Proceedings of PVP2008
2008 ASME Pressure Vessels and Piping Division Conference
July 27-31, 2008, Chicago, Illinois, USA

PVP2008-61631

APPLICATION OF EQUIVALENT CTOD RATIO TO FRACTURE ASSESSMENT OF STRUCTURAL COMPONENTS

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ABSTRACT

Plastic constraint correction using the equivalent CTOD concept has been studied in the IST project. This project was carried out over a 3-year period with the foundation of METI in Japan, and the results were summarized in a draft standard, "Method of constraint loss correction of CTOD fracture toughness for fracture assessment of steel component." Equivalent CTOD ratio β is proposed in terms of constraint loss correction between the fracture performance of steel structures and fracture toughness tests using the Weibull stress as the driving force of brittle fracture. This paper provides the application procedure of Equivalent CTOD ratio to the fracture assessment of structural components. Equivalent CTOD ratio was taken in the fracture assessment diagram, and discussed the applicability by comparison with large scale test result of structural component such as Edge Surface Crack Panel, Center Through-wall crack panel and so on.

INTRODUCTION

Prevention of brittle fracture is the most important issue for securing the safety of steel structures, and a number of assessment methods based on fracture mechanics have been proposed and standardized. In assessing the toughness requirements of structures, material fracture toughness is obtained using compact specimen or 3-point bending tests specimen. However, it is well known that the apparent fracture toughness required in the steel component will differ, depending on the condition of plastic constraint in the vicinity of the crack, particularly when a structure is subjected to large deformation. As methods which consider this effect of plastic constraint on fracture of structural component, 2-parameter approaches such as T-stress, J-Q theory[1], and methods using Weibull stress[2,3] have been studied.

The concept of fracture assessment of structure components using a concept of equivalent CTOD based on the Weibull stress criterion was studied in the WES APD-LDF Committee, and a Japan Welding Society Standard, WES2808[4], "Method for assessment of brittle fracture in steel weldments subjected to cyclic and dynamic large straining," was issued in 2003. The IST Project was carried out over a 3-year period with the aim of generalizing this method using the equivalent CTOD concept[5]. The results of the IST Project were summarized in an ISO draft standard, "Method of constraint loss correction of CTOD fracture toughness for fracture assessment of steel component." This draft standard proposes a method of setting the equivalent CTOD ratio β, corrected for differences in plastic constraint, as a method of rationally assessing and diagnosing the fracture performance of steel structures from fracture toughness tests using the Weibull stress as the driving force for brittle fracture. Concretely, the draft provides methods of calculating the Weibull stress, including FEM, for obtaining the equivalent CTOD ratio, and equations for calculating the equivalent CTOD value for general structural members that can be regarded as wide plates, including center crack panels, through-wall crack panels, and others.

This paper attempts to apply this technique to the FAD (Failure Assessment Diagram) method, which has been adopted in BS7910[6], as a method using the equivalent CTOD ratio in fracture assessments of structures. FAD fracture assessments were performed using the equivalent CTOD ratios for tensile fracture test results of panels having a center through-wall crack or edge surface crack and wide test specimens having surface cracks at geometric discontinuities carried out in the IST Project.

DEFECT ASSESSMENT METHOD USING FAILURE ASSESSMENT DIAGRAM

Outline of FAD in BS7910

The FAD is a defect assessment method which was first adopted in the R6 Approach of the Central Electricity Generating Board (CEGB) in the UK. After many subsequent studies and revisions, it was standardized in BS7910 and API RP579[7], and was recently adopted by FITNET[8] in Europe. As distinctive features of the FAD method, this technique enables continuous assessment of the brittle fracture limit, in which it is possible to apply linear elastic fracture mechanics (LEFM), and the plastic collapse limit at net sections in structural component. Although a certain degree of expertise is necessary in making fracture assessments, assessment results are obtained in the location between assessment point and failure assessment curve in FAD, which is easily understood by general engineers.

