DROP WEIGHT J-R CURVE TESTING USING THE KEY CURVE METHOD

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The Key Curve Method was developed by Ernst et.al.[1] as a method for determination of material J-R curves directly from fracture specimen load displacement records without the use of additional crack length measurement techniques. The method has been used previously by the present author on static specimens of A533B steel[2] and on high rate loading tests on HY130[3] and A533B[4] steel alloys. In the static cases the key curve method was shown to give J-R curves which agreed closely with J-R curves obtained by more conventional unloading compliance methods. The key curve method demonstrated an ability in all cases to accurately predict the extent of crack growth and yields a J corrected for crack growth and other test non linearities.[2] For static tests the complexity of the key curve method and the necessity of additional specimens in general negates many positive features, but for high rate tests the key curve method shows great promise for J-R curve determination.

The objective of the present test program has been to develop a capability to evaluate J-R curves from fracture mechanics specimens at test rates in the range of 100 in/sec. Methods being utilized are the multi specimen - stop block approach utilized by[6]; a potential drop crack length measurement technique; and the key curve method. In this report only the key curve method will be discussed.

EXPERIMENTAL DETAILS

The test machine utilized for these tests was a standard drop weight machine with an instrumented tup. A schematic of the specimen, transducers, and associated electronics is shown in Fig 1. The light probe displacement transducer is offset from the crack and load line by about .02L where L is the specimen length. Both displacement and load transducers had frequency responses in excess of 10kHz. The digital oscilloscope was connected via an instrumentation interface to a microcomputer for data transfer, storage, and analysis as described in the following section.

As shown in Fig 1 the light probe was inserted inside of a stop block apparatus of variable height which straddled the specimen in the center region to obtain a quick and distinct stop of the load tup. To keep the stop block load at reasonable levels additional stop blocks were placed at the sides of the apparatus shown which were hit by the drop weight at approximately the same instant as the load tup impacted its stop block fixture. This procedure required some experience but it was found possible to keep the load tup stopping loads to about 445 kN which was within the tup calibrated capacity.

The material used in this program was a medium strength alloy steel with tensile properties shown in Table 1 and the nominal chemistry shown in Table 2. In these tests the large scale specimens were 1T bend bars in accordance with the ASTM E399 and E561T fracture test methods. The subsize specimens were half scale or ½T specimens except that the notch tip radii were machined to <.07 mm radius rather than being fatigue cracks. The 1T specimens were tested with a drop weight velocity of 2.5 m/sec while the ½T specimens were tested at 1.25 m/sec.

Table 1. Tensile mechanical properties of test steel

Yield strength MPa	Tensile strength MPa	Elongation in 2 inches	RA %
941.0	994.0	19.5	62%

Table 2. Nominal chemisty of test steel

Center Code	Chemical Composition (Wt %)												
	C	Mn	P	Si	Ni	Cr	Mo	V	S	Cu	Al	Co	Ti
FTF	0.11	0.76	0.005	0.03	5.00	0.42	0.53	0.043	0.004	0.022	0.021	0.02	0.008

ANALYSIS

In the Ernst, et.al.[1] analysis, dimensional analysis is used to show that for simple geometries in which the plasticity is confined to the uncracked ligament region, the load displacement relationship must have the form:

$$\frac{PW}{Bb^2} = F1\left(\frac{\Delta}{W}, \frac{a}{W}, \frac{H}{W}, \text{material properties}\right) \qquad 1)$$

where P is applied load, Δ is total load line crack opening displacement, b = uncracked ligament, a is crack length, H = specimen height, W is a + b = specimen width, B = specimen thickness.

Starting from the deformation plasticity theory formula for the path independent J integral that[7]

$$J = \frac{-1}{W}\int_o^{\Delta}\left(\frac{\partial P}{\partial(a/W)}\right)_{\Delta} d\Delta \qquad 2)$$

an incremental formula for J can be obtained in terms of F1 giving

$$dJ = \left[\frac{2b}{W} F1 - \frac{b^2}{W^2}\frac{\partial F1}{\partial(a/W)}\right] d\Delta$$

$$+\left[\int_o^{\Delta} - \frac{2}{W} F1 d\Delta + \int_o^{\Delta} \frac{4b}{W^2}\frac{\partial F1}{\partial(a/W)} d\Delta + \int_o^{\Delta} \frac{b^2}{W^3}\frac{\partial^2 F1}{\partial(a/W)^2} d\Delta\right] da \qquad 3)$$

To evaluate J from an integral of Eqn 3 requires knowledge of the instantaneous crack length. This is obtained by Ernst in a differential form as:

$$da = \frac{\frac{b^2}{W^2}\frac{\partial F1}{\partial(\Delta/W)} d\Delta - dP}{\frac{2b}{W} F1 - \frac{b^2}{W^2}\frac{\partial F1}{\partial(a/W)}} \qquad 4)$$

Essentially if the load displacement record of the specimen under analysis is coincident with the key curve surface when evaluated using the initial flaw size no crack extension is predicted. If the load increment dP falls below that predicted by the key curve Eqn 4 estimates the corresponding increment of crack extension.

