

MASTER

---

---

# Application of the Key Curve Method to Determining J-R Curves for A533 B Steel

---

---

Prepared by J. A. Joyce

U. S. Naval Academy

Prepared for  
U. S. Nuclear Regulatory  
Commission

## **DISCLAIMER**

**This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.**

---

## **DISCLAIMER**

**Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.**

NOTICE

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, or any of their employees, makes any warranty, expressed or implied, or assumes any legal liability or responsibility for any third party's use, or the results of such use, of any information, apparatus product or process disclosed in this report, or represents that its use by such third party would not infringe privately owned rights.

Available from

GPO Sales Program  
Division of Technical Information and Document Control  
U. S. Nuclear Regulatory Commission  
Washington, D. C. 20555

and

National Technical Information Service  
Springfield, Virginia 22161

# Application of the Key Curve Method to Determining J-R Curves for A 533 B Steel

---

Manuscript Completed: January 1980  
Date Published: February 1980

Prepared by  
J. A. Joyce

U. S. Naval Academy  
Annapolis, MD 21402

Prepared for  
Division of Reactor Safety Research  
Office of Nuclear Regulatory Research  
U.S. Nuclear Regulatory Commission  
Washington, D.C. 20555  
NRC FIN No. B7026



## CONTENTS

	PAGE
Acknowledgements	iv
Abstract	1
I. Objective	2
II. Background	3
III. Key Curve Function Development	8
III.1 Material	3
III.2 Testing	8
III.3 Key Curve Assembly	12
III.4 Discussion	13
IV. Discussion of the J-R Curve Evaluation Technique	16
V. Discussion of the Results	20
VI. Conclusions	39
References	40

## Acknowledgements

The author wishes to thank Dr. Pedro Albrecht of the University of Maryland and Mr. John P. Gudas of the David Taylor Naval Ship Research and Development Center in Annapolis for their comments and encouragement during the course of this work.

## Abstract

This report describes the experimental development of a key curve for compact specimens of A533B steel and the use of this experimental key curve to generate the J-Resistance curve directly from the load displacement records without obtaining crack length estimates from unloading compliance, ultrasonics, electric potential or other techniques. In fact two complete key curve functions were developed, the first using subsized fatigue precracked specimens, the second using subsized but machine notched specimens. In each case eight 1/2 T compact specimens with crack lengths from  $a/W = 0.5$  to 0.9 were used to generate a series of digital load displacement records which were assembled in a computer file as the key curve for geometrically similar compact specimens. This key curve can be thought of as defining the locus of load displacement records expected for geometrically similar compact specimens of this material for similar loading conditions if no crack extension were to take place. Deviations between the key curve function and the load displacement record for a particular specimen can then be attributed to crack extension and a calculation for the amount of crack extension can be made. The key curve also allows corrections to be made to J values to account for effects of this crack extension.

In this work J-Resistance curves (J-R curves) were obtained for 1T compact specimens directly from load displacement curves using the key curve formulation and compared with unloading compliance J-R curves obtained previously for the same specimens. Close agreement was found between the critical J values for crack initiation between the two methods. For each specimen the final crack length estimate obtained by the key curve method was found to agree well with the final value obtained by the unloading compliance result, but to fall short of a nine point average measurement for those specimens in which large crack tunneling occurred.

The crack growth correction to J determined by the key curve method agreed well with an approximate analysis for short cracked specimens but disagreed markedly for the deeper cracked specimens.

## I. Objective

The objective of this work was to demonstrate that the Key Curve Analysis technique of Ernst et.al.<sup>[1]</sup> as implemented by Joyce et.al.<sup>[2]</sup> on HY130 steel can be used to determine  $J_{IC}$  and J-Resistance curves (J-R curves) directly from the load displacement records of standard fracture mechanics compact specimens of A533B steel. The principle advantage of this technique is that determinations of crack length by unloading compliance, electrical potential measurements, ultrasonics or other techniques are not required, thus greatly simplifying the experimental test method. Additional advantages are that it frees the engineer from limitations on loading rate and eases limitations on test temperature and test environment. Additional geometrically similar subsize specimens are required, however, to develop the key curve.

This paper presents the methodology used to develop a key curve for a HSST-A533B-02 reactor pressure vessel steel using both precracked and blunt notched subsize compact tension specimens and the application of this key curve to the development of J-R curves for 1TCT specimens of this same material from load displacement records directly. A comparison of these results is then made to the unloading compliance J-R curves obtained previously and reported by Vassilaros, Joyce, and Gudas<sup>[3]</sup>. Specimen geometries with a/W ratios from 0.5 to 0.81 as well as side grooved specimens with total reductions of 10 and 20% where available to check the comparability of the key curve results and the unloading compliance results.

## II. Background

This paper is an extension of recent work by Ernst, et.al. [1] in which the authors show, among other things, that it is possible to construct J-R curves directly from load displacement records for simple specimen geometries if a "Key Curve Function" or "Calibration Function" is available for the material and specimen geometry.

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:

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

Where: P = applied load

$\Delta$  = total load line crack opening displacement

a = crack length

b = uncracked ligament

H = specimen height

W = a + b = specimen width

$\Delta$  = specimen height

It should be noted that in the work by Ernst et.al., [1]  $\Delta/W$  was separated into elastic and plastic parts and the resulting J and crack extension expressions had elastic and plastic contributions. This separation was done only as an analytical convenience. In this experimental work it is more convenient to use the total load line displacement.

Assuming here the applicability of deformation plasticity theory the

formula for the path independent  $J$  integral is given by:<sup>[4]</sup>

$$J = \frac{-1}{W} \int_0^{\Delta} \left( \frac{\partial P}{\partial(a/W)} \right)_{\Delta} d\Delta. \quad (2)$$

Substituting for  $P$  from Eq. (1) into Eq. (2) gives  $J$  as:

$$J = - \int_0^{\Delta} \left( \frac{b^2}{W^2} \frac{\partial F_1}{\partial(a/W)} - \frac{2b}{W} F_1 \right) d\Delta. \quad (3)$$

The differential of  $J$  can be written as

$$dJ = \frac{\partial J}{\partial \Delta} d\Delta + \frac{\partial J}{\partial a} da. \quad (4)$$

Now evaluating from Eq.(3) the terms of Eq.(4) and substituting in Eq. (4) gives:

$$\begin{aligned} dJ = & \left[ \frac{2b}{W} F_1 - \frac{b^2}{W^2} \frac{\partial F_1}{\partial(a/W)} \right] d\Delta \\ & + \left[ \int_0^{\Delta} -\frac{2}{W} F_1 d\Delta + \int_0^{\Delta} \frac{4b}{W^2} \frac{\partial F_1}{\partial(a/W)} d\Delta \right. \\ & \left. \int_0^{\Delta} \frac{b^2}{W^3} \frac{\partial^2 F_1}{\partial(a/W)^2} d\Delta \right] da. \end{aligned} \quad (5)$$

This differential expression can now be reintegrated along any convenient path in the  $\frac{a}{W} - \frac{\Delta}{W}$  space to obtain  $J$ , at least if the partial derivatives  $\partial F_1 / \partial(a/W)$  and  $\partial^2 F_1 / \partial(a/W)^2$  and the differential crack extension  $da$  are somehow available. To obtain an expression for differential crack extension Ernst et.al.<sup>[1]</sup>] take the differential of Eq. (1) with  $\frac{\Delta}{W}$  and  $\frac{a}{W}$  as variables to give

$$dP = \frac{\partial P}{\partial \Delta} d\Delta + \frac{\partial P}{\partial a} da. \quad (6)$$

Evaluating the coefficients in terms of  $F_1$  gives

$$dP = \frac{b^2}{W^2} \frac{\partial F_1}{\partial (\Delta/W)} d\Delta + \left[ \frac{b^2}{W^2} \frac{\partial F_1}{\partial (a/W)} - \frac{2b}{W} F_1 \right] da. \quad (7)$$

Solving for  $da$  gives

$$da = \frac{\frac{b^2}{W^2} \frac{\partial F_1}{\partial (\Delta/W)} d\Delta - dP}{\frac{2b}{W} F_1 - \frac{b^2}{W^2} \frac{\partial F_1}{\partial (a/W)}} \quad (8)$$

Equations (5) and (8) together now allow calculation of  $dJ$  corrected for crack extension and the ratio  $dJ/da$  gives the Paris et.al.<sup>[5]</sup> tearing

modulus from  $T_{mat} = \frac{dJ}{da} \frac{E}{\sigma_0}^2$  (9)

The term in Equation 8 involving  $dP$  can be evaluated from the load displacement record of the specimen. The terms involving

$$F_1, \frac{\partial F_1}{\partial (a/W)}, \frac{\partial^2 F_1}{\partial (a/W)^2}, \text{ and } \frac{\partial F_1}{\partial (\Delta/W)}$$

must be obtained from the key curve and cannot be obtained from the load displacement record of the test specimen.

Following earlier work by Joyce et.al.<sup>[2]</sup> subscale (1/2 T) specimens were used to obtain the key curve function experimentally so that load displacement values to larger  $\Delta/W$  values could be achieved in the 1T specimens without crack extension. It was found, however, that for the A533B steel crack extension occurred too early in the 1/2 T compact specimens to obtain a complete analysis of deep cracked ( $a/W = 0.8$ ) 1TCT specimens. To circumvent this limitation blunt notched specimens were used to obtain a key curve function which allowed analysis of the  $a/W = 0.80$  1TCT specimens to crack extensions of .060 in. and which was extended when necessary at the maximum  $F_1$  value reached to estimate the J-R curve to the end of the load displacement record.

Figure 1 shows load displacement records for two 1/2 TCT specimens, one fatigue cracked to  $a/W = .526$  and the second machine notched to the same depth ( $\pm 0.002$  on a 5 point average) with a notch radius  $< 0.003$  inches. This result and similar results found at other crack lengths show that blunt notched specimens, at least up to the 0.003 inch radius studied here, can be used to give load displacement curves comparable to fatigue cracked specimens. Figure 1 also shows that machined notches gain only a little more deformation without crack extension for short crack lengths in comparison with fatigue cracked specimens, but for longer  $a/W$  values a considerable greater specimen extension is possible in the blunt notched specimen than in the fatigue cracked specimen before crack extension occurs. To complete the analysis of these specimens, at least approximately, this key curve function was extended at the maximum load value reached by each subsize specimen to an  $a/W$  value of 0.20 in. which was adequate to obtain complete J-R curves for the deepest cracked specimens.

The following sections describe the method used to evaluate a key curve function for the compact specimen geometry for a particular A533B steel.