Assessments of general structural component frequently involve fracture phenomena in the intermediate region between brittle fracture and plastic collapse. Because the stress intensity factor K, as the driving force for fracture, is underestimated in the region which exceeds linear elastic deformation, that is, at loading levels where plastic deformation becomes remarkable, a failure assessment curve corrected for plasticity is used. In other words, by giving a ratio (plasticity correction) of the plastic solution and the elastoplastic solution of the stress intensity factor, which is the driving force of fracture in the structural element, based on the FAC, this method attempts to assess structural integrity for failure modes from brittle fracture to plastic collapse simply by calculating the stress intensity factor by only elastic analysis. In order to simplify the assessment method, BS7910-2005 obtains the FAC by the following equation in Level 2 in fracture assessments:

Level 2A : $f(L_r) = \sqrt{\delta_r} = (1-0.14L_r^2)\left[0.3+0.7\exp(-0.65L_r^6)\right]$ (1)

where $Lr=\sigma_{ref} / R_{p\,0.2}$, σ_{ref}: average stress at net section

Level 2B : $f(L_r) = \sqrt{\delta_r} = \left[\frac{E\varepsilon_{ref}}{L_r R_{p0.2}} + \frac{L_r^3 R_{p0.2}}{2E\varepsilon_{ref}}\right]^{-1/2}$ (2)

for $L_r \le L_{r\max}$;and

$$\sqrt{\delta_r}\, or K_r = 0 \quad (3)$$

for $L_r > L_{r\max}$

where E: Young's modulus、ε_{ref}: average strain at net section. The maximum value for L_r is defined as

$$L_{r\max} = (R_{p0.2} + R_m)/\, 2R_{p0.2} \quad (4)$$

To calculate $f(L_r)$ at level 2B, the true stress - true strain curve of the material is needed.

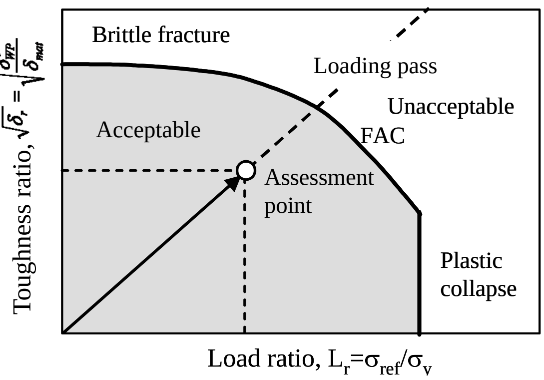


Fig.1 Failure assessment diagram

Figure 1 is a schematic representation of the structural integrity assessment method by the FAD method. The assessment point in the FAD method is the plot given by the toughness ratio K_r on the y-axis and the load ratio L_r on the x-axis. The toughness ratio is obtained from the applied crack driving force and the fracture toughness of the material as shown by the following equation in the case of using CTOD as material fracture toughness:

$K_r=\sqrt{\delta/\delta_{mat}}$

The load ratio on the x-axis can be expressed as the ratio of applied stress and the yield stress of the material, as shown by:

$L_r=\sigma_{ap}/\sigma_y$

If the fracture assessment point plots on the inner side of the FAC (Failure Assessment Curve), this means that the structure containing a defect possesses fitness for service.

Application of equivalent CTOD ratio β to FAD assessment

In cases where a large load acts on a structure, such as would be accompanied by plastic deformation of the structural components, the apparent fracture toughness required in the steel component will differ depending on the condition of plastic constraint in the vicinity of cracks existing in the component. Because tension is frequently the main loading component, particularly in structural members, the stress-strain field around the crack widely spread compared with fracture toughness specimens with a deep crack which is tested under bending loading. Using an equivalent CTOD ratio based on the Weibull stress criterion to compensate for this effect of plastic constraint, application to the FAD method was attempted. This chapter describes the method of applying the equivalent CTOD ratio to the FAD method; the following chapter will introduce examples of application to fracture assessments of center through-thickness crack panels (CTCP) and center surface crack panels (CSCP), and an example of assessment of a panel with a geometric discontinuity, like those found in actual structures, when a crack is introduced at an area of stress concentration occurring at the geometric discontinuity.

