Fracture 1977, Volume 3, ICF4, Waterloo, Canada, June 19 - 24, 1977

SPECIMEN SIZE EFFECT ON J-INTEGRAL FRACTURE TOUGHNESS

D. Sunamoto, M. Satoh, T. Funada and M. Tomimatsu*

INTRODUCTION

In order to analyze quantitatively the safety of a structure against brittle fracture, current engineering level requires to measure the plane strain fracture toughness K_{IC} of the structural steel and to analyze conservatively with linear elastic fracture mechanics. This K_{IC} needs to satisfy ASTM E399 and requires very thick specimens. K_{IC} at room temperature, sometimes, requires a ten-inch thick specimen. Therefore it is not allowed to be taken as a routine work to measure a K_{IC} by ASTM E399. This specimen size requirement is a bottleneck in fracture safe analysis.

Today, J-integral developed by Rice is extended to elastic-plastic region and admitted as an acceptable measure of fracture analysis. With J-integral method, relatively small specimen can result in valid K_{IC} which, by ASTM E399, can be measured from very large specimens. There are many researches on J-integral test analysis (typical method listed in Table 1). The authors studied specimen size effect on J-integral fracture toughness K_J (fracture toughness measured by J-integral method) and defined valid specimen size experimentally.

TEST

240 mm thick A533 Gr.BCℓ.1 steel was used. Chemical compositions and mechanical properties were shown in Table 2. Plane strain fracture toughness K_{IC} of the test material which met ASTM E399 requirements were shown in Figure 1. They used a 240 mm thick compact tension specimen to get valid K_{IC} at -20°C and 4TCT specimen at -50°C.

First, they applied J-integral method to valid K_{IC} test data. They used Rice (1) method shown in Table 1. In plane strain fracture toughness test, notch root displacement was measured. They converted notch root displacement to load point displacement and measured J_c and J-integral fracture toughness K_J as shown in Figure 3 and equation (1).

$$K_J = \sqrt{EJ_c/(1-\nu^2)} \qquad (1)$$

Where, E is Young's modulus, ν is Poisson's ratio, J_c is critical J-integral value. In Figure 3 rotational factor r of 1/3 was used considering the reports by Ingham [1] and Liebowitz [2]. As shown in Figure 3, K_J were almost equal to K_{IC} in elastic region and ASTM E399 requirements were satisfactory to J-integral method.

---

*Mitsubishi Heavy Industries, Limited, Takasago, Japan.

Next, they used 1/2TCT, 1TCT and 2TCT specimens with various crack length ratios shown in Figure 3 and conducted fracture test at -20°C and -50°C. They recorded load-displacement curves on a X-Y recorder and applied 4 J-integral methods shown in Table 1. At this time also notch root displacement was converted to load point displacement as before. Typical load-displacement curves at -20°C were shown in Figure 4. As shown in Figure 4, load-displacement curve of 1/2TCT specimen was not linear and indicated large plastic deformation. But the nonlinearity decreased as specimen size increased. The load-displacement curve of 2TCT specimen was almost linear and the curve of 240 mm specimen was linear.

Almost all specimens suffered from fibrous crack. Photograph 1 showed an example of fibrous crack and stretched zone of a 1TCT specimen (X 300). But this time, they didn't discuss on these micro-behaviour at crack tip. These matter will be reported at other chance.

Test results were listed in Table 4. Example of the comparison between 4 J-integral methods was shown in Figure 5. It was known that 4 methods gave almost same K_J.

The relation between K_J and specimen thickness was shown in Figure 6. K_J from 1/2TCT specimen varied very large. K_J data of 1TCT specimen varied less than 1/2TCT specimen and many of 1TCT specimens and all of 2TCT specimens, which number was limited, were almost equal to K_{IC} value. In Figure 6 also, K_{IC} estimated by another method were shown, such as Equivalent Energy (EE) method and COD. Fracture toughness by COD were greater than K_{IC} and those by EE method gave almost same value as K_J.