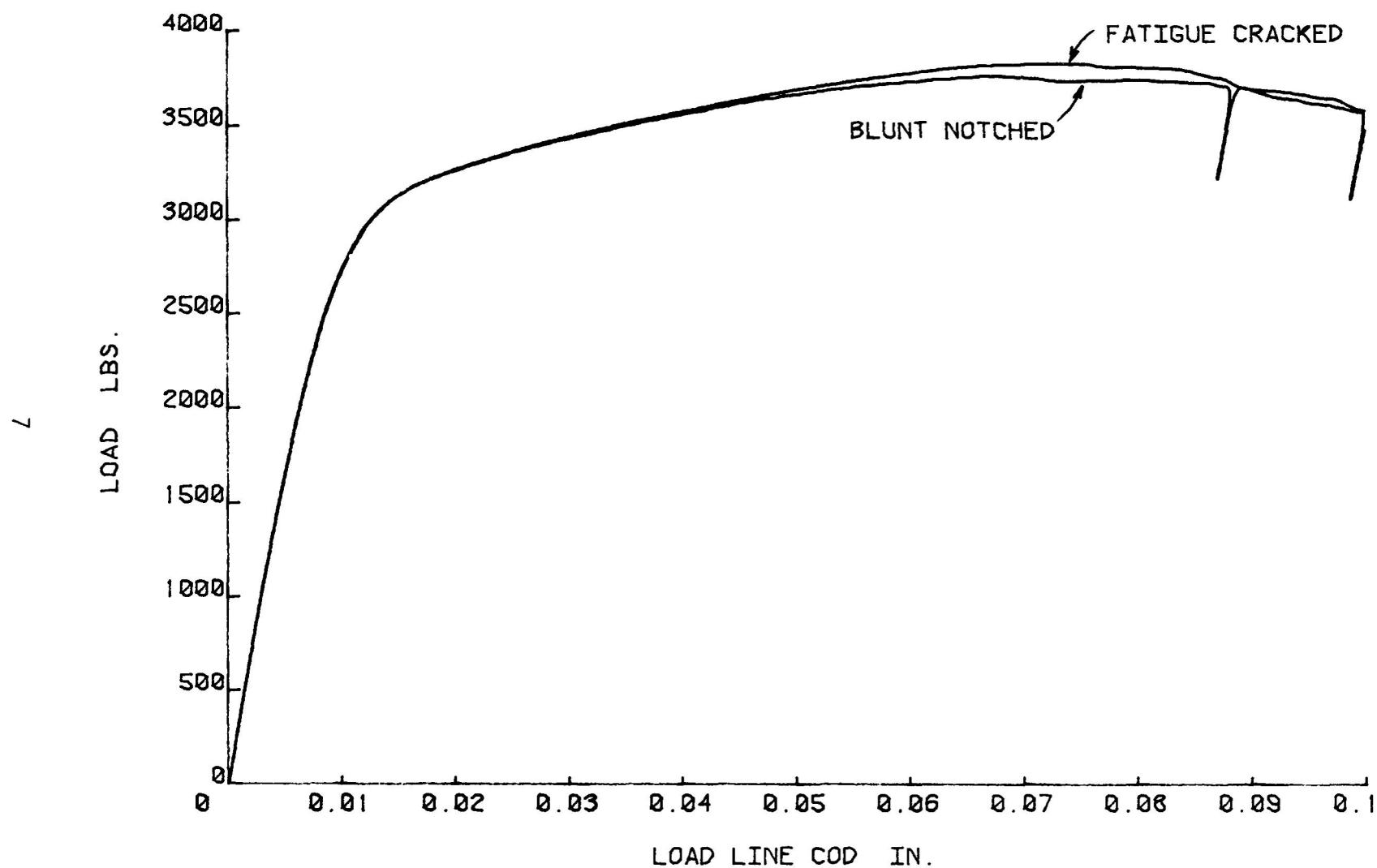


Figure 1. Load displacement curves for 1/2 TCT specimens showing comparability of fatigue cracked and blunt notched specimens.

### III. Key Curve Function Development

#### III.1 Material

Material used in this study was obtained from an HSST-02 plate of A533B steel supplied in 1 inch thickness. The chemical composition of the plate is described in Table 1 and the mechanical properties are presented in Table 2.

#### III.2 Testing

Modified 1/2 T compact specimens were produced according to Figure 2, all with crack planes oriented in the T-L orientation. A total of eight specimens were fatigue precracked to crack lengths between 0.51 and 0.88 a/W. The blunt notched specimens were saw cut with a .003 radius milling cutter to the desired final a/W value.

All tests were carried out at 150°C using computer data acquisition. A standard fracture mechanics clip on displacement gage was mounted on the integral knife edges in the load line of each specimen. Using the computer interactive system for unloading compliance J-R curve determination described by Joyce and Gudas<sup>[6]</sup> the initial specimen compliance was carefully measured at loads below 1/2 the expected limit load. Then starting from zero load, a load displacement record was run to a final COD displacement of 0.15 inches or until the load began to fall noticeably. In order to obtain as smooth a curve as possible no unloadings were taken and no attempt was made to determine when crack extension initiated in these specimens. An unloading was taken just before terminating the test to ascertain that little if any crack extension had occurred to that point. A uniform crosshead speed of 0.01 in/min. was maintained throughout each test. Data points were taken approximately every 0.00015 in. of displacement and the load displacement file

TABLE 1. Chemical Composition of HSST-02 A533B Steel  
Elements in Weight Percent

C	Mn	Ni	Mo	Si	S	P
.22	1.48	0.68	0.52	0.25	0.018	.012

TABLE 2. Tensile Mechanical Properties of  
HSST-02 A533B Steel

.2% Yield Strength psi	Ultimate Tensile Strength psi	Total Elongation %
65,000	90,000	19

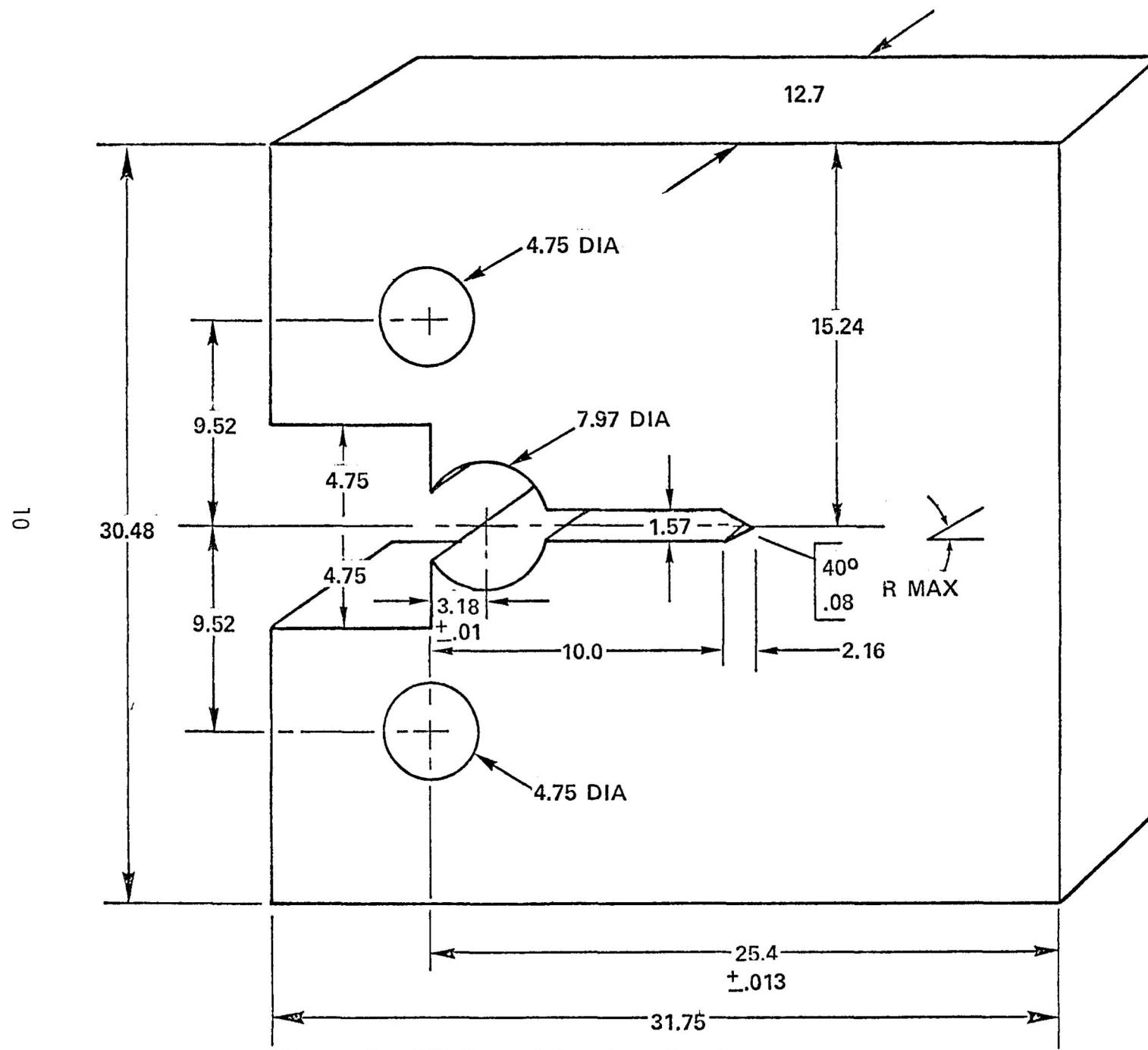


Figure 2. 1/2 Compact Specimen Drawing.

was stored on magnetic tape. After testing each specimen was heat tinted at 370°C for 20 min. and broken open in liquid nitrogen and the fatigue crack length was measured using a five point average technique.

### III.3 Key Curve Assembly

The digital load displacement records for each of the eight subsize specimen tests were sent to the U. S. Naval Academy Honeywell 6060 Time Sharing System. For each file the load and load point displacement were normalized to give:

$$\begin{aligned} P' &= \frac{Pw}{Bb^2} \\ \Delta' &= \frac{\Delta}{W} \end{aligned} \quad (10)$$

where  $B$  is the specimen thickness and  $b$  is the uncracked ligament.

The displacement scale was then smoothed and reduced by an interpolation routine to contain evenly spaced displacement values at 0.0005 in. intervals, to facilitate numerical differentiation. The eight separate files were then assembled into a key curve file of  $x$ ,  $y$ ,  $z$  triples where

$$\begin{aligned} x &= \Delta/W \\ y &= a/W \\ z &= \frac{Pw}{Bb^2} \end{aligned} \quad (11)$$

and

$$\frac{Pw}{Bb^2} = F1(\Delta/W, a/W, C_1, C_2, C_3 \dots) \quad (12)$$

where  $C_1$ ,  $C_2$ , etc. are terms which are assumed to be identical for the 1/2 T calibration specimens and the 1T test specimens to which the analysis is to be applied. Geometrical and material similarity were controlled as closely as possible between the two specimen sizes to assure following Rice, et.al. [7] and Ernst et.al. [1], that the  $F1$  function of Eq. (12) applies to both the 1/2T and 1T compact specimens of this A533B steel.

### Discussion

The result of assembling the load displacement records of the eight 1/2 T CT specimens is the key curve function shown in the computer graphics plot of Figure 3. This particular result corresponds to the blunt notched subsize specimens. This figure shows that the key curves for the shortest specimens were falling noticeably by  $\Delta/W$  values of .080. Figure 4 shows the extended key curve which was obtained by continuing the load displacement record of each specimen out horizontally at the maximum  $F_1$  value achieved to a  $\Delta/W$  value of 0.2.