Procedure of FAD using the equivalent CTOD ratio

The procedure of fracture assessment based on the FAD in BS7910-2005 using the equivalent CTOD ratio β is schematically illustrated in Figure 2. The detailed procedure is described as follows:

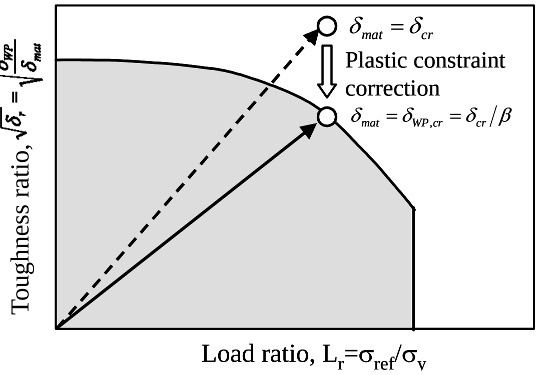


Fig.2 FAD using equivalent CTOD ratio β

(1) Calculate the FAC using tested material's S-S properties

(2) Calculate the stress intensity factor K of the structural component

The stress intensity factor K is calculated by the following methods.

- Refer to K-value handbook
- Analyze by finite element method (FEM)

(3) Calculate the elastic component of CTOD of the structural component

$$\delta_{WP}^{e} = \frac{K^2}{XR_{p0.2}E'} \quad \begin{cases} E' = E & \text{(plane stress)} \\ E' = E/(1-\nu^2) & \text{(plane strain)} \end{cases} \tag{5}$$

where X is a factor (generally in a range between 1 and 2) influenced by the geometric constraint at the crack tip and the work hardening capacity of the material. The X-value is determined in accordance with BS 7910.

The critical CTOD of the standard fracture toughness test specimens shall be obtained in accordance with ISO 12135[10]. A minimum of three test results (critical CTODs) is generally chosen as the CTOD fracture toughness of the steel component. If more than three toughness test results are available, the use of a minimum of three equivalent (MOTE) is recommended.

(4) Convert the CTOD fracture toughness, δ_{cr}, of the material to the critical CTOD of the structural component、$\delta_{WP,cr}$、 using the equivalent CTOD ratio.

$$\delta_{WP,cr} = \delta_{cr} / \beta \tag{6}$$

The equivalent CTOD ratio is calculated according to the procedure at fracture assessment levels I, II and III as described in IST method[11]. The assessment level to be applied shall be decided by agreement among the parties concerned.

(5) Calculate the loading path of the structural component

The loading path of the structural component is calculated as Eq.(7).

$$f(L_r) = \sqrt{\delta_r} = \sqrt{\frac{\delta_{WP}^e(L_r)}{\delta_{mat}}} = \sqrt{\frac{\delta_{WP}^e(L_r)}{\delta_{WP,cr}}} = \sqrt{\frac{\delta_{WP}^e(L_r)}{\delta_{cr}/\beta}} \tag{7}$$

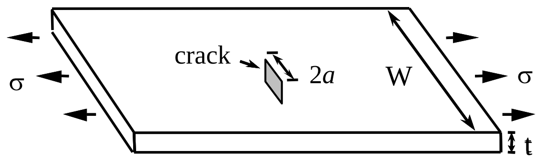
where δ_{mat} is the material fracture toughness.

(6) Determine the L_r

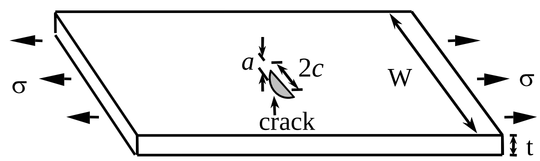
The load ratio L_{rcr} for the structural component of interest is given as the point where the loading path (Eq.7) crosses the FAD curve (Eq.1 or 2). Figure 2 also shows the procedure for determining actual CTOD fracture toughness needed to meet design requirements of structural components, using FAD with constraint loss correction by equivalent CTOD ratio β.

