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The Application of J_{IC} Fracture Criterion to the Fracture of Connections in Steel Structures

Application du critère de rupture J_{IC} au comportement à la rupture d'assemblages en construction métallique

Anwendung des Bruchkriterions J_{IC} auf das Bruchverhalten von Verbindungen im Stahlbau

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1. INTRODUCTION

The criterion based on critical stress intensity factor K_{IC} is applicable to brittle fracture in low stress level, and the design procedure has been satisfactorily established on this account. While, much of our concern is now paid to the fracture in high stress level such as the case of general yielding in the section of members. One of the examples of this kind is the transition fracture of heavy members of framework at room temperature reported by Prof. Ben Kato.[1]

As one of the nonlinear fracture mechanics, the COD criterion is introduced in the introductory report, and strain around crack tip has been related to crack opening displacement by F.M.Burdekin.[2] The COD theory, however, reveals to be indefinite in its physical concept when applied to wider yield portion. On the other hand, comprehensible is the physical concept of J_{IC} fracture criterion[3,4] which is the extension of the concept of energy release rate G to nonlinear region, and because J_{IC} is comparatively insensitive to the scale effect, the specimens to obtain J_{IC} may be made smaller than those for K_{IC}.

In discussing the basic applicability of J_{IC} fracture criterion, J_{IC} value of SM50B(B class) and SM58QT(C class) are obtained from the 3-point bending test at room temperature.

Bending tests are carried out for the specimens of 4 types in various stress distributions,[5] and the fracture configurations are discussed based on J_{IC} fracture criterion.

2. COMPARISON OF J_{IC} VALUES BETWEEN SM50B AND SM58QT

2.1 Specimens and Experimental Procedure

J_{IC} values are obtained from the 3-point bending test for which specimens are made from steel plates 25mm of SM50B and SM58QT. Chemical composition, mechanical properties and Charpy values of the materials are shown in Table-1~3 respectively.

The shape of the specimens, as shown in Fig.-1, is based on ASTM E399-72 and BS DD-19. All specimens are prepared with fatigue crack at the tip of the crack. Three kinds of crack length, 23mm, 25mm and 27mm are adopted for the specimens of SM50B. The crack length for the specimen of SM58QT is either 23mm or 25mm.

The bending test is carried out at room temperature(+20°C) and -65°C. Since it is difficult to determine the displacement δ_C experimentally to initiate crack propagation at room temperature, the crack propagation is checked by cutting the specimens in the cource of experiment after J. A. Begley and J. D. Landes.[6]

The value of J integral is obtained approximately from the following equation.

$$J = \frac{2}{Bb}\int_0^{\delta_i} P d\delta \qquad (1)$$

where, B: Width of the specimen
b: Difference of crack length a from height W
P: Load
δ: Displacement at the loading point

2.2 Test results

Relationships between J value and increment of crack length Δa are shown in Fig.-2 which are lead by P~δ diagrams in the bending test. The results from the experiments on various crack lengths present reasonable J_{IC} values. It is recognized, therefore, that the method proposed by Begley and Landes for determining J_{IC} value should be available.

Fig.-3 shows a comparison of J~Δa relationships between SM50B and SM58QT obtained from the bending test.

In the study by J. R. Rice, et al.[7], J value is calculated for simplified P~δ relationships composed of elastic part and perfectly plastic part beyond general yielding. In this paper, P~δ relations are computed up to the general yield point by applying finite element method. After reaching the general yield point, P~δ relation is assumed as perfectly plastic. Fig.-4 shows the element division of the specimen. Calculated values of J integral are compared with the experimental results in Fig.-5.

It is confirmed that the above method for estimation of J value by calculation should be available.

It is observed in Table-4 that J_{IC} value of SM58QT is considerably smaller than that of SM50B at room temperature. Seeing that J_{IC} value of SM58QT at -65°C is larger than that of SM50B, the difference of J_{IC} values at room temperature should be adequately noted.

3. DISCUSSION CONCERNING THE FRACTURE OF TEE-JOINTS

It is emphasized in the introductory report that the welding condition free of micro cracks and steels possessing enough notch toughness should be substantial to prevent unstable brittle fracture. Further investigation should be focussed on the relations of notch toughness of material and fracture under complex stresses such as connections in steel structure.

Bending tests by using the specimens of 4 types are carried out in various stress states and conditions of test temperature. As shown in Fig.-6, the thickness of the specimens is 25mm and roller span is 280mm.