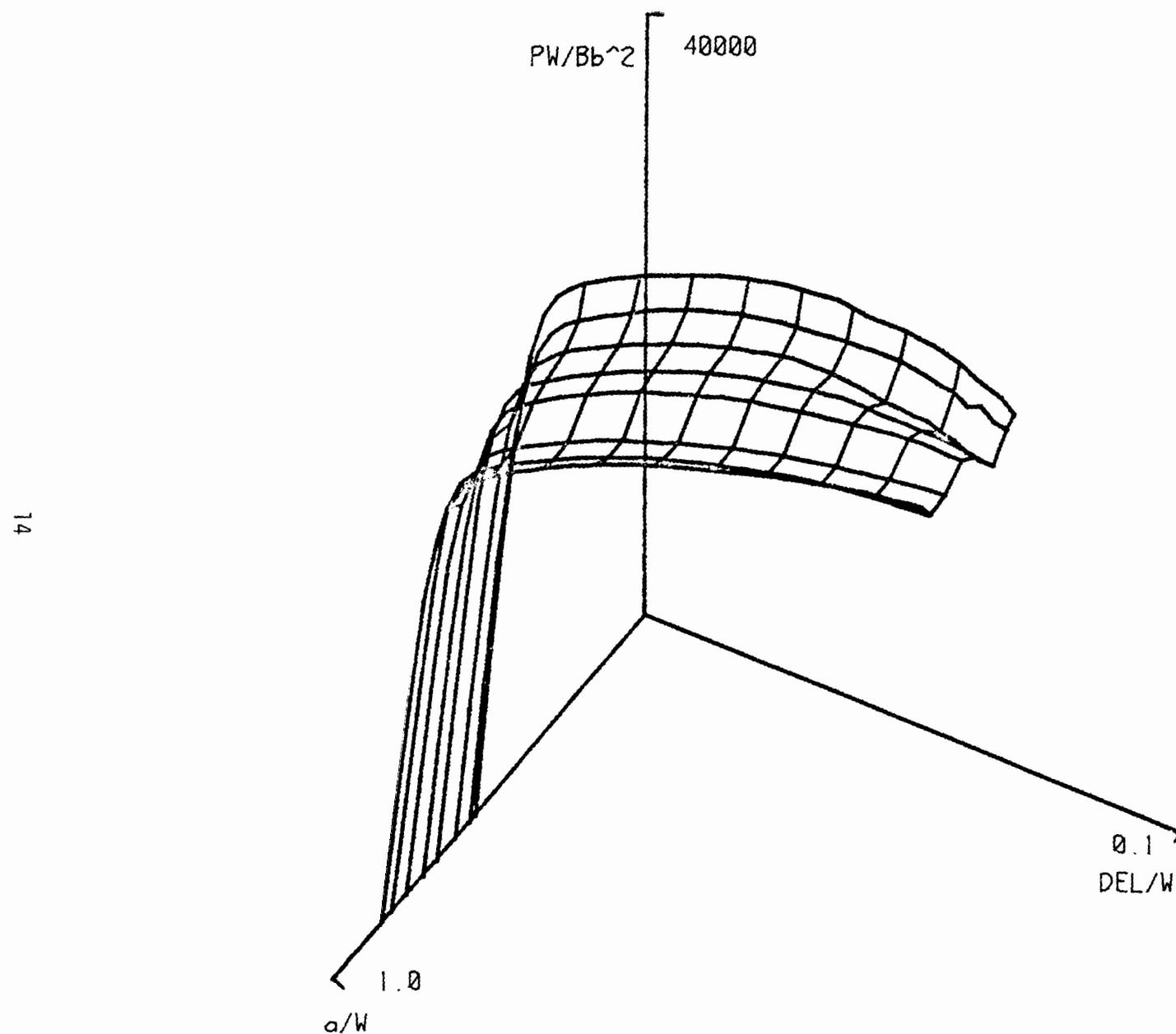


Figure 3. Experimental key curve function for the blunt notched 1/2 TCT A533B specimens.

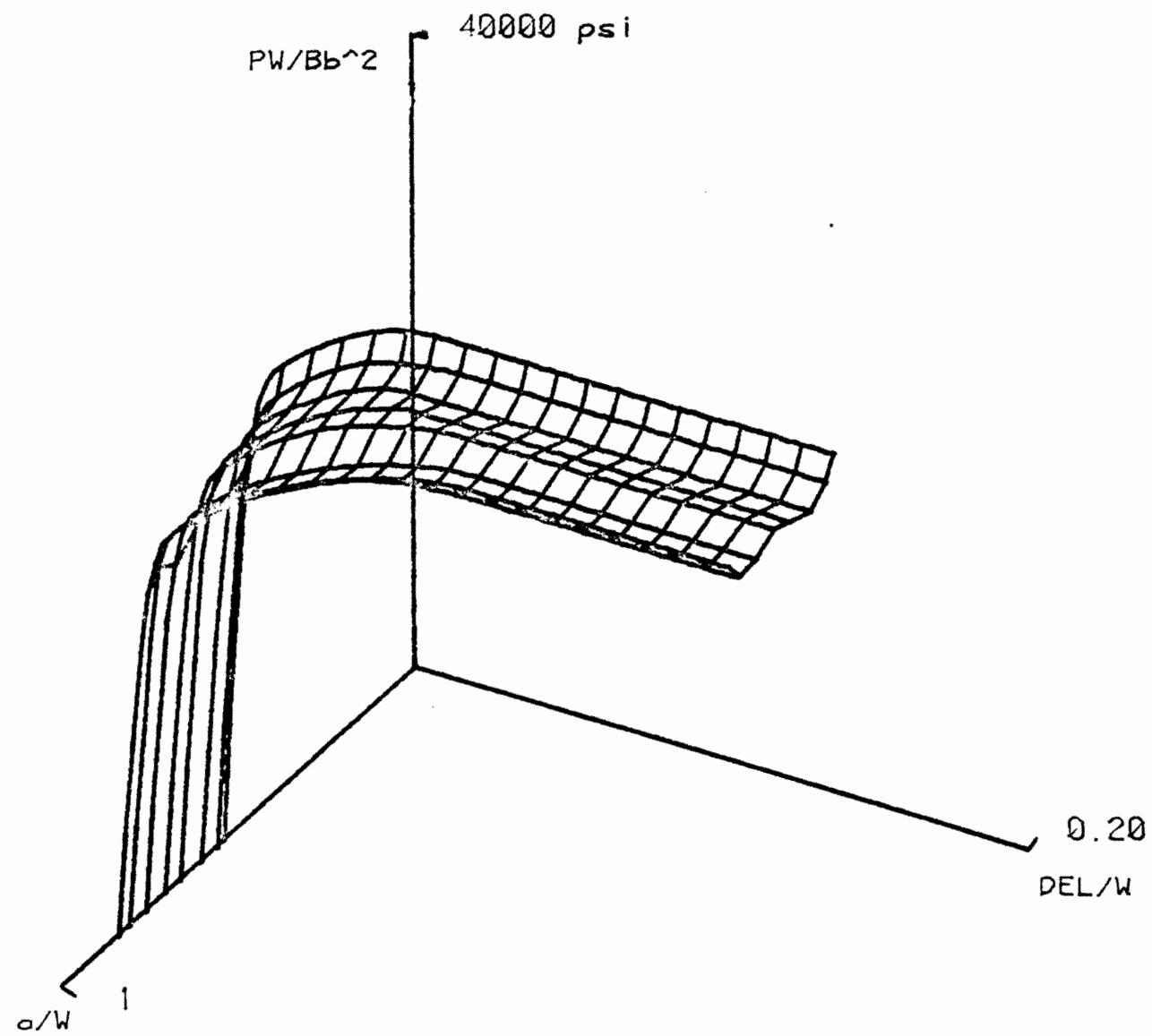


Figure 4. Experimental key curve function for the blunt notched specimens extended at the maximum  $F_1$  values of each individual curve.

#### IV. Discussion of the J-R Curve Evaluation Technique

As outlined in the previous section the key curve used for this analysis is a computer file of results from a series of eight subsize specimens giving a normalized load as a function of crack length and crack opening displacement. This key curve is to be used together with equations (5) and (8) of Section II to develop J-R curves for geometrically similar compact specimens of the same material, directly from their load displacement records. To accomplish this the following quantities based on the key curve file must be evaluated, namely:

$$\begin{aligned}
 F_1, \quad & \int_0^{\Delta} F_1 \, d\Delta \\
 \partial F_1 / \partial (a/W), \quad & \int_0^{\Delta} b \frac{\partial F_1}{\partial (a/W)} \, d\Delta \\
 \int_0^{\Delta} b^2 \frac{\partial^2 F_1}{\partial (a/W)^2} \, d\Delta, \quad & \text{and } \frac{\partial F_1}{\partial (\Delta/W)}. \tag{13}
 \end{aligned}$$

The first of these quantities,  $F_1$ , is just the value of the key curve for a given  $a/W$  and  $\Delta/W$  and can be evaluated from the key curve file using linear interpolation techniques. The second quantity is then just the integral of the first over the load line displacement and is obtained here by the simple summation equation

$$\int_0^{\Delta} F_1 \, d\Delta = \sum_{i=1}^n F_{1i} \, \delta\Delta_i. \tag{14}$$

To obtain the next three quantities a numerical differentiation of the key curve is required with respect to the crack length  $a/W$ .

To accomplish this as accurately as possible it was noticed that the limit load expression for a compact specimen can be written as [8 ]

$$P_{LIM} = \frac{Bb^2\sigma_0}{2W+a} \quad (15)$$

where  $\sigma_0$  is the material flow stress. Writing this in the key curve form of Equation 1 gives

$$\frac{P_{LIM}W}{Bb^2} = F1_{LIM} = \frac{\sigma_0}{2+a/W} \quad (16)$$

To evaluate the quantities  $\partial F1/\partial(a/W)$  and  $\partial^2 F1/\partial(a/W)^2$  of Equations (5) and (8) then, from the computer key curve file at a given value of  $\Delta/W$ , the values of  $F1$  for the subsize specimens are fit with a curve of the form

$$F1 = \frac{1}{A+Ba/W} \quad (17)$$

which is a slightly more general form than that given in equation (16) and then an effective flow stress  $\sigma_0'$  is calculated by setting

$$\frac{\sigma_0'}{2+a/W} = F1 = \frac{1}{A+Ba/W} \quad (18)$$

giving

$$\sigma_0' = \frac{2+a/W}{A+Ba/W} \quad (19)$$

Using this value and the derivatives of Equation (15) gives:

$$\partial F1/\partial(a/W) = \frac{-\sigma_0'}{(2+a/W)^2} \quad (20)$$

and

$$\partial^2 F1/\partial(a/W)^2 = \frac{2\sigma_0'}{(2+a/W)^3} \quad (21)$$

The integrals of these quantities can then be obtained by a numerical summation routine as the program steps along the digital load displacement record.

The final quantity  $\partial F_1 / \partial (\Delta/W)$  is obtained by an iterated least squares fit of a second order polynomial to the load displacement curve of each subsize specimen over a  $\Delta/W$  range of 0.002 inch and an evaluation of the slope at the center of the region from the derivative of the polynomial evaluated at that point. This procedure is run once and stored in a file similar to the key curve file itself and desired values of  $\partial F_1 / \partial (\Delta/W)$  are evaluated by linear interpolation for given values of  $a/W$  and  $\Delta/W$ . To obtain the J-R curves, then, using the above quantities, discrete versions of Equations (5) and (8) are written, namely:

$$\begin{aligned} \delta J_n &= \left[ \frac{2B}{W} F_1 n - \frac{b^2}{W^2} \frac{\partial F_1^*}{\partial (a/W)} n \right] \delta \Delta_n \\ &+ \left[ -\frac{2}{W} \sum_{i=1}^n F_1 i \delta \Delta_i + \frac{4b}{W^2} \sum_{i=1}^n \frac{\partial F_1^*}{\partial (a/W)} i \delta \Delta_i \right] \Delta a_n \end{aligned} \quad (22)$$

and

$$\delta a_n = \frac{\frac{b^2}{W^2} \frac{\partial F_1^*}{\partial (\Delta/W)} n \delta \Delta_n - \delta P_n}{\frac{2b}{W} F_1 n - \frac{b^2}{W^2} \frac{\partial F_1^*}{\partial (a/W)} n} \quad (23)$$

The quantities  $\delta \Delta_n$  and  $\delta P_n$  are the increments in load line displacement and load from point to point on the digitized load displacement record and  $\delta a_n$  and  $\delta J_n$  are the resulting increments in crack length and J.

At each point on the load displacement record of a specimen then, the total  $J$  and  $\Delta a$  are:

$$J = \sum_{n=1}^m \delta J_n \quad (24)$$

$$\Delta a = \sum_{n=1}^m \delta a_n \quad (25)$$

and a complete  $J$ -R curve with a point for each point on the load displacement record is developed. The remaining ligament  $b$ , is adjusted as the crack extends since

$$b = W - a. \quad (26)$$

The initial value of  $b$  used in the analysis is obtained from a heat tint nine point average of the fatigue crack length of the specimen for which the load displacement curve is being analyzed.

