Title	Static Fracture Ductility of Structural Members(WELDING MECHANICS, STRENGTH AND DESIGN)
Author(s)	Horikawa, Kohsuke; Hayashi, Kenji
Citation	Transactions of JWRI. 1982, 11(1), p. 123-129
Version Type	VoR
URL	https://doi.org/10.18910/9671
rights	
Note	

Static Fracture Ductility of Structural Members†

Kohsuke HORIKAWA* and Kenji HAYASHI**

Abstract

The effects of notch ratio, structural stress concentration and mechanical properties of steel on the fracture behavior of structural members were investigated in order to acquire a basic knowledge of their resistance to ductile fracture.

A method was suggested that determined toughness requirements of structural steels according to elongation required of structural members.

KEY WORDS: (Fracture Mechanics) (Ductility) (Notch Effect) (Elongation) (Structural Members) (Static Fracture Test)

1. Introduction

Failures of welded structures, such as bridges and pressure vessels, are often initiated from the connections where stress concentration due to structural discontinuities and residual stress are high. Now, we consider the unstable fracture in welded connections at normal temperature. When a welded crack exist, it propagates as stable fibrous crack and then changes into unstable fracture, while any welded crack does not exist, fracture occurs due to local contraction.

Many studies have been made on the unstable fracture started from stable fibrous crack. An estimation was made on the fracture mechanics energy balance with consideration of the energy flowing into fracture process zone[1]. Investigations were also carried out on the unstable brittle fracture with stable fibrous crack growth in connection with a COD-criterion[2),3]. By the comparison of the results of the J-integral analysis and fractography it is confirmed that the fracture toughness of metallic materials corresponds to a stretched zone width[4]. An analysis was performed by the J-integral Resistance curves on the instability behavior of massive plastic deformation in low strength and high toughness materials, and it was supposed that tearing modulus was the slope of the J-integral Resistance curve as the material's resistance to stable tearing[5),6].

An experimental study was made on the application of the COD-criterion to defect estimation for the connections with a structurally stress concentration in welded structures. The relationships between the crack opening displacement and overall strain in such connections were investigated from the viewpoint that they were required a certain amounts of elongation capacity[7].

In this paper, discussions on the transition from stable crack growth to unstable fracture were made by using the J-integral value defined at maximum load (J_c). Center notched plate specimens and structural model specimens were examined on the behavior of fracture from stable tearing. The specimens were made from mild steel SS41 and high tensile strength steel HT80. Ductilities required for structural members were clarified from the comparison of the J-integral and overall strain in them.

2. Experimental Procedures

For the purpose of the examination on the propagating shear behavior of structural members, tensile tests were performed using center notch specimens and structural specimens which were modeled after welded connections with stress concentration due to structural discontinuities (**Fig. 1**).

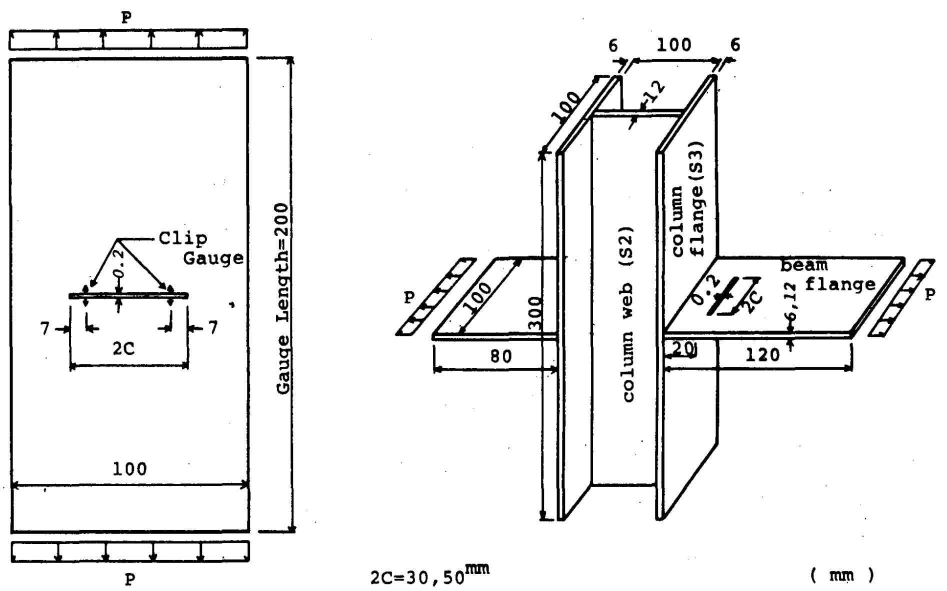
Mild steel SS41 and high tensile strength steel HT80 of the plate thickness with 6 mm and 8 mm were used as the test materials. Chemical compositions and mechanical properties of the used materials are shown in **Table 1** and **2**, respectively.