An alternating evaluation of Eqns (3) and (4) can thus be utilized to evaluate a J-R curve if the F1 function of Eqn (1) is available through analytical or experimental techniques.

For the special case that the key curve of Eqn 1 is independent of crack length Eqns (3) and (4) reduce to the following forms

$$dJ = \frac{2b}{W} F1 \, d\Delta + \int_{o}^{\Delta} \frac{-2}{W} F1 \, d\Delta \, da \qquad 5)$$

$$da = \frac{\frac{b^2}{W^2} \frac{\partial F1}{\partial(\Delta/W)} d\Delta - dP}{\frac{2b}{W} F1} \qquad 6)$$

These forms in fact are useful for the bend bar geometry as demonstrated in the following section.

KEY CURVE DEVELOPMENT

A typical load displacement record for a ½T specimen is shown in Fig 2 both before and after data smoothing. Clearly inertial oscillations are a problem for this geometry tested at a 1.25 m/sec loading rate. A fast Fourier transform scheme was used to numerically smooth the load time trace giving the smoothed load displacement curve shown and then a further correction was applied to remove a machine compliance component.

This process of smoothing and compliance correcting was applied in turn to each of six ½T bend specimens with a/W values of .4,.5,.55,.6,.65,.7. The resulting load displacement curves plotted in the key curve normalization are shown in Fig 3. A band of curves results with oscillations present which are apparently residuals of the smoothing process, material variability, and system noise. No apparent crack length dependence was found in these six results, in agreement with the predictions of Ernst et.al.[1] for the bend geometry. Because the a/W = 0.7 specimen (shown dashed) was so oscillatory, however, this result was not used in subsequent analysis, and the desired key curve was taken as a/W independent and an average of the five other specimen results.

The 1T specimens loaded at 2.5 m/sec also showed oscillatory behavior due apparently to inertial elastic vibrations, and since the frequency of the transients was closer to the overall test frequency these oscillations were somewhat harder to smooth. Nonetheless it was done here in a fashion similar to that used on the subsize specimens. Plotting this result after key curve normalization using the initial remaining ligament dimension gives the result shown in Fig 5. Deviation between the two curves corresponds to a prediction of crack extension which can be evaluated by using Eqn (6) for each increment and accumulating a total crack extension. This process as well as that of calculating J by Eqn (5) were done by microprocessor and the resulting J-R curve is shown in Fig 5. A comparison is made on Fig 5 between two drop weight key curve results and three static results obtained on compact and bend specimens using an unloading compliance method[8].

Clearly these results are in close agreement and imply that this material is not rate sensitive within the range of rates used here.

The final J-R curves, as shown for instance in Fig 5, consist of J-Δa pairs estimated at 2×10^{-6} second intervals. Using this fact both dJ/dt and da/dt can easily be estimated by a numerical differentiation routine. The maximum crack velocity achieved in these tests was approximately 38 m/sec which is impressive but well below a true dynamic crack velocity. This is consistent with fractographic observations that all fracture surfaces in these tests remained fully ductile without even a hint of cleavage fracture. The dJ/dt applied was fairly constant beyond J_{Ic} at a value of 300 MPa•m/sec.

DROP WEIGHT TEARING INSTABILITY

As described under the experimental method the center stop block was used to hold the optical displacement transducer but also to stop the drop weight after specified specimen displacements had been accomplished. This was done so that a multispecimen type J-R curve could be obtained for comparison with the key curve result discussed above. This did not turn out to be possible for this material. Various stop block heights were utilized but only two types of results were obtained, the first with the specimen load rising or the second after the load had fallen to ≅25% of the maximum specimen load. Comparing the observed load displacement records of these specimens with the machine stiffness estimated in the previous section (that is values of approximately 87 MN/m) showed that for this material a ductile tearing instability was occurring as described and utilized earlier in static test situations[9,10]. Figure 6 shows a comparison of the test machine unloading relaxation versus the specimen load displacement curve which, following the lead of Ernst[1], predicts instability with this machine - specimen combination. Further work is needed to verify this observation but the tearing instability prediction of Fig 6 is consistent with the experimental observation that even slight extensions of the allowed bend displacement beyond maximum load (with a measured crack extension of ≅.13 mm) gave crack extensions of ≅ 12.7 mm.

CONCLUSIONS

The following conclusions have been drawn from this work:

1. The key curve technique can be applied to drop weight fracture tests though smoothing and compliance corrections necessitated by the present apparatus cause both difficulty and concern for overall accuracy.