## V. The Discussion of the Results

The specimens analyzed in this study are a matrix of twenty-four 1TCT A533B specimens of varied crack length and side groove geometries which were reported on earlier by Vassilaros et.al.<sup>[3]</sup> as part of a comprehensive study of geometry effects on the J-R curves of A533B steel. The matrix of specimen geometries is shown in Figure 5. These specimens were tested using the computer interactive unloading compliance technique of Joyce and Gudas<sup>[6]</sup> and digital load displacement records were saved on magnetic tape for a possible later re-analysis. A typical load displacement record for one of these specimens is shown in Figure 6. The short unloadings are used by the unloading compliance method to determine the J-R curve, but were ignored by the key curve evaluation scheme.

Figures 7 - 14 show typical J-R curves obtained from the unloading compliance results and the key curve analysis for each crack length at 0% and 20% side groove reduction. The roughness of the key curve J-R curves results from the presence of the unloadings on the load displacement curves which were omitted from the analysis but still produced a lumpiness to the loading part of the load displacement record which affected the key curve analysis. The enlarged detail shown on Figure 6 shows the effect of an unloading on the load displacement curve used by the key curve analysis. Even though the unloading portion (shown dashed on the detail in Figure 6) is ignored by the key curve analysis the local slope of the load displacement curve first falls negative, then suddenly jumps to a large positive number and then goes negative for a distance of about 0.005 inches after which it continues either in a smooth increasing or decreasing fashion until the next

IT COMPACT SPECIMEN GEOMETRIES

a/W	SIDE GROOVE		
	0%	10%	20%
0.5	2	2	2
0.6	2	2	2
0.7	2	2	2
0.8	2	2	2

Figure 5. Specimen test matrix, ASTM A533B Steel at 300F.

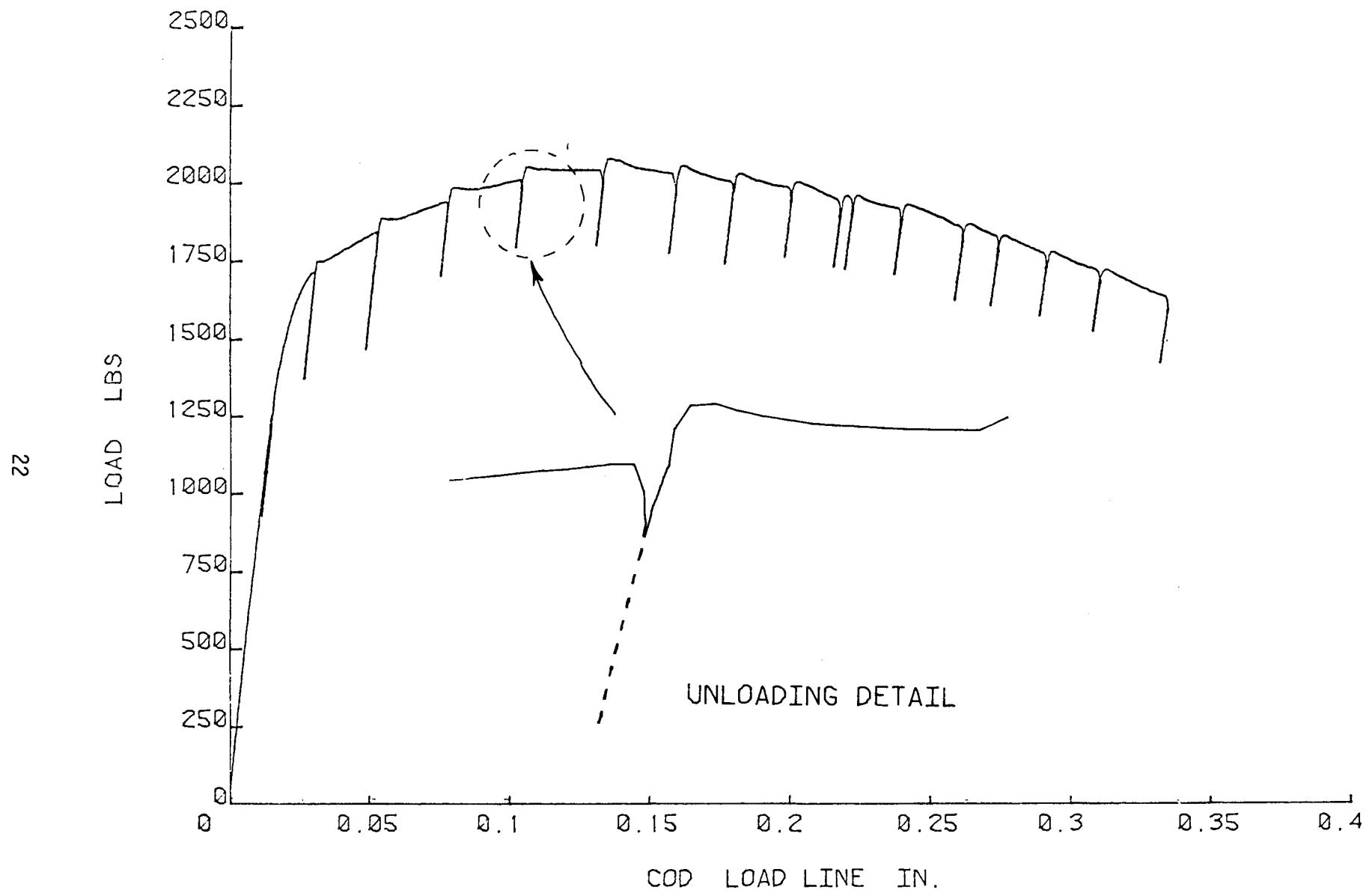


Figure 6. Digital load displacement record for A533B specimen #1-32, 0% side grooved with  $a/W = 0.81$ .

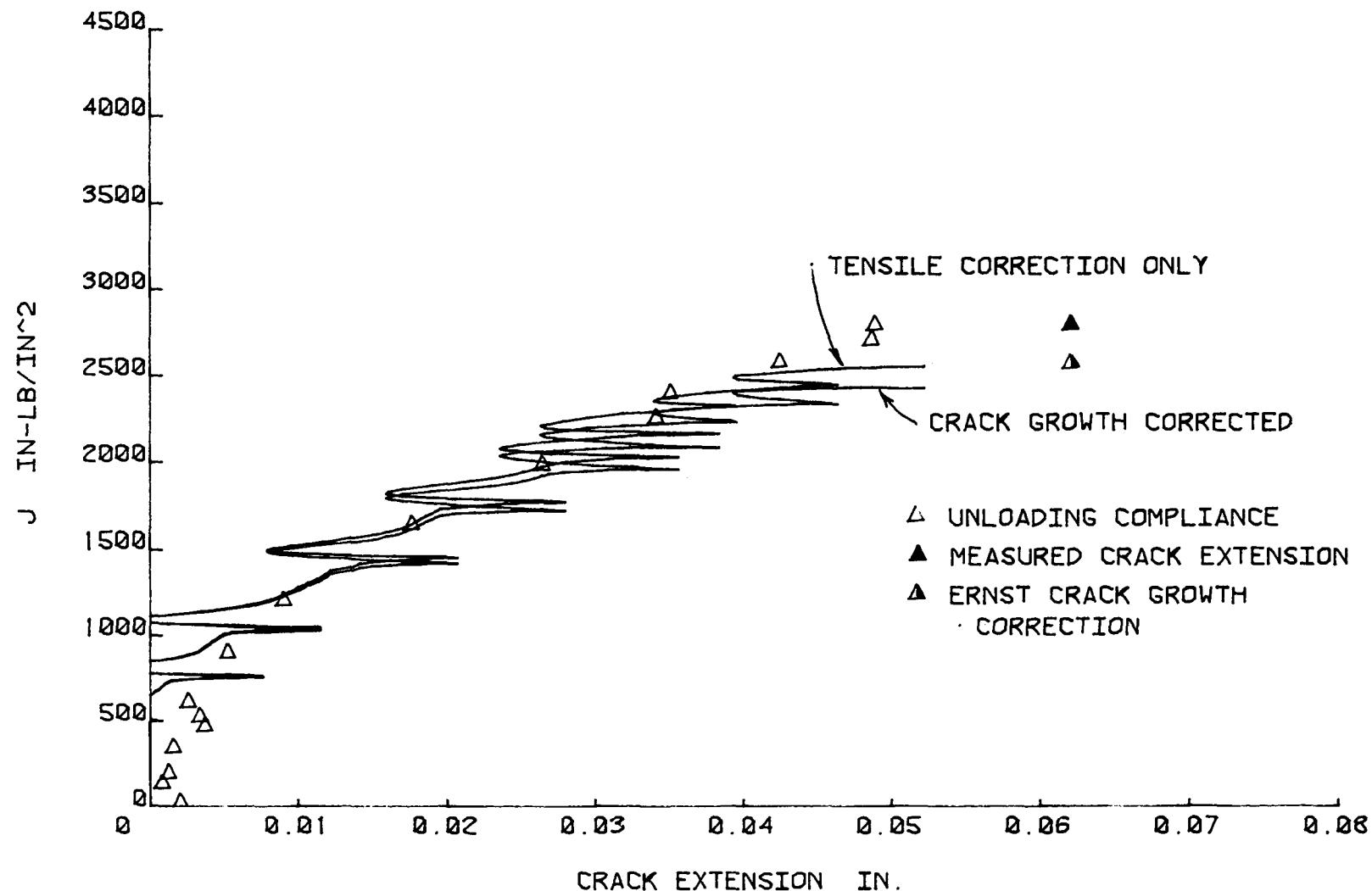


Figure 7. J-R curve comparison for specimen #1-3,  
 $a/W = 0.5$ , 0% side grooves.

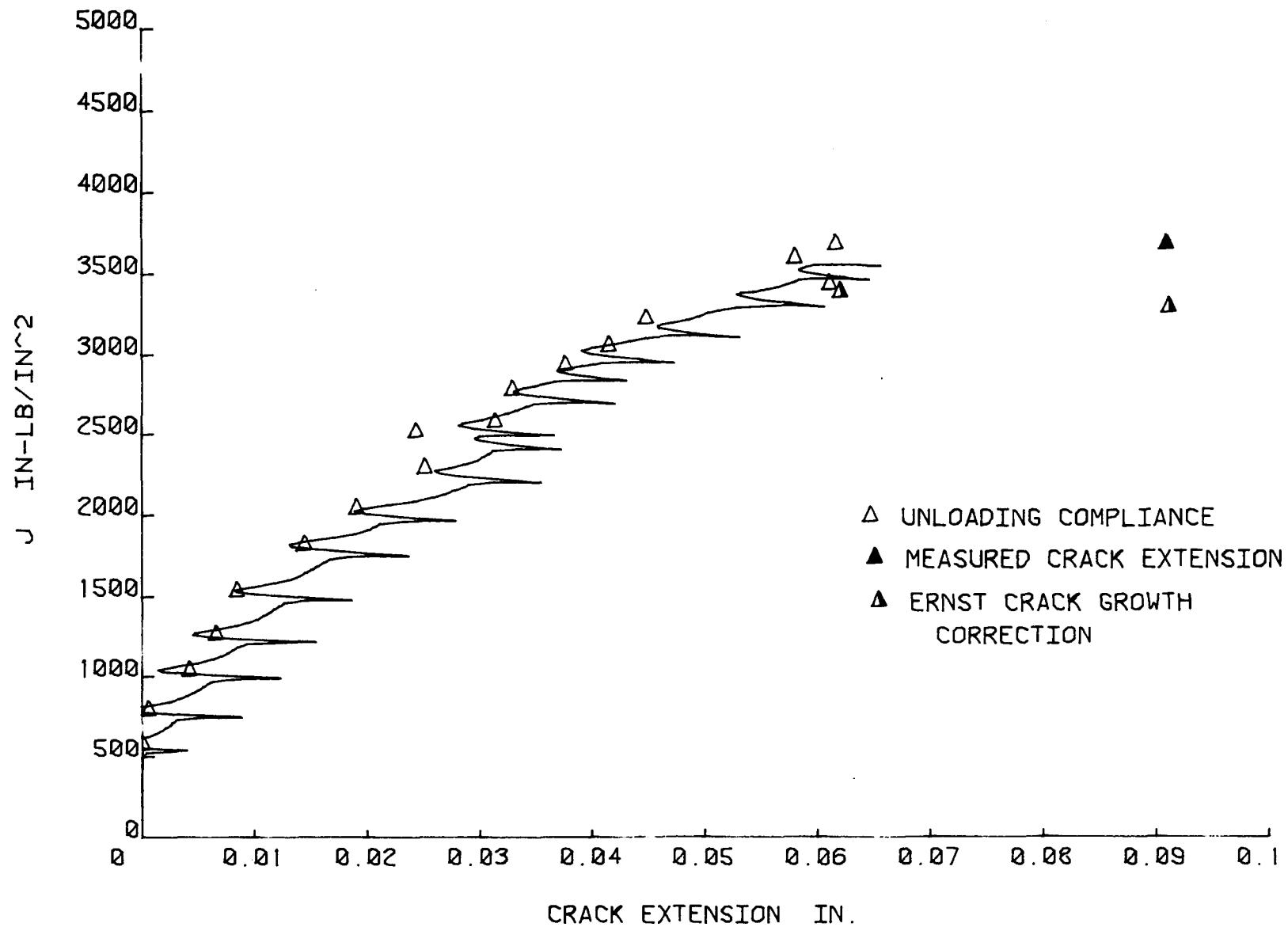


Figure 8. J-R curve comparison for specimen #1-15,  
 $a/W = 0.6$ , 0% side grooves