The strain in the vicinity of a notch tip was measured by wire strain gauges and the COD at the point of 7 mm apart from the notch tip by clip gauges. The elongation of specimen was measured by dial gauges, gauge length 200 mm. The configuration of the plastic zone was observed by the stresscoat attached to the surface of specimen.

As for structural specimens, the change of the distance between two column flanges was also measured by a slide-caliper gauge. The total elongation of the

† Recieved on March 31, 1982
* Associate Professor
** Research Associate, Technological University of Nagaoka

Transactions of JWRI is published by Welding Research Institute of Osaka University, Ibaraki, Osaka, Japan



(a) Center Notch Specimen (b) Structural Specimen

Fig. 1 Specimen configurations

structural specimen minus the distance change of flanges was used as the elongation of specimen.

3. Experimental Results and Consideration

3.1 Evaluation of Experimental Results

The J-integral and COD have been widely used as the effective parameters that represent the stress-strain field surrounding a crack tip in condition of small scale yielding and large scale yielding. The application of the J-integral and COD to the tearing instability (unstable fracture after stable tearing and no interceding cleavage fracture) with crack extension is not exactly proper (the details will be described later), but they can be used at least as parameters that indicate the behavior of plastic deformation near a crack tip.

From the tensile test results on center notched plate specimens with crack length (2C), width (W) and thickness(t) as illustrated by **Fig. 2**, the crack tip opening displacement (CTOD) is given by the ex-

Table 1 Chemical compositions of materials used (%)

Mark	Steel Grade	Plate Thickness	C	Si	Mn	P	S	Cu	Cr	Mo	V	B
S1	SS41	6mm	0.10	0.10	1.00	0.020	0.010					
S2		12	0.12	0.19	0.71	0.027	0.008					
S3 *)		6	0.21	0.01	0.69	0.016	0.009					
H1	HT80	6	0.13	0.26	0.90	0.016	0.004	0.24	0.86	0.32	0.04	0.0008
H2		12	0.16	0.24	0.84	0.023	0.008	0.23	1.02	0.34	0.01	0.0008

*) : S3 was used as a material of the column flange plates (explained later).

Table 2 Mechanical properties of materials used

Mark	Steel Grade	Plate Thickness mm	Yield Strength kg/mm^2	Ultimate Strength kg/mm^2	Total Elongation %	Uniform Elongation %	Reduction of Area %	Maximum True Strain
S1	SS41	6	26.4	42.6	33.7	23.4	63.3	1.003
S2		12	28.5	44.6	37.3	26.9	60.4	0.926
S3		6	38.2	49.1	31.2	20.9	65.9	1.077
H1	HT80	6	86.8	90.6	14.9	6.8	53.0	0.754
H2		12	102.0	108.0	16.7	6.1	61.4	0.953

pression

$$\mathrm{CTOD}=\frac{\phi(C)}{\phi(x)}\cdot v, \tag{1}$$

where v is the crack opening displacement at any point on the x axis and $\phi(x)$ can be evaluated from the applied stress (σ), yield stress (σ_Y) and Young's modulus (E)[8],

$$\phi(x)=\frac{4W\sigma_Y}{\pi^2 E}\sin\alpha\int_{\chi}^{\frac{\pi}{2}}\frac{\cos\alpha}{\sqrt{1-\sin^2\alpha\sin^2\chi}}\ln\left|\frac{\sin(\chi+\psi)}{\sin(\chi-\psi)}\right|d\chi \tag{2}$$

