G04/5

ELASTIC PLASTIC FRACTURE ASSESSMENT USING J-R CURVE BY DIRECT METHOD

E.P. Asta¹ and E. Chomik²

¹ENACE S.A., UTN-FRH Fracture Mechanics Group, L.N. Alem 712, Buenos Aires (1001), Argentina

²CNEA, Av. del Libertador 8250, Buenos Aires (1425), Argentina

ABSTRACT

The structural integrity assessment approach, for ductile fracture may be applied using the J-R curve obtained by direct method from small single specimen fracture tests. Direct method was carried out by means of a developed computational program.

1. INTRODUCTION

The structural integrity assessment of nuclear reactors pressure vessels, primary pipe line and associate systems might be evaluated according to elastic-plastic fracture mechanics methodology. This practice is possible, particularly in upper shelf region, taken into account the elevated fracture toughness values of modern reactor pressure vessels.

In the elastic-plastic evaluation methods, based on the J integral and tearing modulus procedures, an essential input is the material crack growth fracture resistance curve (J-R curve).

It is well known that the single specimen unloading compliance technique and the multiple specimen one are the most used experimental methods for determining J-R curve and elastic - plastic initiation parameters.

In order to simplify J-R determination, direct method from load -load displacement records of the single specimen tests may be employed. This procedure has got advantages such as avoid accuracy problems of the crack growth measuring devices and reducing testing consuming.

This paper presents a structural integrity assessment approach for ductile fracture, using the J-R curve obtained by direct method from single specimen fracture tests. J-R direct method was carried out by means of a developed computational program based on theoretical elastic-plastic expressions. A comparative evaluation has been made between the direct method J resistance curves and the ones obtained by standard testing methodology on typical pressure vessel steels.

2. MATERIALS AND METHODS

2.1 Test method

Fracture toughness tests on four pressure vessels steels were run; their chemical composition and mechanical properties are shown

in Tables 1 and 2. Three point bend specimens with nominal thickness $B = 12.7\text{mm}$ and 6.25mm and size groove 20% were used.

The J-R curve test procedure was performed according to the ASTM requirements (ASTM E-1152-87 and ASTM E-813-87).

2.2 Direct method program (DMP) to estimated stable crack growth

A direct method to obtain J-R curves from load-load displacement records on both size bend specimens has been used. It was carried out by means of a developed computational program based on the following relationships given in elastic-plastic handbook (Kumar et al, 1981):

$$J = F1(P^2/E) + \alpha \sigma_0 \epsilon_0 b H1(P/P_0)^{n+1} \quad (1)$$

$$\delta = F3(P/E) + \alpha \epsilon_0 a H3(P/P_0)^n \quad (2)$$

where:

$\alpha, \sigma_0, \epsilon_0, n$ = Ramberg-Osgood equation parameters

P_0 = limit load per unit thickness

b = remanent ligament: $W - a$

$F1(a); H1(a/w, n); H3(a/w, n)$ = calibration functions

The DMP code was developed in the following parts:

- Input part, that provide necessary input data such as: yield strenght, Ramberg-Osgood parameters, dimensions of the specimens and load-load displacement point pairs ($P-\delta$) selected from $P-\delta$ experimental records.
- $F1, H1$ and $H3$ data, select proper calibration functions by means of a specific interpolate method.
- Elastic-plastic analysis routines using a iterative method based on equations (1) and (2).
- Output part, that provide $J-\Delta a$ values to obtain J-R curve.

The program contains analysis routines for two types of fracture specimens: compact tension and three point bending. In the DMP is possible to select the elastic-plastic analysis either plane stress condition or plane strain one.

The program also includes a correction on load displacement point values taking into consideration brinelling effect and test machine fixture compliance (Asta et al, 1991).

3. RESULTS

The measured and estimated crack growths from direct method program, are compared in Table 3.

J-R curves estimated from DMP program corresponding to nominal thickness $B = 12.7\text{mm}$ and 6.25mm are showed in Figure 1.

4. DISCUSSION AND CONCLUSIONS

The estimated final crack lengths that were calculated applying direct method show, in most cases, an error lower than a maximum allowed value by standards (4%) compared with measured ones by heat tinting. However, some specimens show an error slightly higher than 4%, it is observed on smallest bend specimens of the testing set, Table 3.

The error on estimated stable crack growth, Δa , compared with the measured ones by heat tinting is around a maximum allowed value (15%). Nevertheless, the smallest bend specimens with $B=6.25\text{mm}$ show error values higher than 15%.

A possible explanation about these errors leads to extraneous compliance between specimen and test machine fixture not completely compensated by displacement correction factor used in the program. Therefore, it is necessary to continue the analysis on this particular subject in order to improve better accuracy.