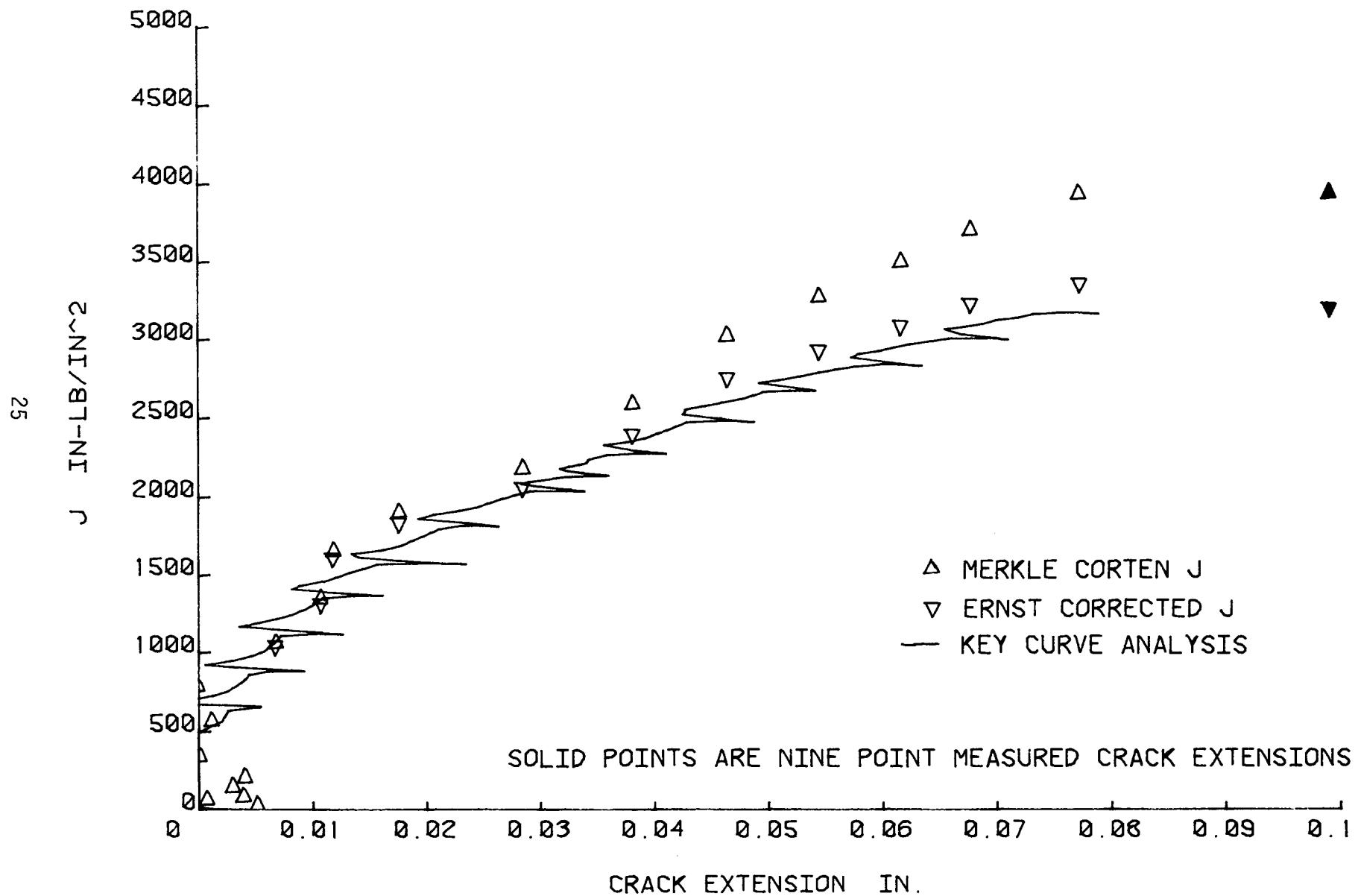


Figure 9. J-R curve comparison for specimen #1-18,  $a/W = 0.7$ , 0% side grooves.

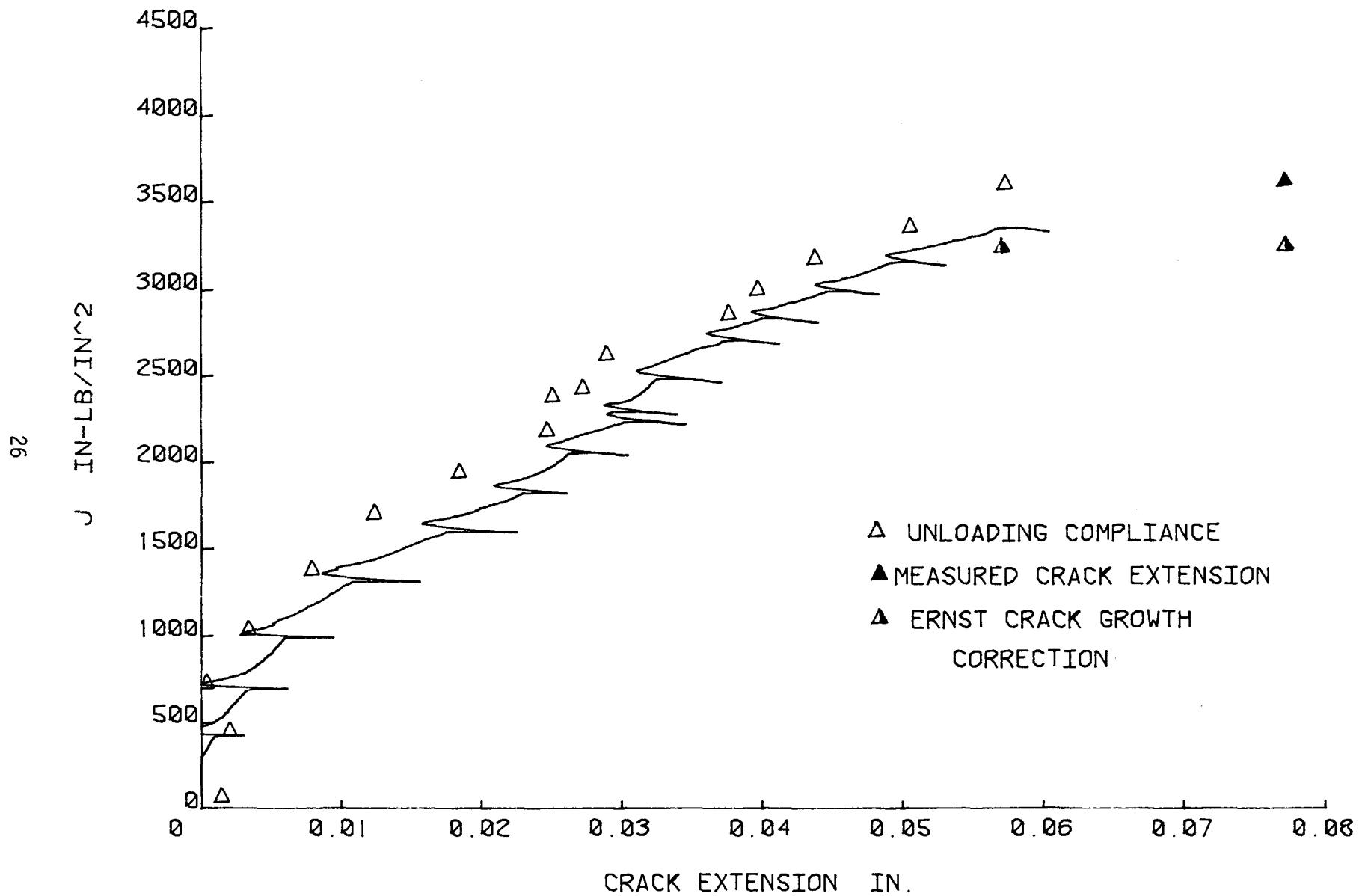


Figure 10. J-R curve comparison for specimen #1-30,  $a/W = 0.8$ , 0% side grooves.