And α, χ, ψ, and a are given by

$$\left.\begin{array}{l}\sin\alpha=\sin\left(\pi\frac{a}{W}\right),\\ \cos(\pi\sigma/2\sigma_Y)=\sin(\pi C/W)/\sin\alpha,\\ \sin\chi=\sin(\pi x/W)/\sin\alpha,\\ \sin\psi=\cos(\pi\sigma/2\sigma_Y),\\ \text{and } a=C+R \text{ (R: plastic zone size).}\end{array}\right\} \tag{3}$$

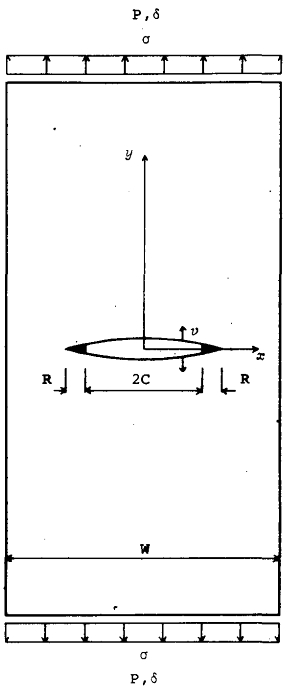


Fig. 2 Geometry and coordinate systems for Center Notched Plate

The J-integral is given by[9]

$$J=G+\frac{1}{t(W-2C)}\{2\int_0^{\delta}Pd\delta-P\delta\}, \tag{4}$$

where G is the energy release rate based on linear elastic fracture mechanics concepts and P and δ are the applied load and load-point displacement, respectively.

If the crack is deep enough that plasticity is confined to the ligament, the plastic component of δ is equal to that of v. As a consequence, eq. 4 may be rewritten

$$J=G+\frac{1}{t(W-2C)}\{2\int_0^{v}Pdv-Pv\}. \tag{5}$$

The critical values of J and CTOD (J_c and $CTOD_c$) defined at maximum load can be used as an index which represents the material's resistance to tearing instability. Hence, the overall strain of notched plates at maximum load is considered as the elongation capacity of notched plates similarly to the uniform elongation measured in the uni-axial tension test. Hereafter, the overall strain defined at maximum load was refered as *fracture ductility* in this paper.

3.2 Members' Behavior at Maximum Load

At maximum load, from the balance of the increase of the member's strength due to the strain hardening and the decrease of the member's strength following to deformation, the expression