Considering the matter described above, they inquired the specimen size by which valid K_{IC} could be obtained. Necessary specimen size parameter α was shown in Figure 7. α was calculated by equation (2)

$$\alpha = \min\,(a,\ B,\ W-a)\cdot E\cdot\sigma_y\cdot/(1-\nu^2)\cdot K_J^{\,2}\ . \qquad (2)$$

Contrary to Begley's [7] and Griffis's [8] reports that required α to be greater than 50 and 100 respectively, α needed to be greater than 40 in order to get K_J as K_{IC}.

Figure 8 showed crack length ratio dependence of K_J, and it is known that crack length ratio should be greater than 0.4.

CONCLUSION

The authors conducted fracture test to a steel which plane strain fracture toughness was known and applied J-integral analysis. They obtained the following results.

1) No significant difference was recognized between J-integral methods.
2) Specimen size parameter α was to be greater than 40.

REFERENCES

1. INGHAM, T. et al, Proceedings of the Conf. Pract. Appl. Fracture Mech. Pressure-Vessel Technol., London, 1971.
2. LIEBOWITZ, H. et al, Symposium Mechanical Behaviour of Materials, Kyoto, 1974.
3. RICE, J. R. et al, ASTM STP 536, 1973, 231.
4. KANAZAWA, T. et al, IIW X-779-75, 1975.
5. RICE, J. R. et al, ASTM STP 514, 1972, 40.
6. MERKLE, J. G. et al, ASME Publication 74-PVP-33.
7. BEGLEY, J. A. et al, ASTM STP 514, 1972, 1.
8. GRIFFIS, C. A. et al, NRL Report 7676, 1974.

Photograph 1 Observation of Stretched Zone

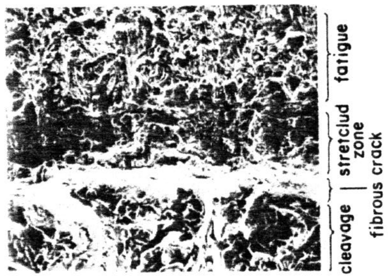


Table 1 J_C Method with Single Specimen

origin	equation
Rice (1) (3)	$J_C = \frac{2S}{B(W-a)}$
Kanazawa (4)	$J_C = -\left(\frac{1}{W-a} \cdot \frac{\alpha_{II}}{W}\right)P\delta_C + \left(\frac{2}{W-a} - \frac{\alpha_{II}}{W}\right)S$
Rice (2) (5)	$J_C = \frac{P\delta_C}{B(W-a)}\left\{1 + \frac{16D^2}{\beta\pi}\left(\frac{P}{P_L}\right)^2\right\}$ for $P<P_L$
Merkle (6)	$J_C = \frac{2}{B(W-a)} \cdot \frac{1+\alpha}{1+\alpha^2} \cdot S + \frac{2}{B(W-a)} - \frac{\alpha(1-2\alpha-\alpha^2)}{(1+\alpha^2)^2}(P\delta_C - S)$

Table 2 Test Material

1) Chemical compositions (%)

	C	Si	Mn	P	S	Ni	Mo
Cheok analysis	0.19	0.23	1.40	0.008	0.007	0.63	0.55

2) Mechanical properties

Tensile properties				Charpy transition temperature		Drop weight test
σ_y (MPa)	σ_B (MPa)	δ (%)	φ (%)	$_vT_{rE}$ (°C)	$_vT_{rS}$ (°C)	NDT (°C)
483	607	25.0	47.0	-5	-5	-20

Table 3 Correlation Between K_{IC} and K_J by Rice (1) Method Obtained from Plane Strain Specimen