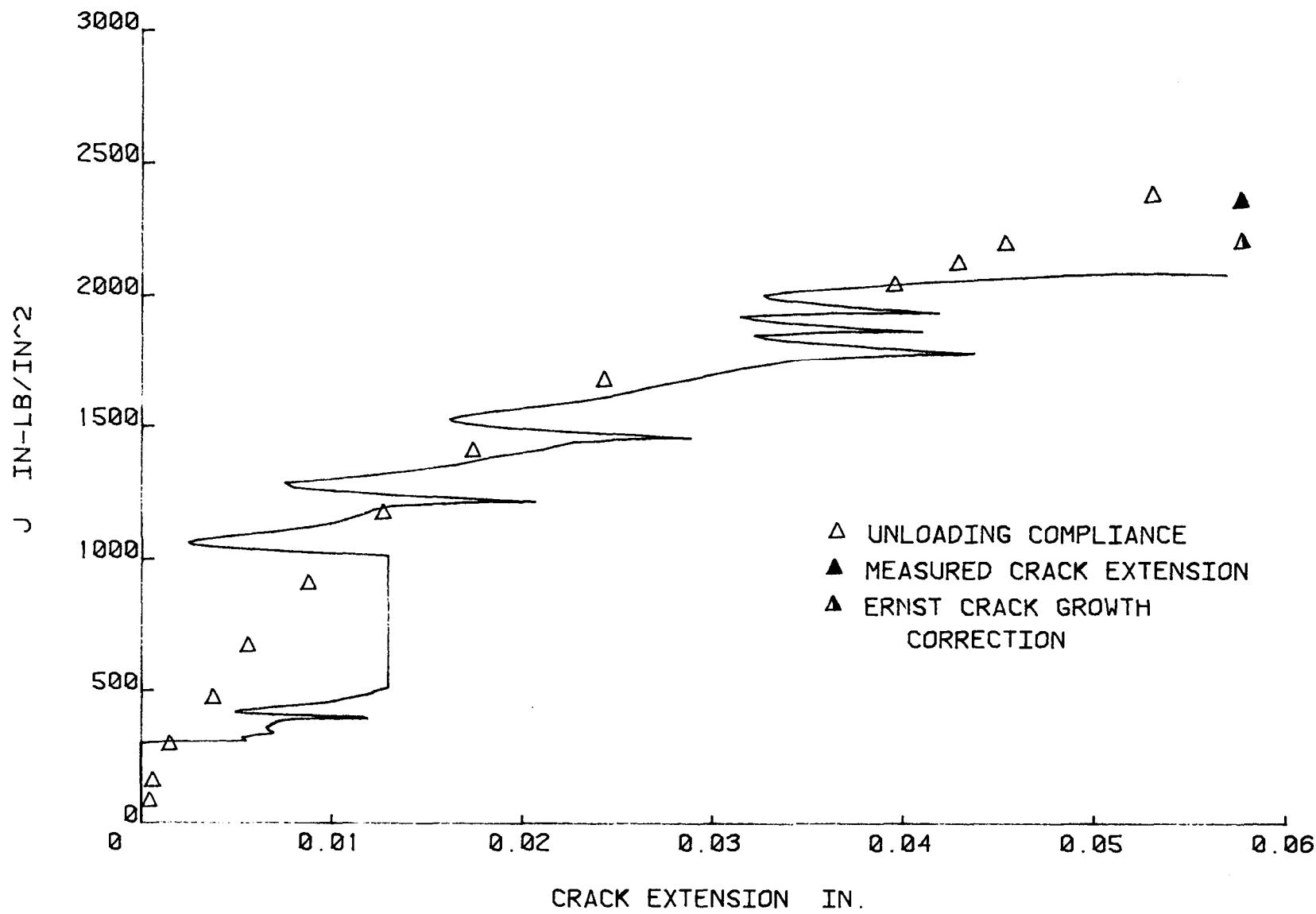


Figure 11. J-R curve comparison for specimen #1-18,  $a/W = 0.5$ , 20% side grooves.

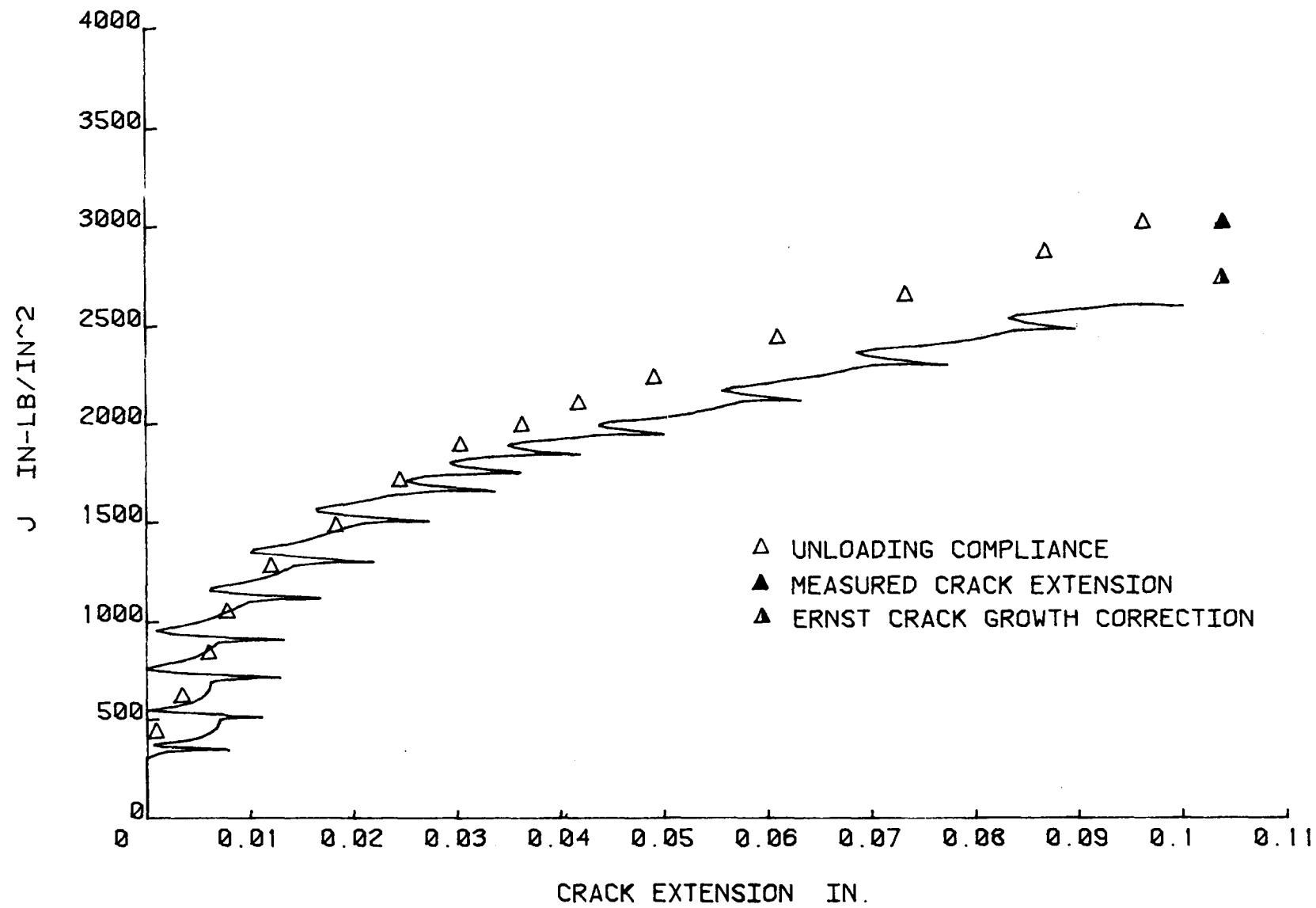


Figure 12. J-R curve comparison for specimen #1-13,  $a/W = 0.6$ , 20% side grooves

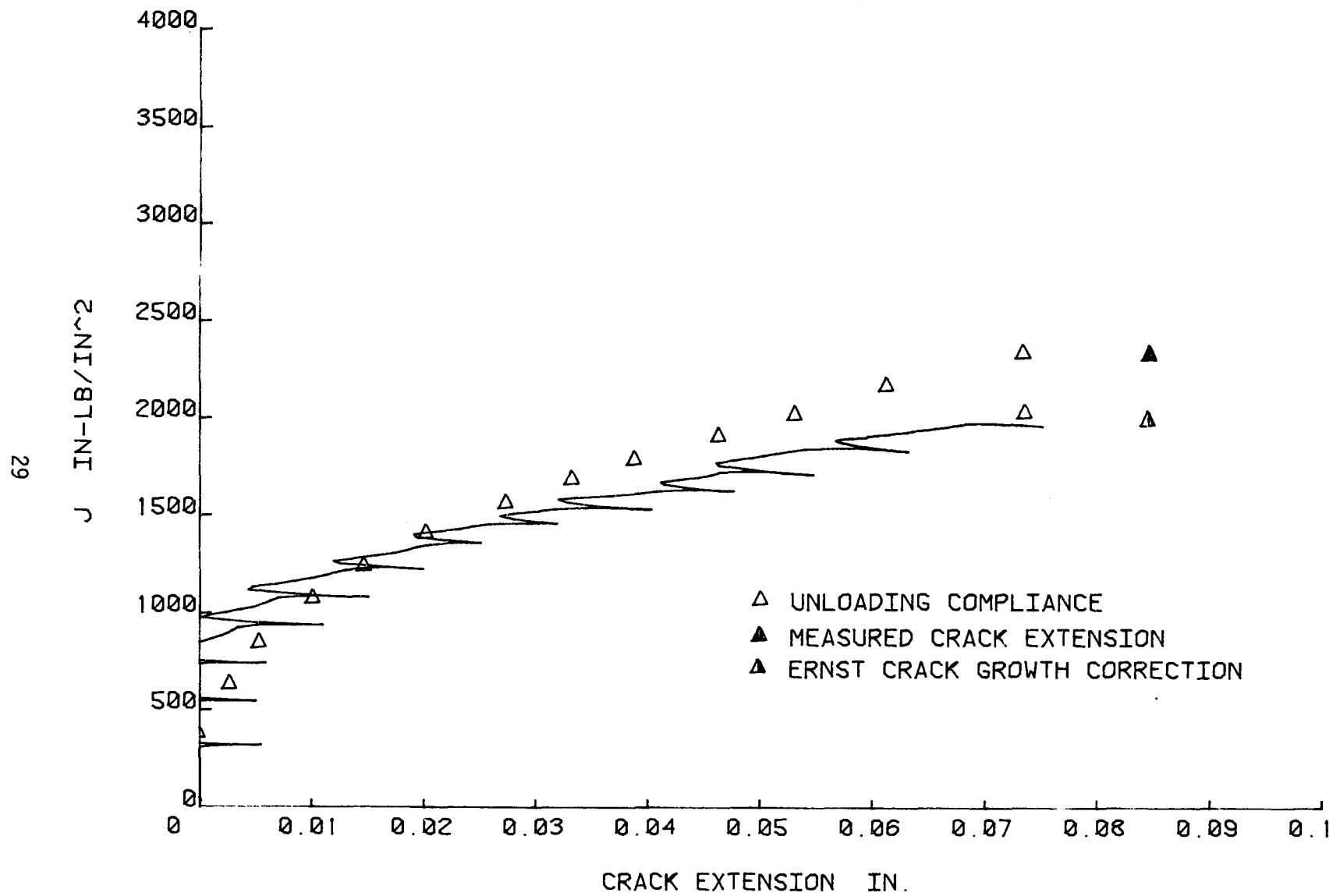


Figure 13. J-R curve comparison for specimen #1-23,  $a/W = 0.7$ , 20% side grooves.