$$dP=\sigma dA+Ad\sigma=0 \quad \text{(A: sectional area)} \tag{6}$$

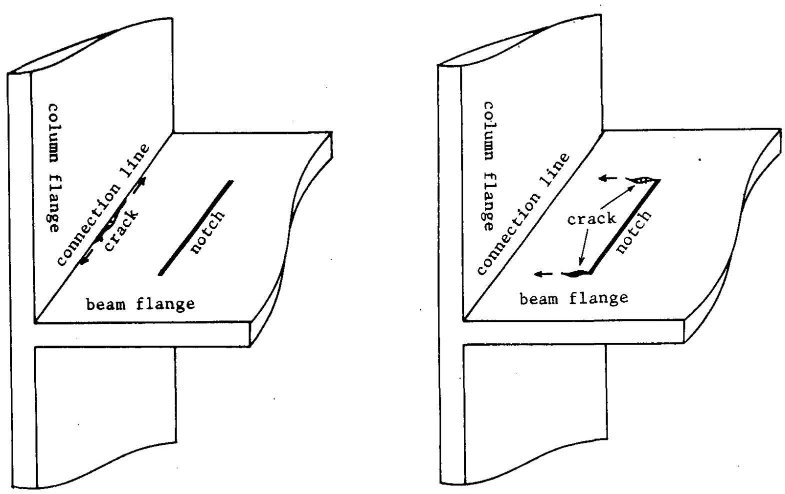
is formed. The smooth plate results in break at maximum load owing to the necking. The notched plate results in break owing to the decrease of its sectional area according to the crack extention or necking, so it can be said that the crack extention or necking dominate the maximum load. Hence, the method which considered the effects of the crack extention or necking must be used so as to pursue the member's behavior in the vicinity of the maximum load. The COD is the parameter of deformation in plane and can not deal with the necking because the necking includes the out-of plane deformation. The J-integral is the potential energy release rate at the crack growth. Strictly speaking, the J-integral can not be applied to fracture with the necking because the potential energy is not released by the necking. The treatment on the necking by the energy method may not be denied.

J_c and $CTOD_c$ of tested specimens are given by **Table 3**. In SH-12-30, the crack initiated from the central portion of the column flange near the beam to column flange connection and then the crack propagated outwards slowly along the beam-column connection line (**Fig. 3**(a)). In SH-6-30 and SH-12-50, the crack initiated from the neighborhood of the notch tip towards the beam-column connection and broke in sliding mode (Fig. 3(b)). The fracture surfaces of remaining specimens in Table 3 were perpendicular to plate surface in the middle of the plate thickness up to about 2 mm from the notch tip, and slant beyond that. The notch strength ratio of center notch specimens was almost equal to 1.0 and that of structural specimens was from 0.45 to 0.88 owing to

Table 3 Some Critical Values at Maximum Load

Specimen	Mark	Material used	Notch Length mm	Notch Strength Ratio	Clip Gauge Displacement v mm	$CTOD_C$ mm	$J_C(\delta)$ kgmm/mm²	$r=\frac{J_C(\delta)}{J_C(v)}$	$m=\frac{J_C(\delta)}{\sigma_Y \cdot CTOD_C}$
Center Notch	NS-6-30*	S1	30	0.98	3.53	2.39	106	1.01	1.68(1.05)**
	NS-6-50	S1	50	0.98	2.84	1.77	80	1.05	1.68(1.05)
	NS-12-30	S2	30	0.95	3.90	2.64	159	0.90	2.11(1.35)
	NS-12-50	S2	50	1.00	4.57	2.86	166	0.97	2.03(1.30)
	NH-6-30	H1	30	0.98	1.76	1.16	141	0.93	1.40(1.34)
	NH-6-50	H1	50	1.00	2.05	1.28	160	0.97	1.44(1.38)
	NH-12-30	H2	30	1.05	3.22	2.25	305	0.89	1.33(1.25)
	NH-12-50	H2	50	1.06	2.94	1.92	304	1.01	1.55(1.47)
Structural	SS-6-30	S1	30	0.78	5.00	3.39	120	0.96	1.34
	SS-6-50	S1	50	0.88	5.69	3.56	136	1.01	1.44
	SS-12-30	S2	30	0.45	5.79	3.56	119	1.19	1.17
	SS-12-50	S2	50	0.49	6.07	4.12	145	0.80	1.23
	SH-6-30	H1	30	0.64	——	——	——	——	——
	SH-6-50	H1	50	0.63	5.00	2.02	220	1.00	1.26
	SH-12-30	H2	30	0.33	——	——	——	——	——
	SH-12-50*	H2	50	0.53	——	——	——	——	——

*): NS-6-30; Center Notch Specimen, SS41, plate thickness = 6mm and notch length = 30mm
SH-12-50; Structural Specimen, HT80, plate thickness = 12mm and notch length = 50mm
**): $m = J_C/(\sigma_B \cdot CTOD_C)$, σ_B : Ultimate Strength (kg/mm²)



(a) (b)

Fig. 3 Fracture Mode

stress concentration. The stress concentration factor depends on the stiffness ratio of the beam flange to the column flange. The larger the plate thickness of the beam flange is, or, the higher the strength of the beam flange is, the larger the stress concentration factor grows[10].

