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R. C. Barnes

MELBOURNE

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ABSTRACT

The shortcomings of various experimental techniques associated with the production of reliable instrumented Charpy test records are examined for the case of materials which show substantial ductility prior to fracture. A simple procedure for calibration and testing which avoids these problems and has direct relevance to fracture toughness properties is discussed.

CONTENTS

* * * *

AN EVALUATION OF THE RELIABILITY OF INSTRUMENTED CHARPY TEST RECORDS

1. INTRODUCTION

Dynamic tests such as the Charpy impact test yield information regarding the energy absorbed in breaking the test piece. This approach is useful in comparing materials but gives virtually no information regarding intrinsic properties of the material such as fracture toughness. To gain more information regarding these material properties and, to some extent, the operative state of stress, the machine may be instrumented to produce dynamic measurements of load as a function of either time or deflection of the test piece. Numerous investigations (1-11,16) have been carried out using this approach, but in the majority of cases no real attempt has been made to report either the accuracy or the significance of the measurements.

The parameter used to determine the accuracy of the oscilloscope test record of force-deflection or force-time in most of these investigations is the energy absorbed during the test. Numerous investigators (1,5,7,14,16) have produced data showing varying degrees of correlation between energy absorbed by the machine and the area under the recorded load-time curve. For the latter determination either a uniform decrease in velocity during impact is postulated or a constant velocity during impact is assumed; a correction is then applied to the resultant energy.

More recently, load-deflection data has been produced directly using capacitive (4,5,7) and optical (3,7,10) principles to produce the deflection measurement. Once again, the energy correlation has been the factor used to measure the accuracy of the test record.

This paper will examine the shortcomings of these approaches and will attempt to establish a more applicable framework in which reliable interpretation of instrumented Charpy test records can be carried out.

The interpretation of these records will be discussed in a subsequent communication.

2. THE ENERGY CORRELATION

As previously mentioned, in most of the published work the accuracy of the test record is checked by comparing the impact machine reading of the energy absorbed during the test with that derived from the area under the recorded load-time or load displacement diagram. Agreement between the two is commonly within 10% (10,11) although accuracies ranging from complete agreement (1,4,7,8) to errors of the order of 30% (5,7,10,16) have been claimed for given energy levels. The correlation depends on the level of the energy absorbed.

It is known however, that energy is absorbed by means other than by fracturing the test pieces (12,13,15) such as by the test piece supports, the machine foundation and framework, translation of the broken parts of the test piece, the pendulum and striker, and drag in the case of a partially broken test piece. With the exception of the striker and pendulum, no allowance is made for this energy absorption since no suitable techniques exist for measuring either the total or constituent parts of this loss. Thus inherent in the energy correlation approach is an error of unknown magnitude, because the amounts of energy lost through many of the above mechanisms are variable.

In "C" type pendulum machines jamming readily occurs when testing low energy absorbing materials i.e. < 7 J. At the higher energy absorption levels, the broken halves of the test piece rebound into the swinging pendulum thus removing energy from the pendulum. This energy loss is not "seen" by the instrumented striker but it is erroneously included in the machine indicated energy (12,13). At higher energy levels, the machine-indicated energy values may be in error by up to 15% (at low energy absorption levels, this error may be several hundred per cent).

The very subjective nature of the method used to measure the areas under the test records (planimetering) can introduce large variations in estimates of energy for the same record. Errors can be accentuated if the operator averages arbitrarily the high frequency oscillations often present on the curves or worse still tries to compensate for slight errors in the measurements such as when the oscilloscope trace passes below the zero load ordinate. This problem becomes critical in the low energy absorption range due to the high frequency oscillations which predominate in this portion of the test record. The nature of these oscillations is of major significance in the case of brittle materials where interest lies in measuring dynamic fracture loads and toughness.

3. THE DERIVED ENERGY

The energy absorbed in the impact test may be derived from the area under the load-time or load-displacement curve.

(a) Energy Derived from Load-Time Curves

The energy absorbed may be arrived at by measuring the area under the curve and assuming a constant velocity. The error arising from this assumption may be allowed for by applying the following correction (1) :

$$E = E_t \left(1 - \frac{E_t}{4\,E_o} \right)$$

where E is corrected energy

E_t is derived energy

E_o is initial energy of striker

Alternatively, since the absorbed energy is directly related to the difference between the original and final velocity of the striker (assuming none of the previously mentioned losses occur) and since this change in velocity is proportional to the reaction force, the absorbed energy can be determined by integration of the load-time curve and using the following equation (11) :

$$E = \frac{1}{2}\,mV_o^2 - \frac{1}{2}\,m \left(V - \int_o^t \frac{F\,dt}{m} \right)^2$$

where E is absorbed energy

m is mass of pendulum,

V_o is velocity of pendulum before impact,

V is velocity of pendulum after impact,

F is the force on the striker and t is time.