Figure 2 corresponding to material D shows a comparative analysis of the J initiation values, between unloading compliance method and direct one, defined according with ASTM blunting line criterion ($J_{0.2}$) and the J value (J_i) obtained where the power law fit crossed the blunting line defined by stretch zone width (SZW) theoretical expression (Kobayashi et al, 1983; Kiyotsugui et al, 1983; Heerens et al, 1988) given by:

$$SZW = 0.4 d n^* J/E \quad (3)$$

where:

$$d n^* = E / \sigma_0 d n$$

$d n$ = factor relating CTOD to J-integral

σ_0 = reference stress of a power law fit to the true stress-strain curve.

J-initiation values at SZW and $J_{0.2}$, from unloading compliance technique and direct method program, show an acceptable agreement. In the same manner J-R curves estimated from the both methodologies present a good fitting each other.

For the smallest bend specimens an acceptable agreement between direct method and multiple specimens J-R curves is observed, Figure 3.

Finally, direct method used to obtain J-R curve by mean of the computational program, DMP, presented in this paper verifies a reasonable agreement, for engineering purpose, with unloading compliance technique and multiple specimen one. Therefore, a simple testing methodology could be applied on small specimen using DMP to determine a suitable J initiation parameter and J-R curve to apply in elastic-plastic fracture mechanics assessment methods such as CEGB R6 Rev.3 (Milne et al, 1986) and EPRI Handbook (Kumar et al, 1981).

REFERENCES

ASTM E 1152-87(1987). Standard Test Method for Determining J-R curves.

ASTM E 813-87(1987). Standard Test Method for J_{Ic} , A measure of Fracture Toughness.

Kumar, V. et al. (1981). An Engineering Approach for Elastic-Plastic Fracture Analysis, EPRI Report-NP1931.

- Asta, E.P. et al(1991).Evaluation of J-R Curve Test Methods on Materials for Reactor Pressure Vessels,SMIRT11 Transactions Vol.G pp225-229.
- Kobayashi,H. et al.(1983).Evaluation of Blunting Line and Elastic-Plastic Fracture Toughness,ASTM STP 803, pp II-420-438.
- Kyotsugu, O. et al(1983).Evaluation of Several JIc Testing Procedures Recommended in Japan.ASTM STP 803, pp II-308-419.
- Heerens,J.et al(1988).Results of a Round Robing on Stretch Zone Width Determination,Fatigue Fract.Engng.Mater.Strut.,Vol 11 N1,pp19-29.
- Milne,I.et al(1986).CEGB Report R/H/R6,Rev.3.

Table 1. Chemical composition (%)

Material	C	S	Si	Mo	Cu	Cr	Mn	P	Ni
A	0,160	0,001	0,12	0,6	0,01	0,1	1,37	0,012	0,6
B	0,175	0,001	0,17	0,5	0,18	0,1	1,33	0,019	0,6
C	0,168	0,001	0,18	0,5	0,01	0,1	1,33	0,012	0,7
D	0,180	0,005	0,25	0,5	0,04	0,1	1,33	0,007	0,7

A = A533 Gr. B Cl. 1 (hot rolled)

B = A533 Gr. B Cl. 1 (hot rolled)

C = A533 Gr. B Cl. 1 (forging)

D = A508 Cl 3 (forging)

Table 2. Mechanical properties at room temperature.

Material	Rp 0.2 [MPa]	Rm [MPa]	A ₅ (%)	Z (%)	$\sigma_y = \frac{R_p 0.2 + R_m}{2}$ [MPa]
A	476	601	25,2	73,8	538,5
B	565	677	26,6	73,8	621,0
C	473	627	29,1	72,0	550,0
D	440	580	26,4	71,0	510,0

Table 3. Estimated and measured crack growth, direct method.

Specimen	Thickness B (mm)	Initial Crack Length (mm)	Final Crack Length (mm)		afm-af (mm)	Error %	Crack Growth Δa		$\Delta a_m - \Delta a_p$ (mm)	Error %
			ao measured	afm measured	af estimated					
A-1	12.7	15.31	17.58	16.83	0.75	4.2	2.27	1.92	0.35	15.4
B-1		15.86	17.30	17.75	-0.45	2.6	1.44	1.25	0.19	13.2
C-1		15.61	17.59	17.16	0.43	2.4	1.98	1.70	0.14	14.0
C-2		15.02	16.28	16.10	0.18	1.1	1.26	1.17	0.09	7.1
D-1	6.25	16.04	17.67	17.22	0.45	2.5	1.62	1.21	0.41	25.3
B-2		7.96	10.20	9.68	0.52	5.1	2.24	1.72	0.52	23.0
A-2		8.12	9.42	8.83	0.59	6.2	1.36	1.03	0.33	24.0

Figure 1. J-R curve results by direct method.

Figure 2.J-R curve obtained by direct method, $B=12.7\text{mm}$

Figure 3.J-R curve by direct method, $B=6.25\text{mm}$