The ratio(r) of the J_c-value given by a load-point displacement ($J_c(\delta)$) to the J_c-value by a clip-gauge displacement ($J_c(\nu)$) was from 0.80 to 1.19. Therefore, $J_c(\nu)$ coincides with $J_c(\delta)$ rather well. This results from that the plastic deformation is confined to the remaining ligament. Both J_c and $CTOD_c$ were relatively constant values in the same material and specimen even for different notch lengths. It seems, however, that the reason, why the $CTOD_c$ was widely scattered and the $CTOD_c$ of center notch specimens differed much from the $CTOD_c$ of structural specimens, was that the crack propagated and the CTOD didn't represent the crack tip opening displacement any longer. On the contrary, J_c of center notch specimens was in comparatively good agreement with J_c of structural specimens, although J_c was not considered the crack extention.

The relation between J_c and $CTOD_c$ was dependent upon the flow stress (σ_{flow})[5]. As center notch specimens broke at the stress level of the tensile strength (σ_B) rather than the yield stress (σ_Y), σ_{flow} was equal to σ_B. And σ_{flow} of structural specimens coincided with σ_Y, because they fractured at the relatively low load.

3.3 Relationship between J-integral and Net Stress

The relation between the J-integral and net stress is illustrated in **Fig. 4**. Here, the longitudinal axis is the ratio of the J-value to the elastic component of the J-value ($G=K_I^2/E$, where K_I is the stress intensity factor at opening mode in plane state of stress), and the lateral axis is the net stress (σ_N), normalized by the yield stress (σ_Y). Notched plate series of NH and NS showed the abrupt non-linearity when σ_N was close to σ_Y. Specimens of NH series fractured at $\sigma_N/\sigma_Y=1.0$ and those of NS series fractured at about $\sigma_N/\sigma_Y=1.5$ due to plastic flow. Structural specimens of SS and SH series showed the non-linearity from comparatively lower stress (below $\sigma_N/\sigma_Y=0.5$) because of structural stress concentration. The plastic deformation expanded slowly to fracture in the lower stress than NS and NH series. As for notched plate specimen series, NS and NH, test specimens of plate thickness 12 mm showed the non-linearity earlier than that of 6 mm, for the deformation behavior of specimens in the plate thickness 6 mm was more close to the plane state of stress. SS series, however, was opposite to notched plate series because the effect of stress concentration on the non-linearity was more serious than the effect of the plate thickness. From the above facts, it is noted that the mechanical properties and stress concentration affects on the relation between the J-integral and net stress.

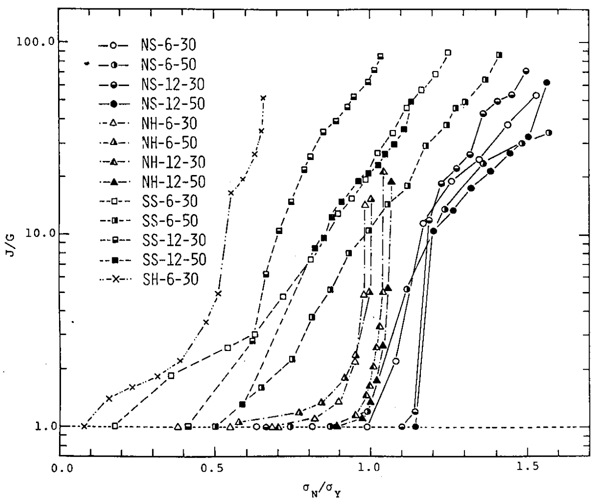


Fig. 4 Relationship between J-integral and Net Stress

3.4 J-integral and Crack Tip Opening Sisplacement

In small scale yielding and large scale yielding, the relation between the J-integral and CTOD assuming as Dugdale model is given by the expression[11]

$$J=m\sigma_Y\cdot CTOD, \tag{7}$$

where m is a value dependent on the triaxiality of stress and it is considered that $m=1$ in the plane state of stress and $1<m<3$ in the plane state of strain.