2. The key curve obtained for the three point bend geometry is apparently crack length independent. This result has been predicted but has not been demonstrated by static tests.

3. The particular medium strength alloy steel tested here demonstrates no measurable toughness increase thru the range from static tests (.25 mm/min) to 2.5 m/sec drop weight tests.

4. All specimen tests were conducted on the ductile upper shelf with fully ductile fracture surfaces resulting. No cleavage fracture was observed on the fracture surfaces.

5. Crack velocities of up to 38 m/sec were obtained in these tests. An impressive value but far below that usually observed in dynamic elastic fractures (on the order of 250 m/sec).

6. Ductile tearing instability occurs for the alloy tested in a drop weight machine and this made impossible attempts to obtain a multiple specimen J-R curve from the tests for comparison with the key curve result.

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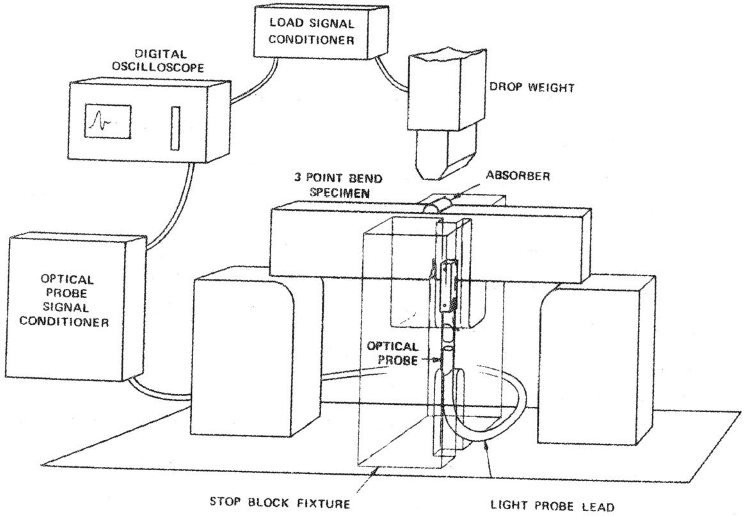

Figure 1. Schematic of drop weight specimen, transducers, and associated electronics.

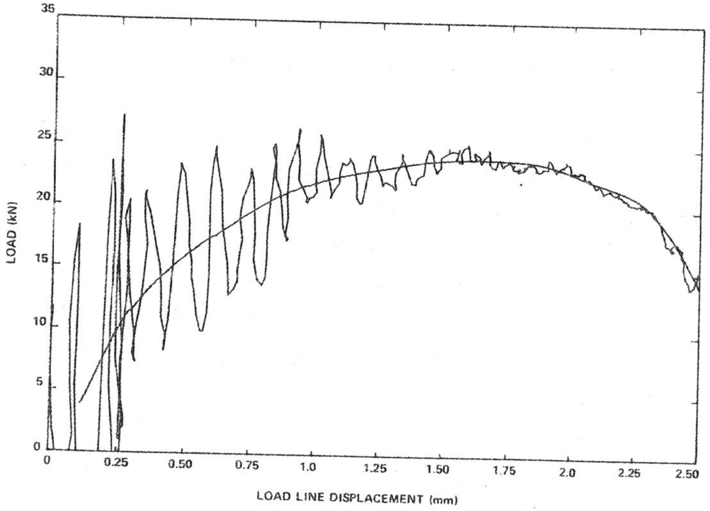

Figure 2. Load displacement record, smoothed and unsmoothed, for a ½T bend bar.

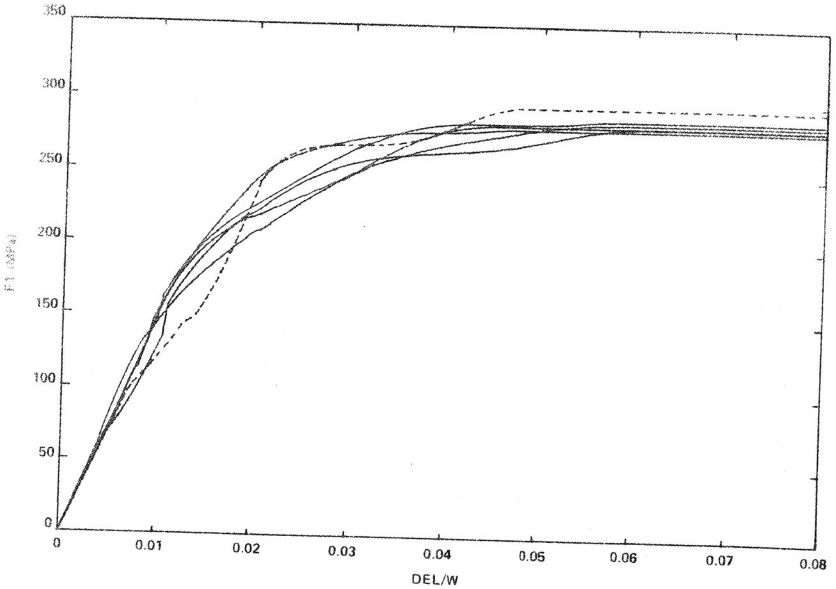

Figure 3. Key curve results from six ½T bend bards.