FRACTURE ASSESSMENT OF CTCP and CSCP

The applicability of the equivalent CTOD ratio to FAD assessments was verified using a panel having a through-crack in the center (center through-thickness crack panel: CTCP) and a panel having a surface crack in the center (center surface crack panel: CSCP), which are representative structural models. Table 2 shows the shapes and dimensions of the CTCP and CSCP specimens, crack dimensions, strength properties of the tested materials together with the results of the fracture toughness test and the wide plate tests.



(a) Center Through-thickness Crack Panel: CTCP



(b) Center Surface Crack Panel: CSCP

Fig.3 CTCP and CSCP test specimens

Table 1 Test conditions and results of CTCP, CSCP

Type	Crack size	W	t	Steel	$R_{P0.2}$	TS	Y/T	Temp.	δ_{cr} [mm]			σ_{ref}	δ_{WP}
	[mm]	[mm]	[mm]	Notation	[MPa]	[MPa]		[°C]	Max.	Min.	Av.	[MPa]	[mm]
CTCP1	2*a*=50	250	25	SM490YB	530	646	0.82	-100	0.37	0.027	0.11	560	0.62
CTCP2	2*a*=50	250	25	SM490YB	530	646	0.82	-100	0.37	0.027	0.11	534	0.51
CTCP3	2*a*=160	400	20	SM400B	344	491	0.70	-85	-	-	0.12	322	-
CTCP4	2*a*=160	400	20	SM400B	344	491	0.70	-80	-	-	0.15	328	-
CTCP5	2*a*=160	400	20	SM400B	344	491	0.70	-70	-	-	0.19	323	-
CTCP6	2*a*=160	400	20	HW685	963	1009	0.95	-80	-	-	0.17	925	-
CTCP7	2*a*=160	400	20	HW685	963	1009	0.95	-80	-	-	0.17	967	-
CTCP8	2*a*=160	400	20	HW685	963	1009	0.95	-60	-	-	0.21	947	-
CSCP1	2c=47, *a*=9	250	25	SM490YB	530	646	0.82	-100	0.37	0.027	0.11	511	0.88
CSCP2	2c=47, *a*=9	250	25	SM490YB	530	646	0.82	-100	0.37	0.027	0.11	528	0.64
CSCP3	2c=47, *a*=9	250	25	SM490YB	530	646	0.82	-100	0.37	0.027	0.11	515	1.10

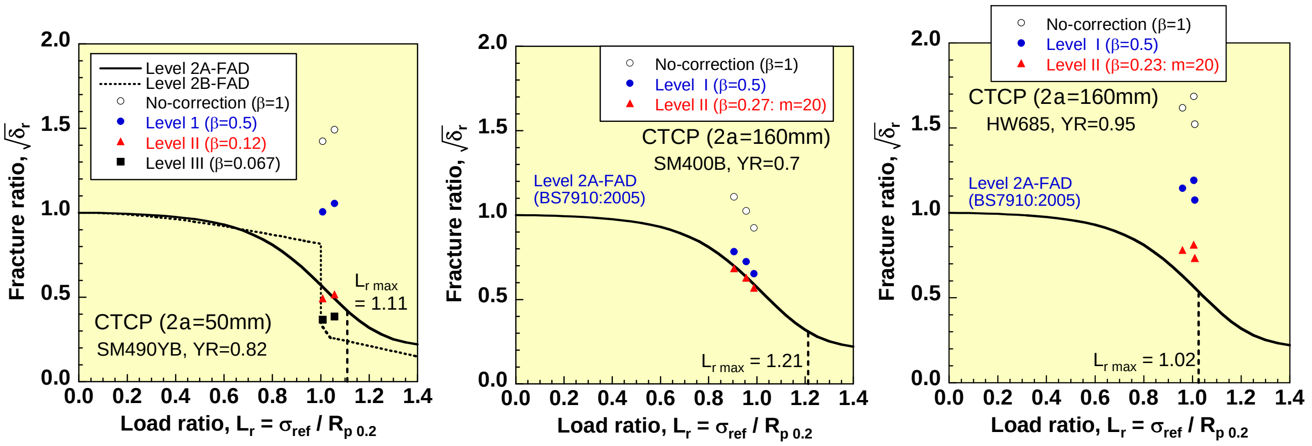
Figure 4(a), (b) and (3) show the fracture assessments of the CTCP on the FAD according to the assessment procedure described in the previous chapter for the SM490YB, SM400B and HW685 steel, respectively. The FAC includes the BS7910 Level 2A and Level 2B curves shown in Eq. (1) and (2). Because all the assessment points (relationship between K_r and L_r at fracture) without the plastic constraint correction plotted on the outer side of the FAC, it can be understood that fracture toughness can be evaluated conservatively using the FAD. At assessment Level I, 0.5 is used as the equivalent CTOD ratio β. With assessment Level II, the equivalent CTOD ratio is obtained using the Eq.(8) prepared in the draft standard using a Weibull shape parameter m = 20. At Level III, standard fracture toughness test (CTOD) tests on multiple specimens were performed in order to obtain Weibull shape parameter m by Weibull stress analysis. In this study , m=36 is obtained for SM490YB and the equivalent CTOD ratio is obtained using the Eq.(8) as well as Level II procedure.