In this paper, within the range from small scale yielding to general yielding, the relation between J and CTOD was given by the expression

$$\log CTOD=0.79\log(J/\sigma_Y)+0.024\,. \tag{8}$$

for both center notch specimens and structural specimens as shown in **Fig. 5**. This result is in relatively good agreement with the case that $m=1$ in eq. 7, but it is noted that there are some difference between the two equation. The reason of this difference seems that eq. 7 has neglected the effects of the strain hardening and flow stress. From the fact that eq. 8 is valid also for structural specimens with stress concentration, it is noted that the stress con-

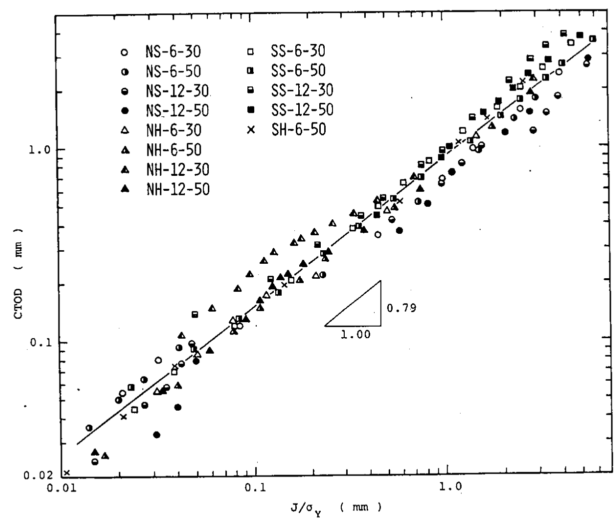


Fig. 5 Relationship between J/σ_Y and CTOD J/σ_Y (mm)

centration has no influence on the relation between J and CTOD.

3.5 Relationship between J-integral and Overall Strain

In conventional Rice's J-integral, eq. 4, setting the elastic and plastic component of J as J_{el} and J_{pl} respectively, they become

$$J_{el}=G=K_I^2/E\,, \tag{9}$$

$$\text{and } J_{pl}=\frac{1}{t(W-2C)}\left\{2\int_0^{\delta}Pd\delta-P\delta\right\}. \tag{10}$$

The stress intensity factor K_I of a internally notched plate of finite width is given approximately by the expression using the applied stress (σ)

$$K_I=\sigma\sqrt{\pi\cdot C}\left(\sec\frac{\pi C}{W}\right)^{\frac{1}{2}}. \tag{11}$$

As the relation between (σ) and the load-point displacement(δ) is $\sigma\cong E\sigma/l$ (l: plate length), subsutituting eq. 11 and this into eq. 9, it becomes

$$J_{el}\cong\left\{\frac{\pi CE}{l^2}\sec\left(\frac{\pi C}{W}\right)\right\}\delta^2\,, \tag{12}$$

and, as a result, J_{el} is proportional to δ squared.