The specimen of J-type has the ratio of thickness to width 25:35 and this type is a model to expect plane stress. The ratio

Table-1 Chemical Composition (%)

Grade of Steel	C	Si	Mn	P	S	Cu	Cr	Nb	V
SM50B PL25mm	0.16	0.39	1.46	0.014	0.025	0.01	—	—	—
SM50B PL65mm	0.16	0.46	1.45	0.008	0.007	0.31	0.03	0.036	—
SM58QT PL25mm	0.12	0.27	1.11	0.012	0.007	—	0.16	—	0.03

Table-2 Mechanical Properties

Grade of Steel	Y.P.	T.S.	EL.	φ
SM50B PL25mm	41	60		73
SM50B PL65mm	39	56	38	77
SM58QT PL25mm	55	71	30	71

Y.P.: Yield Point(kgf/mm²)
T.S.: Tensile Strength(kg/mm²)
EL.: Elongation(%)
φ: Reduction of Area(%)

Table-3 Charpy Values

Grade of Steel		$_vE_0$	$_vT_{rE}$	$_vT_{rS}$
SM50B PL25mm	Surface	15.1	-6	-7
	(1/2)t	12.5	-12	-10
SM50B PL65mm	Surface	30.0	-67	-65
	(1/2)t	30.0	-52	-54
SM58QT PL25mm		24.0 *		

$_vE_0$: Absorbed energy at 0°C, but * is at -5°C(kgf.m)
$_vE_{rE}$: Energy transition tempetrature (°C)
$_vE_{rS}$: Surface transition temperature (°C)

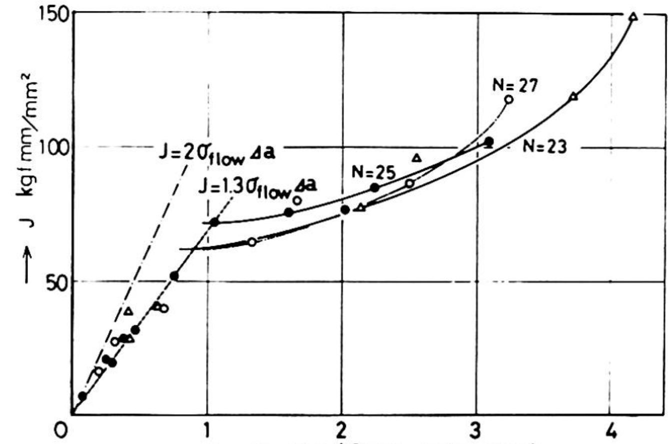

Fig.-2 Relations between J and Δa (SM50B)

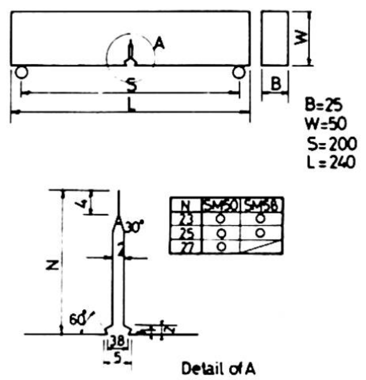

Fig.-1 Specimens for the 3-point bending test

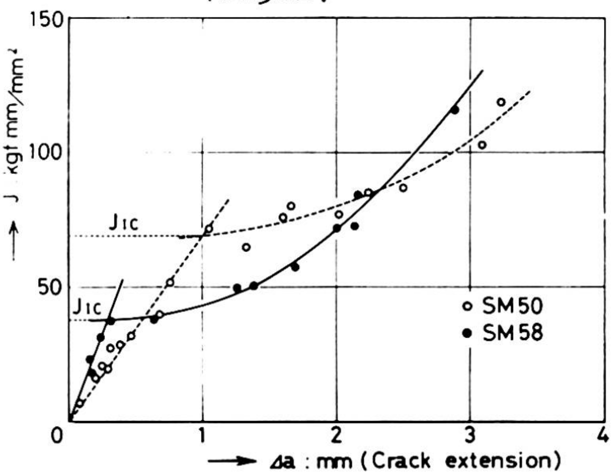

Fig.-3 A comparison of J~Δa relations between SM50B and SM58QT

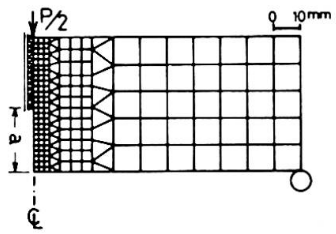

Fig.-4 Element division

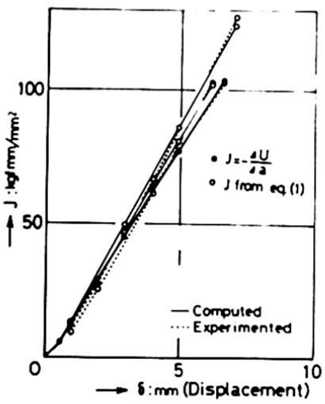

Fig.-5 Relations between J and δ

Table-4 J_{IC}(kgf.mm/mm²) values

Grade of Steel	Test Temperature	
	15°C	-65°C
SM50B pl25	63	12.8
SM58QT PL25	43	15.1