Temperature (°C)	Specimen	K_{IC} (MPa·m$^{1/2}$)	K_J (MPa·m$^{1/2}$)
-125	2TCT	74.4	73.2
-100	2TCT	70.1	70.4
-100	4TCT	67.0	66.0
-75	4TCT	98.6	101.4
-20	240mmCT	151.0	143.5

Table 4 Test Results

Temp. (°C)	Speci-men	No.	a (mm)	B (mm)	W (mm)	a/W	max. load P_{max} (KN)	K_{max}	$K_J^{(1)}$ (Rice 1)	$K_J^{(2)}$ (Kanazawa)	$K_J^{(3)}$ (Rice 2)	$K_J^{(4)}$ (Merkle)
-20°C	½TCT	JH-1	9.1	12.8	25.6	0.36	36.4	117	326	275	-	357
		-2	10.4	12.8	25.6	0.41	24.0	87.1	122	121	122	135
		-3	10.9	12.7	25.4	0.43	27.3	106	241	206	-	262
		-4	14.1	12.8	25.6	0.55	17.9	98.9	291	238	-	310
		-5	10.8	12.7	25.4	0.42	17.3	66.7	277	221	227	300
		-6	16.2	12.8	25.6	0.63	11.1	84.0	299	235	-	316
		-7	16.3	12.7	25.4	0.64	10.5	83.7	252	258	-	272
		-8	17.7	12.8	25.6	0.69	6.0	59.9	84	78	-	89
		-9	17.7	12.7	25.4	0.70	7.6	78.8	259	215	-	272
	1TCT	JO-1	15.7	25.4	50.8	0.31	142	148	313	283	-	344
		-2	20.9	25.4	50.8	0.41	93.2	123	157	162	162	174
		-3	20.7	25.4	50.8	0.41	93.7	122	156	160	160	172
		-4	25.9	25.4	50.8	0.51	71.3	123	162	129	-	173
		-5	25.8	25.4	50.8	0.51	62.4	107	147	127	136	159
		-6	30.0	25.4	50.8	0.59	42.8	97.4	120	122	129	130
		-7	30.1	25.4	50.8	0.59	49.4	114	193	172	-	206
		-8	38.1	25.4	50.8	0.75	16.5	80.6	155	135	152	162
		-9	41.1	25.4	50.8	0.81	9.6	66.4	157	126	144	163
	2TCT	JT-1	53.3	50.8	101.6	0.52	202	129	140	148	148	153
		-2	52.2	50.8	101.6	0.51	204	126	137	142	142	150
-50°C	½TCT	JH-11	8.5	12.7	25.4	0.33	31.0	96.1	155	182	-	174
		-12	8.7	12.7	25.4	0.34	32.8	103	195	180	-	214
		-13	10.5	12.7	25.4	0.41	27.2	102	184	166	-	200
		-14	10.9	12.7	25.4	0.43	24.5	95.5	134	130	137	147
		-15	10.3	12.7	25.4	0.41	17.7	64.8	116	114	-	128
		-16	11.1	12.7	25.4	0.44	15.1	60.2	125	115	111	136
		-17	16.6	12.7	25.4	0.65	6.9	58.0	65	68	72	72
		-18	15.8	12.7	25.4	0.62	10.7	78.1	155	133	-	165
		-19	18.2	12.7	25.4	0.72	5.3	61.7	136	114	-	143
		-20	18.4	12.7	25.4	0.72	5.0	60.2	82	77	87	86
	1TCT	JO-21	26.1	25.4	50.8	0.51	56.9	99.5	113	119	121	124
		-22	25.9	25.4	50.8	0.51	52.6	90.9	97	104	114	107
	2TCT	JT-21	52.7	50.8	101.6	0.52	182	114	117	127	125	129
		-22	53.2	50.8	101.6	0.52	131	83.7	84	91	87	92