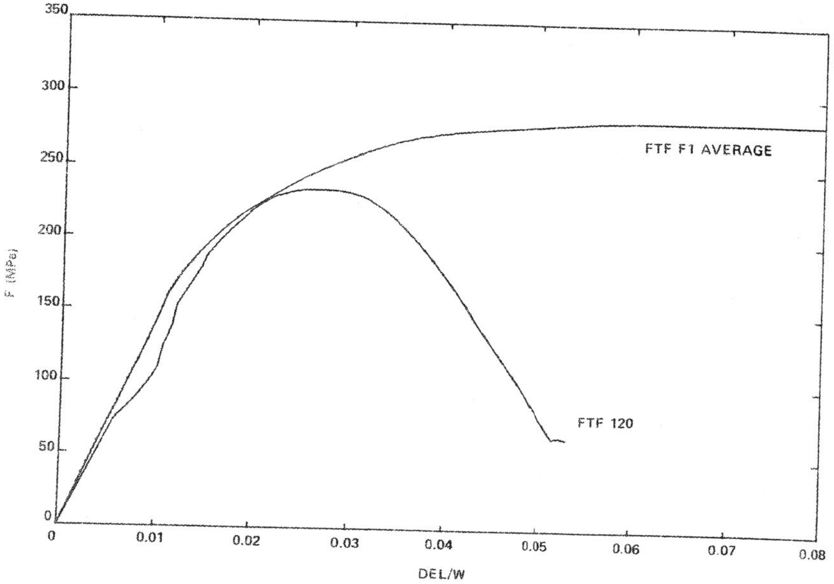

Figure 4. Key curves comparison of 1T and ½T specimens.

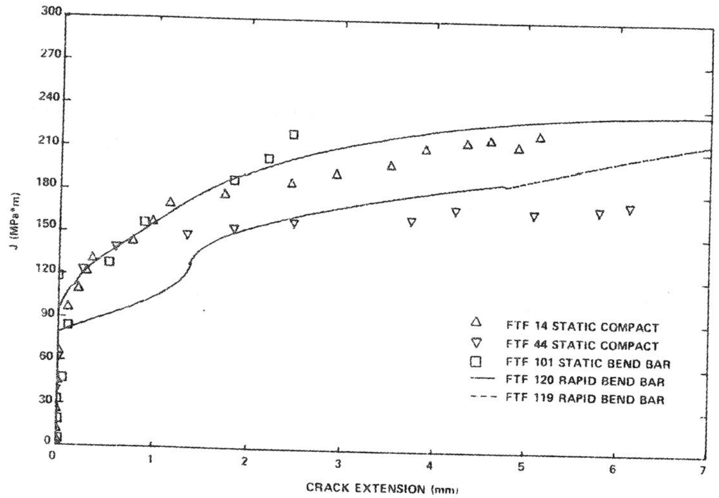

Figure 5. J-R curves from drop weight testing compared to static test results.

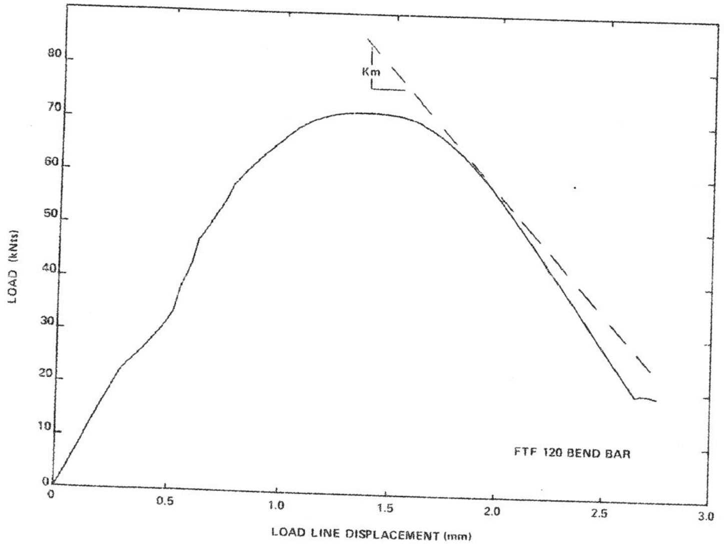

Figure 6. Load displacement plot of 1T specimen showing prediction of tearing instability beyond maximum load.