While presuming a increment of eq. 10

$$dJ_{pl}=\frac{1}{t(W-2C)}\,(Pd\delta-P\delta)\,. \tag{13}$$

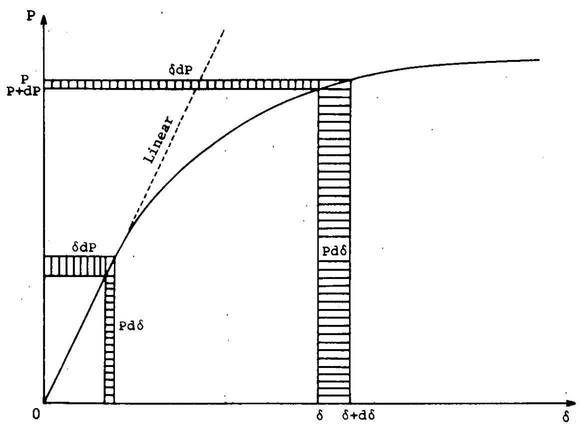


Fig. 6 Load-Displacement Curve

In **Fig. 6**, if the relation between load (P) and displacement(δ) is linear, $dJ_{pl}=0$ because $Pd\delta=\delta dP$. As the plastic deformation is increasing, dJ_{pl} is reaching to the proportional value of $Pd\delta$, that is, J_{pl} is proportional to δ because $Pd\delta\gg\delta dP$. As a consequence, in the case with massive plastic deformation,

$$J_{pl}\propto\delta\,. \tag{14}$$

J is in proportion to the square of δ by eq. 12 for small scale yielding on account that $J_{el}\gg J_{pl}$, and to δ by eq. 14 for general yielding on account that $J_{pl}\gg J_{el}$. Therefore, now, setting that $\log J=n\log\delta+C$ (C: constant), it is expected that 1) $n=2$ for small scale yielding, 2) $1<n<2$ from large scale yielding to general yielding and 3) $n=1$ after general yielding.

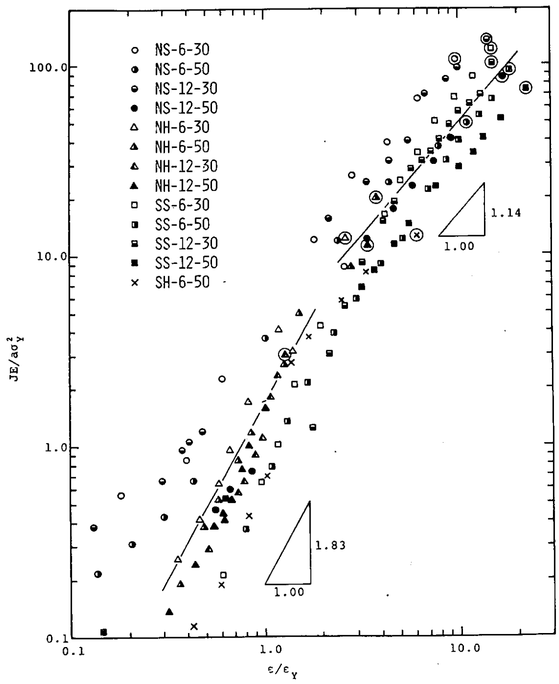


Fig. 7 Non-dimensional J-integral, $JE/a\sigma_Y^2$, vs. Overall Strain, $\varepsilon/\varepsilon_Y$

The relationship between J and overall strain (ε) is illustrated in **Fig. 7** (Circle points indicated the maximum value of elongation which was refered as fracture ductility.), and was obtained by the expression regardless of stress concentration using regression estimates,

$$JE/a\sigma_Y^2\propto(\varepsilon/\varepsilon_Y)^{1.83}\quad(\varepsilon/\varepsilon_Y\leqq 2.0) \tag{15}$$

$$\text{and } JE/a\sigma_Y^2\propto(\varepsilon/\varepsilon_Y)^{1.14}\quad(\varepsilon/\varepsilon_Y>2.0) \tag{16}$$

where ε_Y is the yield strain. The obtained results agreed with the above mentioned concept rather well. If the overall strain applied to structural members is already known, toughness requirements, expressed by J, of materials can be determined by eq. 15 and 16. Therefore, it seems that eq. 15 and 16 give an essential information about the selection of materials.

Fracture ductility, representing the elongation capacity of structural members with cracks, had the relation, regardless of stress concentration such as notch ratio and structural stress concentration, that

$\varepsilon/\varepsilon_Y \fallingdotseq 10$ in SS41 and $1<\varepsilon/\varepsilon_Y<6$ in HT80. From this it is found that fracture ductility of structural members is greater in SS41 than in HT80.