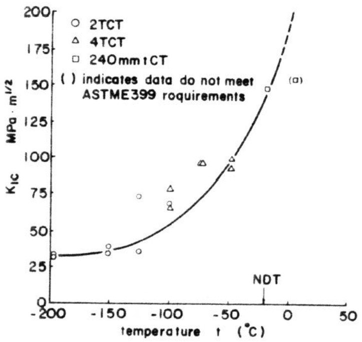


Figure 1 Plane Strain Fracture Toughness K_{IC} of Test Material

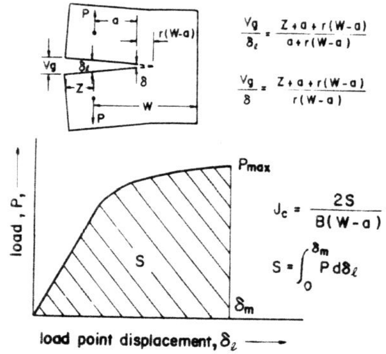
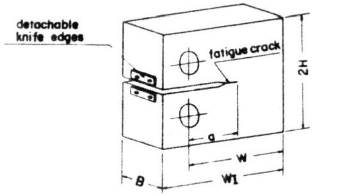


Figure 2 Experimental J-Integral Value



	B	W_I	2H	W	a/W
½TCT	12.7	31.8	30.4	25.4	0.3 ~ 0.8
1TCT	25.4	63.5	61.0	50.8	
2TCT	50.8	127.0	122.0	101.6	≈0.50

(mm)

Figure 3 Compact Tension Specimen

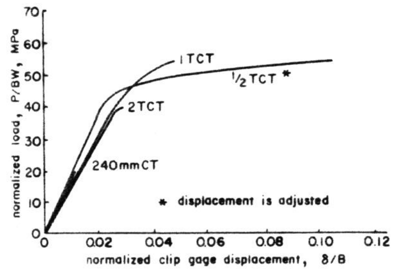


Figure 4 Typical Load-Displacement Curves (-20°C, a/w ≈ 0.5)

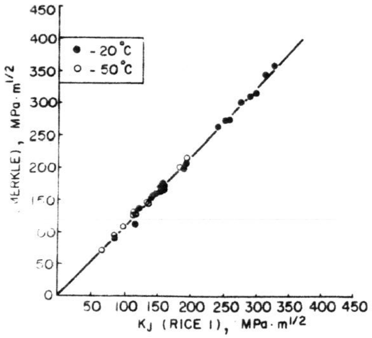


Figure 5 Comparison Between J-Integral Methods

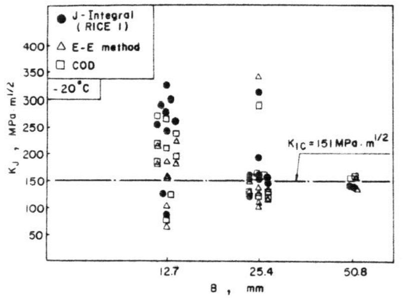


Figure 6 Variation of K_J on Specimen Thickness

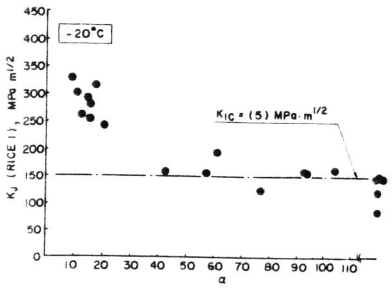


Figure 7 Necessary Specimen Size Parameter α to give Valid K_J

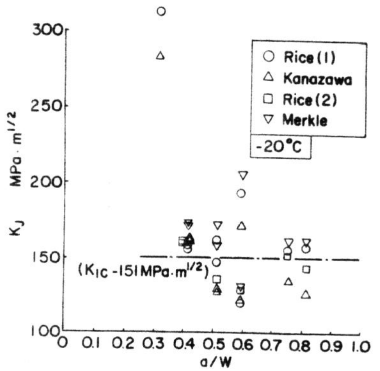


Figure 8 Correlation Between K_J and Crack Length Ratio