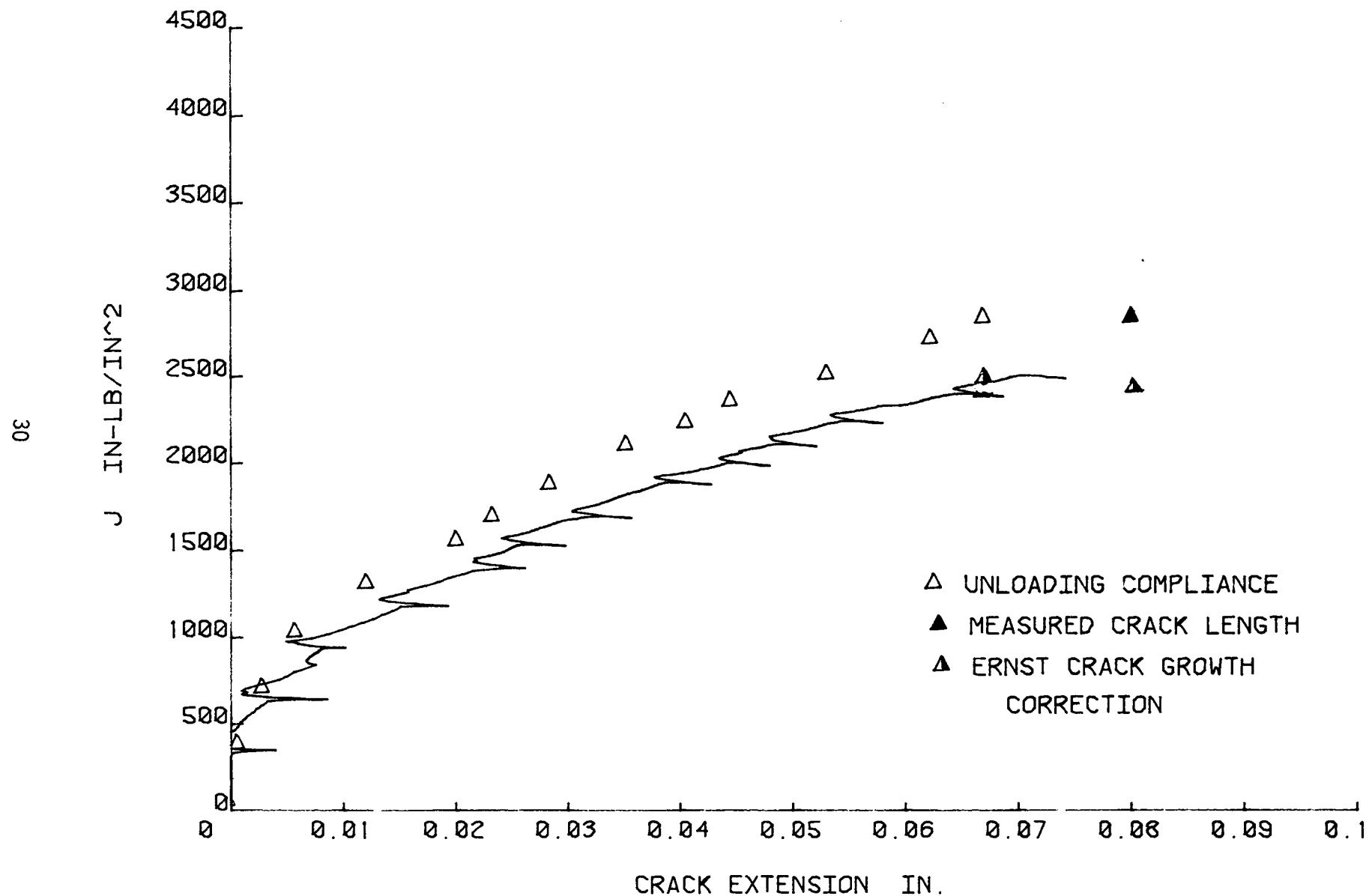


Figure 14. J-R curve comparison for specimen #1-27,  $a/W = 0.8$ , 20% side grooves.

unloading occurs. It would be possible to filter out these effects but this would involve making judgements as to the extent of the effects of the unloading and it was felt that this would possibly bias the results of the analysis. It is felt a great credit to the method that these wrinkles in the load displacement record had as little effect as the key curve method as they did. In the future when the key curve method is used on load displacement records which do not include unloadings very smooth J-R curves will result. It must be noted that the key curve method obtains J values corrected for crack extension which causes the key curve J-R curves to run at a lower slope. Figure 7 shows the correspondence between the unloading compliance result and the key curve result both with and without the crack growth correction terms. The crack growth correction of the J value causes a lower J-R curve to result than is the case when it is omitted. The approximate analysis of Ernst<sup>[9]</sup> correcting for crack extension effects is shown on Figure 8 at every unloading compliance data point and on the other figures at the final test point.

The final crack extension values obtained by the key curve method are also seen to be in excellent agreement with the unloading compliance estimates and tend in each case to under estimate the nine point measured values obtained after the specimen tests. This is a different result than that obtained by Joyce et.al.<sup>[2]</sup> using a similar key curve method on HY130 steel which gave final crack length estimates more in agreement with the measured crack length than the unloading compliance value. In the previous analysis the quantities  $\partial F_l / \partial (a/W)$  and  $\partial^2 F_l / \partial (a/W)^2$  were evaluated from the experimental F1 file by fitting a linear relationship with respect to  $a/W$  at each

$\Delta/W$  value and evaluating  $\partial F_1/\partial(a/W)$  = the slope and  $\partial^2 F_1/\partial(a/W^2) = 0$ . The roughness of the data did not seem to allow fitting a different form of function. When this model was changed to that described in the previous section it was found that the crack extension estimates were reduced and corresponded closely to the unloading compliance result. A fit of an equation of the form of Equation 17 to a particular section of data at  $\Delta/W = 0.080$  is shown in Figure 15. A straight line fit would generate a line with a smaller negative slope and of course no curvature, a result which is intuitively unsatisfactory since it implies a Merkle Corten tensile correction to  $J$  term in Equation 5 that is not a function of  $a/W$ . This sensitivity of the method to the magnitude of the terms  $\partial F_1/\partial(a/W)$  and  $\partial^2 F_1/\partial(a/W)^2$  requires further study.

A complete table of results is included in Table 3. The values of  $J_{IC}$  and  $dJ/da$ , tabulated there were obtained using the procedure recommended by Clarke et.al. [8] in which a least squares best fit straight line is fit to all data in the range from 0.15 mm beyond the blunting line defined by

$$J = 2 \sigma_0 \Delta a \quad (27)$$

up to 1.5 mm of crack extension beyond this same blunting line. The measured crack extensions were obtained using a nine point average of measurements taken across the fracture surface after the specimens had been heat tinted and broken open at liquid nitrogen temperature. An average of the two surface measurements and the seven remaining points were summed and divided by eight to give the recorded value. The major conclusion drawn from these results is that the key curve method accurately evaluates the critical  $J$  value and the average  $R$  curve slope at least in comparison to typical unloading compliance results, even when it is applied to side grooved specimens.

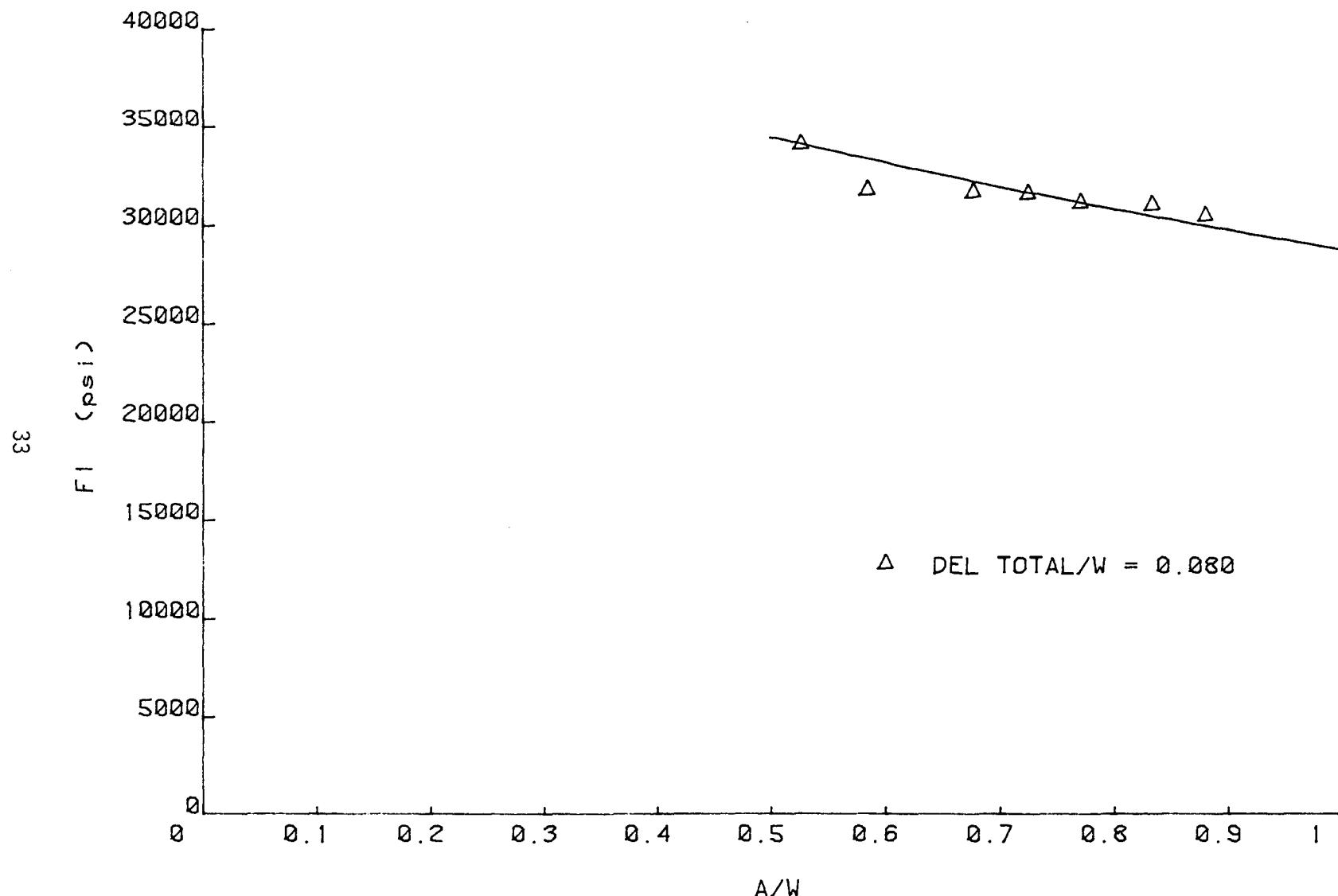


Figure 15. Plot of fitting equation used for key curve differentiation with respect to  $a/W$ .

TABLE 3.

J-R Curve Data Summary

		Specimen #					
a/W = .5		1-3	1-2	1-6	1-1	1-8	1-7
$J_{IC}$ in-lb/in <sup>2</sup>	UC*	1342	1995	1194	1189	1173	1148
	UCE	1356	2027	1219	1229	1184	1272
	KC	1302	1803	1519	1235	1399	1207
$dJ/d\Delta a$ 1b/in <sup>2</sup>	UC	35576	41664	39128	34660	26624	29237
	UCE	31141	34685	34605	29562	23224	23188
	KC	30245	31247	39904	27162	30977	32456
$\Delta a$ in.	Meas	.062	.114	.067	.099	.059	.112
	UC	.049	-	.054	.070	.053	.102
	KC	.051	.086	.052	.085	.053	.076

		Specimen #					
a/W = .6		1-14	1-15	1-10	1-11	1-13	1-12
$J_{IC}$ in-lb/in <sup>2</sup>	UC	1644	1965	1122	1361	1347	1155
	UCE	1696	1966	1166	1405	1358	1179
	KC	1585	1544	1094	1176	1651	1506
$dJ/d\Delta a$ 1b/in <sup>2</sup>	UC	30363	34440	31197	35493	21455	18596
	UCE	24589	27144	25633	28963	17167	14462
	KC	25074	39144	25370	38550	23064	20862
$\Delta a$ in	Meas	.067	.091	.093	.104	.104	.094
	UC	.044	.062	.079	.081	.096	.090
	KC	.055	.063	.082	.076	.090	.075

\*Table Key

UC - Unloading compliance result

UCE - Ernst corrected unloading compliance result

KC - Key curve analysis result

Meas. - 9 point average measurement

TABLE 3. (continued)

		Specimen #						
a/W = .7			1-18	1-20	1-22	1-21	1-23	1-19
$J_{IC}$ in-lb/in <sup>2</sup>	UC	1481	1786	1724	1497	1246	1193	
	UCE	1607	1818	1792	1536	1261	1217	
	KC	1116	1971	1801	1747	1499	1410	
$dJ/da$ 1b/in <sup>2</sup>	UC	38665	37191	25683	29683	17168	18249	
	UCE	27865	27061	17061	21546	11892	12973	
	KC	29642	29595	30876	32800	19071	18907	
$\Delta a$ in	Meas	.099	.102	.070	.079	.086	.092	
	UC	.077	.077	.053	.068	.072	.073	
	KC	.080	.071	.045	.054	.068	.070	

		Specimen #						
a/W = .8			1-30	1-32	1-26	1-25	1-27	1-29
$J_{IC}$ in-lb/in <sup>2</sup>	UC	1713	1797	1186	1538	1259	904	
	UCE	1762	1830	1252	1570	1362	1073	
	KC	1178	1493	1343	1274	1118	905	
$dJ/da$ 1b/in <sup>2</sup>	UC	42111	27831	31829	23330	26607	29180	
	UCE	26711	13500	20129	12114	14564	17720	
	KC	46679	27046	28072	35428	23071	44146	
$\Delta a$ in.	Meas	.078	.101	.094	.079	.082	.085	
	UC	.057	.074	.077	.070	.069	.070	
	KC	.058	.076	.067	.066	.074	-	

Key curve results included in Table 3 were obtained using the key curve function evaluated from the fatigue cracked subsize specimens. This was found to be possible for specimens with  $a/W$  values from 0.5 to 0.7. A slightly extended fatigue based key curve function was used for the non-side grooved  $a/W = 0.7$  specimens. For the  $a/W = 0.8$  specimens the blunt notched key curve formulation was used and this had to be extended at the maximum  $F_1$  value to handle the non-side grooved specimens #1-30 and #1-32.