of M-type is 25:125 to expect plane strain state. B_T-type is made of steel plate 25mm with a Tee-joint where is welded. Tee flange of this type is the same dimension as M-type. The specimen of A_T-type is shaped from steel plate 65mm in order to eliminate the influence of welding. The dimension of A_T-type is same as that of B_T-type except fillet portion. The fillets of A_T and B_T-type are shown in detail in Fig.-7, respectively. The radius r at the toe of fillet in A_T-type specimen is determined to be 2mm in order to approach the same condition as the welded part in B_T-type. B_T specimen is built up by manual welding and stress relief annealing is not treated after welding. A_T and B_T-type are both pull-bend specimens.

The specimens of J-type, M-type and B_T-type are made from the steel plate which is dealt with at the preceding section. The properties of SM50B plate 65mm for A_T-type are also shown in Table-1~3. J_{IC} values for these mother metals and welded portion of the joint are summarized in Table-5.

Fig.-8 shows the relationships between the maximum bending angle θ_{max}(degree) and the test temperature T°C obtained from these bending tests.[4] It is observed in this figure that the more complex the stress state is, the smaller θ_{max} is. Especially, the specimen of B_T-type with welded joint might be the most fragile in these 4 types.

J values of the specimens are estimated by the method described at previous section. Element divisions are shown in Fig.-9.[4] J values are obtained by computing two P~δ relationships of the cases a/W=0 and a/W=2/25. Fig.-10 shows the computed results of P~δ relationships.

J_C value for each specimen which is J value at fracture of the specimen is determined by θ_{max} and P~δ curves. The ratio of J_C to J_{IC} is shown in Table-5.
This result indicates that the more complex the stress distribution of the specimen is, the smaller J_C/J_{IC} is. This ratio comes to almost unit in the case of B_T.

4. Conclusion

J_{IC} values of SM50B and SM58QT both of which are obtained from the 3-point bending test at -65°C are remarkably equal, nevertheless J_{IC} value of SM58QT is approximately 2/3 of that of SM50B at room temperature.

Experimental results from bending tests on various stress states of 4 types specimens indicate that the more complex the stress distribution is, the more fragile the joint of steel structure is. And this phenomenon can be explained by J_{IC} fracture criterion.

Finally, it should be pointed out that the independence of path in J integral is valid only under the deformation theory, and it is not directly applicable to the frames in which stress redistribution may take place significantly. J integral in this paper is introduced beyond limitation in this sence. It is necessary, therefore, to obtain more basic experimental data in order to apply J_{IC} fracture criterion in practice.