(b) Energy Derived from Load-Deflection Curves

Theoretically, the energy is easily obtained by measuring the area under the curve without applying any corrections. However, with some methods of measurement, as will be shown, this approach may provide no better accuracy than the load-time derived energy.

4. THE LOAD MEASUREMENT

The load is usually measured using strain gauges attached to either the striker or the anvils, or less frequently by instrumentation of the test piece itself.

It has been shown (17) than anvil instrumentation produces a load response which lags striker instrumentation by 3.2 rad. This means that anvil instrumentation does not have the necessary sensitivity to record transient signals such as the fracture profile of a brittle material. This precludes the use of instrumented anvils.

The static calibration of the strain gauged striker has been well documented by Eberhardt (4), Radon and Turner (3); however, the relevance of this calibration with respect to the dynamic test situation has only been assumed. To overcome the problem, tension and bend tests were carried out over a range of strain rates as detailed in Annex A using aluminium alloy 2024-T4, a relatively strain-rate-insensitive material. The results of these tests provide a link between the static calibration, as described elsewhere (4), and the dynamic test situation so that some degree of confidence can be maintained as to the validity of the loads measured dynamically for non-brittle materials.

5. DISPLACEMENT MEASUREMENT

A number of displacement measuring systems have been developed (3,4,5, 7,10) but, as shown below, none have been able to give more than an approximation of the actual displacement during any given interval of time in the impact test. These systems involve either :

(i) Optical displacement measuring systems which utilise one of the following two general arrangements :

(a) light source - moving mirror - photocell system,

(b) light source - moving light blanking arrangement - photocell system.

In the first system a point light source is moved across a sensor and moves proportional to the displacement of the pendulum, whereas in the second system a sensor is exposed to a varying proportion of light source by a moving light blanking arrangement attached to the pendulum. Each of these optical systems is subject to errors which, as the energy absorbed by the test piece drops, become progressively worse. General sources of error for type (a) systems arise from vibration of the pendulum and non-uniformity of light source. In type (b) systems, the added problem of light reflection from other parts of the machine reduces accuracy.

(ii) Variable resistance systems, in which a wiper moves on a slide wire potentiometer, are accurate providing no rapid decelerations occur due to impulse loads. Unfortunately, during impact tests this is precisely what does occur. Large errors are introduced during deceleration by vibration both in the plane of swing of the pendulum and transverse to that plane. These vibrations result in loss of contact between the pendulum wiper and the slide wire potentiometer.

(iii) Capacitive systems are also subject to error due largely to limitations in electronic instrumentation as detailed below.

The capacitive displacement measuring system (4) employs an a.c. capacitance bridge with a carrier frequency of 25 kHz. The signal is rectified and filtered to provide the displacement measurement which is displayed on the oscilloscope. The response of this output amplifier/ filter combination is shown in Figure 1.

It can be seen that an error will be caused by filtering of the carrier frequency because the frequency of the displacement signal is of a similar level. Furthermore, the cutoff for the filter is generally specified at 3 dB attenuation which effectively means :

$$\text{volts out} = 0.7 \text{ volts in}$$

That is, a 30% reduction in signal at 5 kHz (in this case). This reduction will increase markedly with increase in frequency.

Thus by using an output amplifier/filter combination of the type shown, test signals will be greatly attenuated as they fall well within the band of influence of the filter. This problem may be overcome by using a carrier frequency substantially greater than signal frequencies likely to be encountered (say 500 kHz).

Aspects of electromechanical interactions which may occur and influence the test data were examined experimentally in Annex B. Using a variable resistance displacement measuring system in conjunction with the capacitive system (4), velocity sensitivity was measured. The effect of vibration on the capacitive displacement measurement was also considered. Results indicate that the present system (4) is subject to velocity errors and is sensitive to lateral vibration.

6. DISCUSSION

There are potentially numerous sources of error in the instrumented impact test record which may be disguised if energy is used as the criterion for assessing accuracy of the test record. The correlation between the test record and the machine energy is not appropriate since the data most likely to be used in fracture toughness measurements is the load at fracture and, to a lesser extent displacement. Due to the subjective nature of the techniques used to assess area under the load-time or displacement curves, this measure of accuracy is open to doubt. Secondly, when deriving energy from the load-time curve, an exact displacement at any given time during the impact cannot be obtained due to the assumption of constant velocity used in the derivation. Thirdly, not all the energy lost by the pendulum is 'seen' by the instrumented striker, therefore one would expect a degree of scatter and mismatch in indicated energy absorbed and energy derived from the instrumented test record.