The use of this blunt notched key curve function did seem to effect the key curve J-R curves somewhat as shown for example in Figure 16 for a non-side grooved  $a/W = 0.7$  specimen (#1-18). The blunt notched key curve result gives a J-R curve with a slightly lower  $J_{IC}$  value and slightly higher slope than the result of the fatigue cracked key curve analysis. This effect seems to be present in the  $a/W = 0.8$  results of Table 3 in which the key curve results, based on the blunt notched specimens, give markedly lower  $J_{IC}$  values and higher  $dJ/da$  values than the unloading compliance results.

The comparison between the Ernst crack growth correction and the key curve result is also seen to be very good for non-side grooved specimens with shorter crack lengths. A poorer comparison is seen for the  $a/W = 0.7$  and 0.8 specimens, for which the Ernst equation predicts a larger correction than seems justified by the key curve results. The key curve results for the  $a/W = 0.8$  specimens are, however, questionable since they are showing excessively low  $J_{IC}$  values and high  $dJ/da$  values as discussed above, probably because of the use of the blunt notched key curve.

For the side grooved specimens in Table 3 it is hard to make any clear cut statements. For these specimens the key curve method is in error to

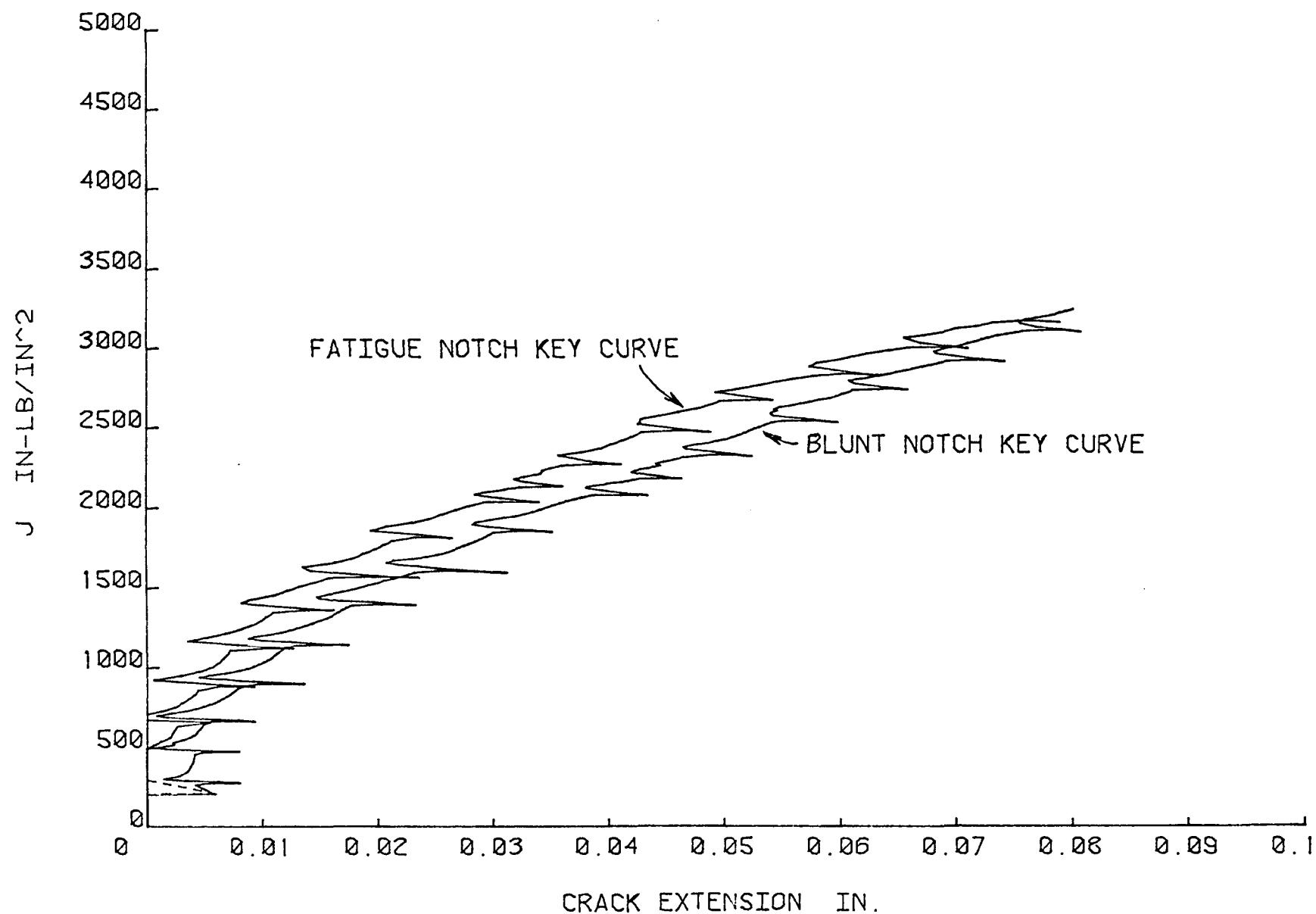


Figure 16. Comparison of J-R curves resulting from a fatigue based key curve and a blunt notched key curve for specimen #1-18.

some extent because of the lack of geometric similarity between the subsize specimens and the side grooved 1TCT specimens. At least these specimens grow with a straight crack front which is geometrically similar to the specimens used to obtain the key curve function. On the other hand the non-side grooved specimens tend to become geometrically non-similar as the crack extends because of the dramatic tunneling which occurs in these specimens. The unloading compliance  $J$  values are in turn inaccurate since they are obtained from the Rice<sup>[4]</sup> analysis as corrected by Merkle and Corten<sup>[10]</sup> which does not account for the perturbation of the stress field produced by the side grooves.

Overall, though, for the side grooved specimens, as with the deeper cracked non-side grooved specimens, it can be seen that the key curve results compare much more closely with the non-corrected unloading compliance results than they do with the Ernst corrected unloading compliance results.

## VI. Conclusions

The principle conclusion of this work is that the key curve function can be applied to determine J-R curves directly from the load displacement records of compact specimens of A533B steel. A key curve function obtained from blunt notched (<.003 in. R) or fatigue cracked specimens can be used, but the fatigue cracked specimens are to be preferred. Results obtained using the blunt notched specimens appear to give conservative  $J_{IC}$  values but higher  $dJ/da$  values than those resulting from fatigue cracked specimens.

The Ernst<sup>[9]</sup> crack growth correction to J calculation appear to be accurate for non side grooved specimens up to  $a/W = 0.7$  but for deeper cracked specimens or side grooved specimens its accuracy could not be demonstrated by these results.

## References

1. Ernst, H., Paris, P. C., Rossow, M and Hutchinson, J. W., "The Analysis of Load-Displacement Relationships to Determine J-R Curve and Tearing Instability Material Properties, "ASTM STP 677, 1979, pp. 581-599.
2. Joyce, J. A., Ernst, H. and Paris, P. C., "The Direct Evaluation of J-Resistance Curves from Load Displacement Records," presented at the 12th National Symposium on Fracture Mechanics, ASTM, St. Louis, Mo., June 1979.
3. Vassilaros, M. G., Joyce, J. A. and Gudas, J. P., "Effects of Specimen Geometry on the J-I-R Curve for ASTM A533B Steel", presented at the 12th National Symposium on Fracture Mechanics, ASTM, St. Louis, Mo., June 1979.
4. Rice, J. R., J. Appl. Mech., 35, 1968, pp. 379-386.
5. Paris, P. C., Tada, H., Zahoor, A and Ernst, H., in Elastic-Plastic Fracture, J. D. Landes, J. A. Begley and G. A. Clarke, Eds., ASTM STP 668, Philadelphia, PA, 1979, pp. 5-36.
6. Joyce, J. A., and Gudas, J. P., in Elastic-Plastic Fracture J. D. Landes, J. A. Begley and G. A. Clarke, Eds., ASTM STP 668, 1979, pp. 451-468.
7. Rice, J. R., Paris, P. C. and Merkle, J. G., "Some Further Results on J-Integral Analysis and Estimates," ASTM STP 536, 1973.
8. Clarke, G. A., Andrews, W. R., Begley, J. A., Donald, J. K., Embley, G. T., Landes, J. D., McCabe, D. E., and Underwood, J. H. Journal of Testing and Evaluation, 1, Jan. 1979.
9. Ernst, H., Washington U, St. Louis, Mo. private communication.
10. Merkle, J. G., and Corten, H. T., J. Pressure Vessel Tech., 96 1974, pp. 286-292.

U.S. NUCLEAR REGULATORY COMMISSION  
BIBLIOGRAPHIC DATA SHEET

1. REPORT NUMBER (Assigned by DDC)

NUREG/CR-1290

## 4. TITLE AND SUBTITLE (Add Volume No., if appropriate)

Application of the Key Curve Method to Determining J-R Curves for A533B Steel

2. (Leave blank)

3. RECIPIENT'S ACCESSION NO.

## 7. AUTHOR(S)

J. A. Joyce

## 5. DATE REPORT COMPLETED

MONTH | YEAR  
January | 1980

## 9. PERFORMING ORGANIZATION NAME AND MAILING ADDRESS (Include Zip Code)

U.S. Naval Academy  
Annapolis, MD 21402

## DATE REPORT ISSUED

MONTH | YEAR  
January | 1980

6. (Leave blank)

8. (Leave blank)

10. PROJECT/TASK/WORK UNIT NO.

11. CONTRACT NO.

## 12. SPONSORING ORGANIZATION NAME AND MAILING ADDRESS (Include Zip Code)

Metallurgy & Materials Research Branch  
Division of Reactor Safety Research  
U.S. Nuclear Regulatory Commission  
Mail Stop 1130 SS  
Washington, DC 20555

## 13. TYPE OF REPORT

Technical report

## PERIOD COVERED (Inclusive dates)

## 15. SUPPLEMENTARY NOTES

14. (Leave blank)

## 16. ABSTRACT (200 words or less)

This report describes the experimental development of a key curve for compact specimens of A533B steel and the use of this experimental key curve to generate the J-Resistance curve directly from the load displacement records without obtaining crack length estimates from unloading compliance, ultrasonics, electric potential or other techniques. In fact two complete key curve functions were developed, the first using subsized fatigue precracked specimens, the second using subsized but machine notched specimens. In each case eight 1/2 T compact specimens with crack lengths from  $a/W = 0.5$  to 0.9 were used to generate a series of digital load displacement records which were assembled in a computer file as the key curve for geometrically similar compact specimens. This key curve can be thought of as defining the locus of load displacement records expected for geometrically similar compact specimens of this material for similar loading conditions if no crack extension were to take place. Deviations between the key curve function and the load displacement record for a particular specimen can then be attributed to crack extension and a calculation for the amount of crack extension can be made. The key curve also allows corrections to be made to J values to account for effects of this crack extension.

## 17. KEY WORDS AND DOCUMENT ANALYSIS

## 17a. DESCRIPTORS

## 17b. IDENTIFIERS/OPEN-ENDED TERMS

## 18. AVAILABILITY STATEMENT

Unlimited

## 19. SECURITY CLASS (This report)

Unclassified

## 21. NO. OF PAGES

## 20. SECURITY CLASS (This page)

Unclassified

## 22. PRICE

S