$$\beta_{2a(CTCP)} = \beta_{0(CTCP)} \cdot (2a/13.8)^{0.4} \qquad (8)$$

where β_0 is the equivalent CTOD ratio for referent crack size. With respect to SM400B, HW685, equivalent CTOD ratio is obtained from only Level I and Level II procedure due to lack of the CTOD test data.

The results also show that sufficient integrity can be secured with this steel component when a crack with this shape and dimensions is assumed. In this figure, the plots shown by solid symbols are the results when the equivalent CTOD ratio is applied in accordance with Level I, Level II and Level III in the IST method. Assessment accuracy has improved dramatically in comparison with the case where the fracture toughness test results are applied without correction by using the equivalent CTOD. Assessment points with Level II and Level III of the equivalent CTOD ratio are all located beside or on the FAC.

Figure5 shows the results from the fracture assessments of the CSCP on the FAD for SM490YB steel. The FAC also includes the BS7910 Level 2A and Level 2B curves shown in Eq. (1) and (2). The results show the almost same tendency as Fig.4 with the CTCP. It can be understood that the FAD method gives conservative assessments of component integrity in the intermediate region between the region where brittle fracture is controlling to the region where plastic collapse is controlling. In Fig.5, all the assessment points without the



(a) SM490YB (b) SM400B (c) HW685

Fig.4 Fracture assessment of CTCP

plastic constraint correction plotted on the outer side of the FAC. The plots shown by solid symbols are the results when the equivalent CTOD ratio is applied in accordance with Level I, Level II and Level III in the IST method. At assessment Level I, 0.5 is used as the equivalent CTOD ratio β. With assessment Level II and Level III, the equivalent CTOD ratio is obtained using the Eq.(9) with a Weibull shape parameter m = 20 and 36, respectively.