The use of a strain-gauged striker as the force measuring sensor has been verified dynamically for non-brittle fracture without recourse to absorbed energy measurements for correlation. Other calibration procedures of a semi-dynamic nature which involve removal of the striker from the impact machine, appreciably change the conditions under which the loads are applied and therefore cannot be considered to have the same direct applicability.

It has been shown elsewhere (10) that there are many problems associated with recording displacements using photoelectric and electrical resistance techniques. It is shown here that the capacitance technique for the measurement of displacement may also be erroneous and that commercially available instrumentation may require considerable modification if it is to function without the problem of velocity sensitivity.

Thus, for fracture toughness applications, load-time measurements present the most economic and reliable method of instrumentation to date.

7. CONCLUSIONS

The use of energy absorbed in the Charpy impact test as a measure of accuracy of the load-time (or load-deflection) diagram has been shown to be inaccurate.

The accuracy of the load measuring system has been verified dynamically for non-brittle fracture using a simple procedure.

The accuracy of data obtained from the various striker displacement measuring systems is shown to be questionable.

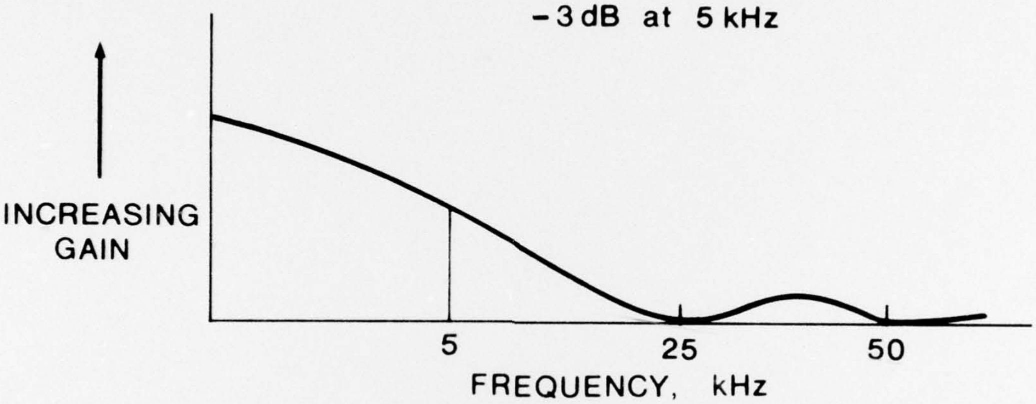

FIG. 1 - Response curve of output amplifier/filter combination.

ANNEX A

VERIFICATION OF THE DYNAMIC LOAD MEASUREMENT

The following tests were carried out using aluminium alloy 2024-T4, a relatively strain-rate-insensitive material. The strain-rate-insensitivity was first established by carrying out conventional tensile tests and instrumented impact tension tests (see Table 1). In the latter test the load-time curve precluded yield loads being measured. However, in this case, where some ductility existed, a reliable measurement of the maximum load was made. These results indicate that, for the purposes of the experiment, the material was strain rate insensitive. Static and dynamic bend tests on notched and unnotched Charpy test pieces of 2024-T4 aluminium alloy were also made. The "V" notch was 1.5 mm deep. A typical load-time oscilloscope record of an unnotched bend specimen during impact is shown in Figure A1.

The results are given in Table A2 and indicate that, within the accuracy of the recording instrumentation, there is no significant difference in the maximum loads measured using the instrumented striker and independent test rig built to the exact dimensions of a Charpy impact test machine used for the lower strain rate tests.

These results support the use of a static force calibration (4) for load measurement in the dynamic test situation. The problem of frequency response due to the very short rise time of the impact force was overcome by using a d.c. bridge for the measurement of load.