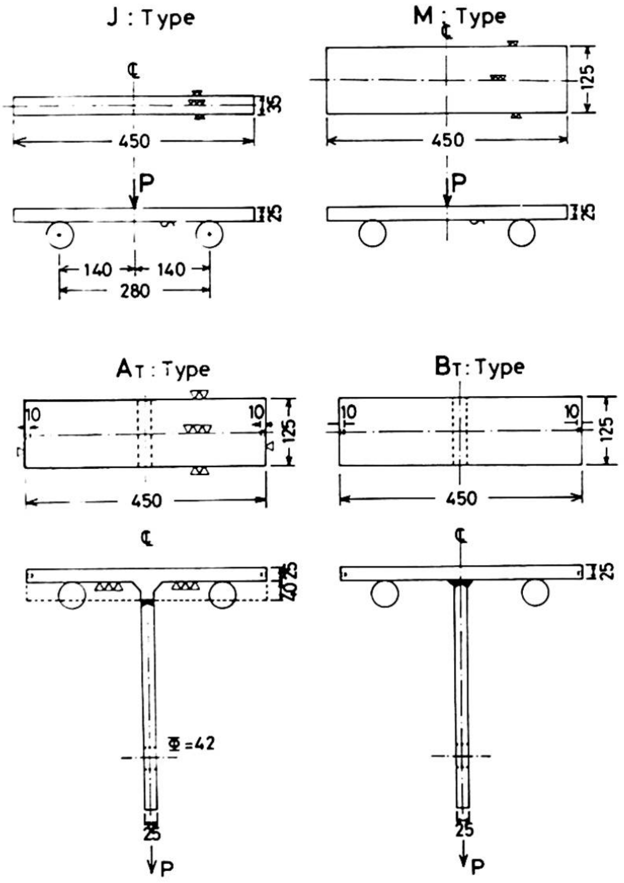

Fig.-6 Specimens of 4-types for bending tests

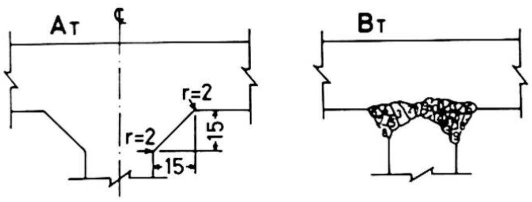

Fig.-7 Details of the fillets

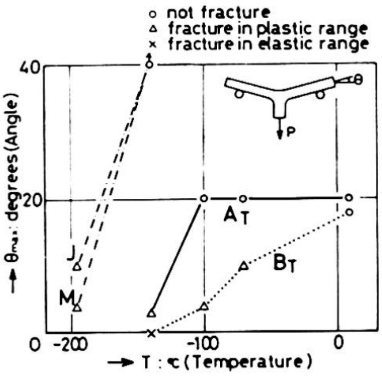

Fig.-8 Test results

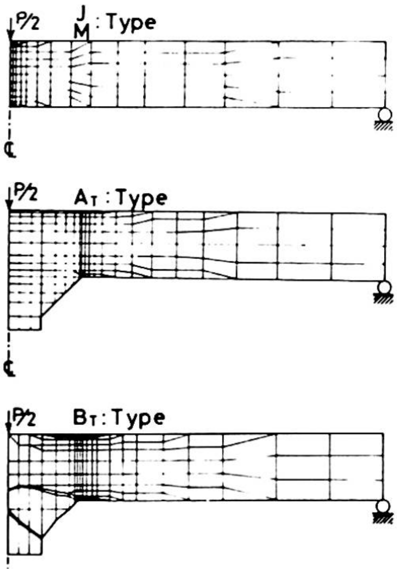

Fig.-9 Element division for 4-type specimens

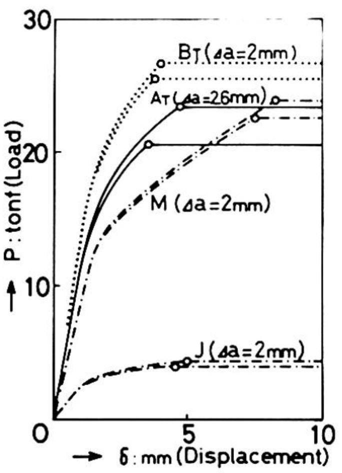

Fig.-10 Computed results

Table-5 J_C Value and the Ratio to J_{IC}

	J-type	M-type	A_T-type	B_T-type
$J_C(\frac{kgf.mm}{mm^2})$	35.46	8.42	143.11	30.38
$J_{IC}(\frac{kgf.mm}{mm^2})$	0.49	0.49	76.24	26.80
J_C/J_{IC}	72.4	17.2	1.88	1.13

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SUMMARY

J_{IC} values are compared between SM50B and SM58QT. Both are remarkably equal at -65° C, nevertheless J_{IC} value of SM58QT is approximately 2/3 of that of SM50B at room temperature. Bending tests on various stress states of 4-types specimens are carried out, and the experimental results indicate that the more complex the stress distribution is, the more fragile the joint of steel structure is. This phenomenon can be explained by J_{IC} fracture criterion.

RESUME

Les valeurs de J_{IC} sont comparées pour les aciers SM50B et SM58QT. Elles sont remarquablement identiques à - 65° C, bien que, à la température ambiante, la valeur J_{IC} du SM58QT ne soit que les 2/3 de celle du SM50B. Des essais de flexion sous différents états de contraintes ont été effectués sur des éprouvettes de 4 types. Les résultats expérimentaux montrent que, plus la distribution de contraintes est complexe, plus les assemblages sont fragiles. Ce phénomène peut être expliqué à l'aide du critère de rupture J_{IC}.

ZUSAMMENFASSUNG

Die J_{IC} Werte werden für die Stähle SM50B und SM58QT verglichen. Beide sind praktisch gleich bei -65° C, obwohl bei Raumtemperatur der J_{IC} Wert des SM58QT nur ungefähr 2/3 des Wertes des SM50B beträgt.Biegeversuche unter verschiedenen Spannungszuständen wurden an Proben mit 4 Ausbildungsformen durchgeführt; die experimentellen Ergebnisse haben gezeigt, dass die Gefahr eines Sprödbruches bei Stahlbauverbindungen mit der Komplexität der Spannungsverteilung zunimmt. Dieses Verhalten wird mit dem Bruchkriterium J_{IC} erklärt.