$$\beta_{2c(CSCP)} = \beta_{0(CSCP)} \times (2c/40)^{k_{CSCP}(m)/2} \quad (9)$$

where $k_{CSCP}(m) = \frac{1}{\exp\{0.1(m-33)\}+1}$

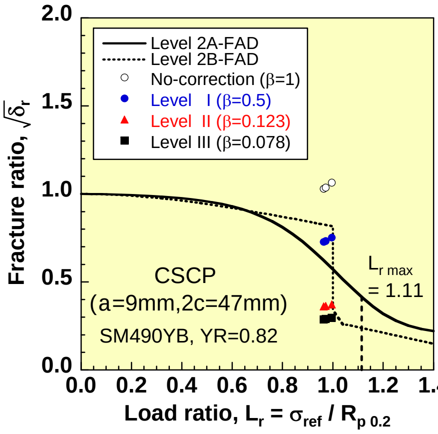


Fig.5 Fracture assessment of CSCP

Assessment accuracy has improved dramatically in comparison with the case where the fracture toughness test results are applied without correction by using the equivalent CTOD. Assessment points coincide with fracture limit when the FAC obtained by Eq.(2) is used because this steel shows yield elongation in S-S curve. Assessment points with the equivalent CTOD ratio are all located beside or on the FAC. Thus, by using the FAD method, it is possible to assess the integrity of structural components for failure modes from brittle fracture to plastic collapse from the results of a fracture toughness test simply by calculating the stress intensity factor from an elastic analysis. However, as can also be seen in the example presented here, this method frequently gives excessively conservative assessments, particularly in the elastoplastic fracture region. Therefore, in pursuing more rational assessments, it appears necessary to include the effect, on the fracture limit, of differences in the degree of plastic constraint between the fracture toughness specimen and the actual structural component in this fracture region.

FRACTURE ASSESSMENT OF ESCP WITH GEOMETRICAL DISCONTINUITY

Unlike fracture toughness test specimens, actual steel structures contain geometric discontinuities. In many cases, defects exist in the areas of stress concentration originating from these discontinuities. Therefore, this chapter will examine the applicability of the equivalent CTOD ratio to FAD assessments when a crack exists in a stress concentration by performing an FEM analysis simultaneously with a tensile test of a panel with a surface crack at the point of geometric discontinuity (edge surface crack panel: ESCP). The steel used in this test is a SM490B grade steel for welded structures with a thickness of 25mm. Figure 6 shows the shape and dimensions of the wide plate test specimen with a geometric discontinuity[12], which was prepared in order to verify the applicability of the equivalent CTOD ratio in the FAD assessment to an area of stress concentration at a geometric discontinuity. After machining EDM notches in two areas of stress concentration, high cycle bending loading was applied to introduce a corner fatigue pre-crack with a 1/4 elliptical shape with a surface length of approximately 20mm and a depth of approximately 6mm. Monotonous tensile loading was then applied at a test under the test temperature of -100°C.

The CTOD at the deepest point in the crack was obtained from the FEM analysis results by ABAQUS 6.3 using the tangent method after the verifying of crack mouth opening displacement between the experiment and the analyses.

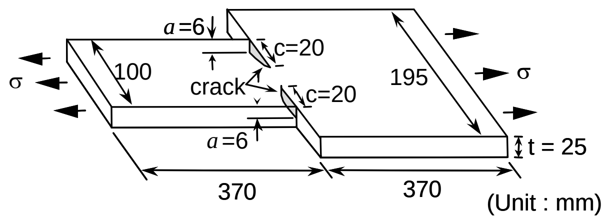


Fig.6 Geometry of ESCP with geometrical discontinuity test specimen

Table2 Test conditions and results of ESCP with geometrical discontinuity

Type	Crack size [mm]	Steel Notation	$R_{P0.2}$ [MPa]	TS [MPa]	Y/T	Temp. [°C]	δ_{cr} [mm] Max.	Min.	Av.	σ_{ref} [MPa]	δ_{WP} [mm]
US 1	c=20, *a*=6	SM490B	445	627	0.71	-100	0.165	0.014	0.062	455	0.40
US 2	c=20, *a*=6	SM490B	445	627	0.71	-100	0.165	0.014	0.062	410	0.16
US 3	c=20, *a*=6	SM490B	445	627	0.71	-100	0.165	0.014	0.062	427	0.48
US4	c=20, *a*=6	SM490B	445	627	0.71	-100	0.165	0.014	0.062	421	0.36
US 5	c=20, *a*=6	SM490B	445	627	0.71	-100	0.165	0.014	0.062	431	0.31
US 6	c=20, *a*=6	SM490B	445	627	0.71	-100	0.165	0.014	0.062	426	0.32