TABLE A1

TENSILE PROPERTIES OF 2024-T4 ALUMINIUM ALLOY AT VARYING STRAIN RATES

Displacement Rate mm/s	Ultimate Tensile Strength MPa	Reduction in Area %
2×10^{-2}	503	21
5×10^{1}	501	20
5×10^{3}	506	22

TABLE A2

MAXIMUM LOADS MEASURED DURING BEND TESTS ON NOTCHED AND UNNOTCHED 2024-T4 ALUMINIUM ALLOY

Displacement Rate mm/s	Unnotched Beam Max. load kN	"V" Notched Max. load kN
2×10^{-2}	16.0	8.9
5×10^{3}	15.8	8.9

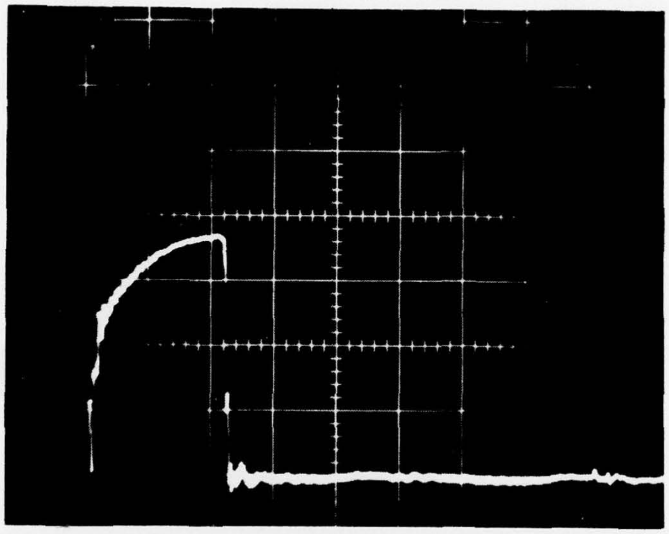

FIG. A1 - Typical load-time record of unnotched impact bend test on 2024-T4 aluminium alloy. Loading rate 5 x 10 ^{3} mm/s

ANNEX B

ELECTROMECHANICAL INTERACTIONS IN CAPACITIVE DISPLACEMENT MEASUREMENT

Using a capacitive displacement system described elsewhere (4), the following experiment was carried out to establish the validity of the displacement measurement. A wiper was attached to the striker and a single slide wire potentiometer was attached to the machine base plate. The displacements measured by the slide wire potentiometer and capacitor circuits were fed into the vertical and horizontal channels of an oscilloscope. At low velocities, no separation occurred between forward and reverse swings of the pendulum. However, at normal impact velocity, 5×10^3 mm/s, a lag of 0.5 mm occurred. With a smoothing filter in the capacitive circuit this lag increased to 1.1 mm but without a smoothing filter in the capacitive circuit, the displacement signal measured in an actual test was too noisy for displacement measurements and thus could not be used for assessing the lower energy absorbing materials in instrumented impact tests as shown in the oscilloscope trace in Figure B1.

The apparent "reverse" displacements shown here are the result of the rapid deceleration, as discussed, and of transverse vibrations which manifest themselves as apparent changes in displacement. Transverse vibrations of the pendulum are introduced by a lack of geometry in the system which results from allowed tolerances in test piece alignment and the mode of failure of the test piece. Transverse vibrations introduce small, but measurable, changes in partial capacitance in a vertically mounted measuring capacitor, which are not completely eliminated by duplicating the electrode-earthed blade system.

It should be noted that the use of the variable resistance system in this manner where no impact occurs, i.e. at constant velocity, yields quite accurate displacement measurements for the reasons previously stated. Thus there is also a velocity-dependent error in the displacement measurement of the system.

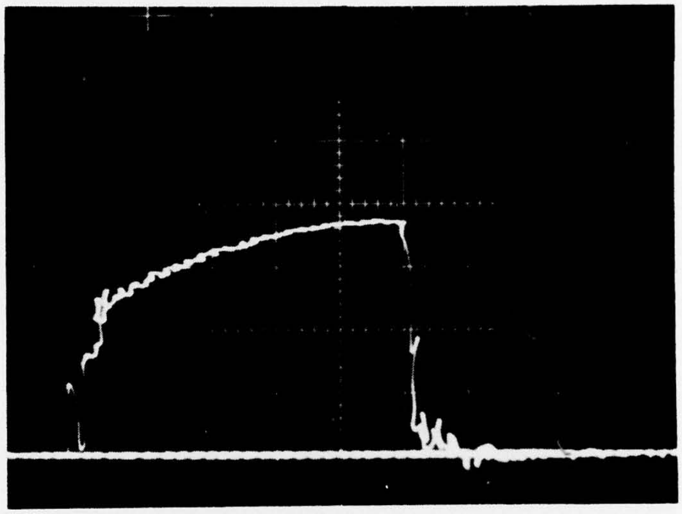

FIG. B1 - Typical record of unnotched impact bend test on 2024-T4 aluminium alloy using capacitive displacement measuring system without smoothing filter. Rate 5 x 10^3 mm/s (load-displacement).

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