4. Conclusions

With respect to tearing instability of structural members from stable fibrous crack growth, the effects of notch ratio and stress concentration due to structural discontinuities on elongation capacities of structural members were investigated based on the consideration of required ductilities for structural members. Main conclusions are summarized as follows;

(1) The J-value defined at maximum load (J_c) was independent of stress concentration due to notches and structural discontinuities. The relation between J_c and $CTOD_c$ was dependent upon flow stress.

(2) Within the limits of this experiment, the relationship between J and CTOD was independent of stress concentration and dependent only upon yield strength (σ_Y) of the material. The relation is given by the expression

$$\log CTOD = 0.79 \log (J/\sigma_Y) + 0.024 .$$

(3) The relation between the non-dimensional J and overall strain (ε) was given by the expression

$$JE/a\sigma_Y^2 \propto (\varepsilon/\varepsilon_Y)^{1.83} \quad (\varepsilon/\varepsilon_Y \leqq 2.0)$$

and $$JE/a\sigma_Y^2 \propto (\varepsilon/\varepsilon_Y)^{1.14} \quad (\varepsilon/\varepsilon_Y > 2.0) .$$

(4) Fracture ductility, expressing the elongation capacity of structural members with cracks, is greater in mild steel SS41 than in high tensile strength steel HT80 regardless of stress concentration.

Acknowledgement

The authors would like to acknowledge the continuing gaidance and encouragement of Professor Y. Maeda of Osaka University and Professor M. Sasado of Technological University of Nagaoka.

References

1) J.R. Rice; "An Examination of the Fracture Mechanics Energy Balance from the Point of View of Continuum Mechanics", Proc. 1st Int. Conf. on Fracture, 1965.
2) K. Satoh, M. Toyoda and Y. Itoh; "Unstable Brittle Fracture with Stable Fibrous Crack Growth", J. of the Soc. of Naval Arch. of Japan,. Vol 141 (1977), 268–274 (in Japanese).
3) K. Satoh, M. Toyoda and Y. Itoh; "General Yielding Fracture of Low Strength Steels with Surface Type Shallow Notch", J. of the Soc. of Naval Arch. of Japan, Vol 144 (1978), 309–315 (in Japanese).
4) H. Nakamura, H. Kobayashi and H. Nakazawa; "J-integral Evaluation of Stretched Zone Width and Its Application to Elastic-Plastic Fracture Toughness Test", Trans. of the Japan Soc. of Mech. Eng., Vol 46A (1979), 336–345 (in Japanese).
5) P.C. Paris, H. Tada, A. Zahoor and H. Ernst; "The Theory of Instability of the Tearing Mode of Elastic-Plastic Crack Growth", ASTM STP 668 (1979), 5–36.
6) J.H. Hutchinson and P.C. Paris; "Stability Analysis of J-Controlled Crack Growth", ASTM STP 668 (1979), 37–63.
7) K. Nagai, K. Kajimoto and K. Taniguchi; "On the Characteristics of Brittle Fracture Initiation in a Structurally Stress Concentrated Region", J. of the Soc. of Naval Arch. of Japan, Vol 144 (1978), 420–428.
8) B.A. Bilby, A.H. Cottrell, E. Smith and K.H. Swinden: "Plastic Yielding from Sharp Notches", Proc. Roy. Soc. A, Vol 279 (1964), 1–9.
9) J.R. Rice, P.C. Paris and J.G. Merkle; "Some Further Results of J-integral Analysis and Estimates", ASTM STP 536 (1973), 231–245.
10) M. Hoshino, K. Horikawa and T. Okumura; "Strength of Connections with Heavy Stress Concentration Due to Structural Discontinuities", IIW Doc. X-572–70 (1970), 1-12.
11) J.R. Rice, Ed. by Liebowitz, H.; "Fracture II", Academic Press, New York (1968), 191. .