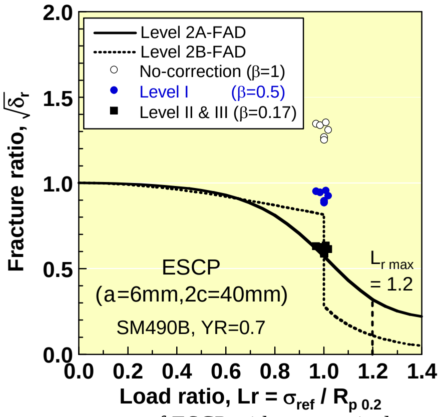


Fig.7 Fracture assessment of ESCP with geometrical discontinuity

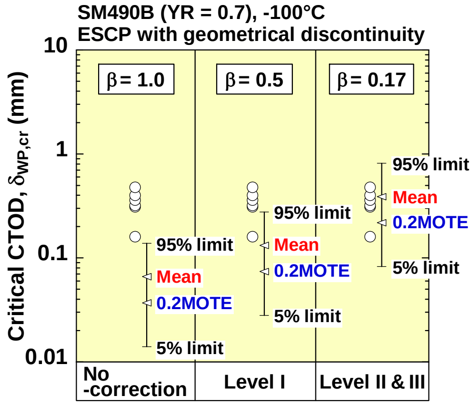


Fig.8 Comparison of critical CTODs measured and estimated with from CTOD test results

Figure 7 shows the results the fracture assessments of the ESCP with geometrical discontinuity on the FAD for SM490YB steel. The FAC also includes the BS7910 Level 2A and Level 2B curves shown in Eq. (1) and (2). At assessment Level I, 0.5 is used as the equivalent CTOD ratio β. With assessment Level II and Level III, the equivalent CTOD ratio is obtained using the Eq.(10) with a Weibull shape parameter m = 20.

$$\beta_{2c(ESCP)} = \beta_{0(ESCP)} \cdot (2c/30)^{k_{ESCP}(m)/2}, \tag{10}$$

where $k_{ESCP}(m) = \dfrac{1}{\exp\{0.1(m-40)\}+1}$

The assessment points without plastic constraint correction show all plots well above the FAC, indicating that assessment at β = 1 gives extremely conservative results. Looking at the results of assessments using Level I (β=0.5) and Levels II and Level III (β=0.17) by the IST method, the difference between assessment points and the FAC diminishes as assessment Level risings. Assessment accuracy has improved dramatically in comparison with the case where the fracture toughness test results are applied without correction by using the equivalent CTOD. Assessment points coincide with fracture limit when the FAC. Assessment points with the equivalent CTOD ratio are all located on the FAC.

Figure 8 shows the comparison of critical CTODs measured in ESCP tests with geometrical discontinuity and estimated from standard fracture toughness tests by using the equivalent CTOD ratio as a bar scale. This bar scale also indicates mean value and 0.2 minimum of three equivalent (MOTE). As an assessment level goes up, test results approach the range of critical CTOD values estimated from the standard fracture toughness test results, and it is checked that estimated accuracy improves so much.

By evaluation of Levels II and Level III, all the test results are especially contained in the estimated range, and highly precise estimation of critical CTOD of steel component is possible by using the equivalent CTOD ratio. And it is also confirmed that IST constraint correction method using the equivalent CTOD ratio is applicable to the assessment of the integrity of structural components with geometrical discontinuity.

SUMMARY AND CONCLUSIONS

Application of the equivalent CTOD ratio to FAD assessments was attempted with Center Through-thickness Crack Panel (CTCP), Center Surface Crack Panel (CSCP), and Edge Surface Crack Panel (ESCP), in which a crack exists in an area of stress concentration. The main conclusions are as follows:

(1) The accuracy of fracture limit assessments can be improved by using the equivalent CTOD ratio β to compensate for differences in plastic constraint in fracture assessments of CTCP and CSCP, which are general structural members.

(2) In FAD assessments in accordance with BS7910, assessment accuracy was dramatically improved by using β.

(3) In cases where an area of stress concentration exists, it is also possible to improve accuracy in assessments of the fracture limit by using the equivalent CTOD β to compensate for differences in plastic constraint.

ACKNOWLEDGMENTS

This research was carried out and studied by the Standards Verification Project "Standardization of Procedures for Assessment of the Fracture Toughness of Steel Materials" Committee (IST Project; Chairman: Prof. Fumiyoshi Minami, Osaka University) of the Japanese Ministry of Economy, Trade and Industry (METI). The authors wish to thank the members of the Committee and all those concerned for their cooperation.

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