Constraint Assessment of Brittle Fracture of Steel Components, ISO 27306 vs. FITNET FFS

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Abstract

ISO 27306 and FITNET FFS have been developed recently for correction of constraint loss in structural components. Both methods employ the Weibull stress as a driving force of brittle fracture. Nevertheless, the dissimilarity is found between the two methods. This paper compares ISO 27306 with FITNET FFS in terms of the constraint correction ratio. Discussion is conducted on 2-dimensional (FITNET) vs. 3-dimensional (IST) approach.

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Selection and peer-review under responsibility of ICM11

Keywords: fracture assessment; constraint effect; brittle fracture; ISO 27306; FITNET FFS; Weibull stress criterion

1. Introduction

Structural components generally show higher resistance to brittle fracture than the standard fracture toughness specimen with a deep crack. This is due to a loss of constraint in structural components, most of which are subjected to tension whereas the fracture toughness specimen is in bending. Recently, the FITNET FFS [1] and IST method [2] have been developed in Europe and Japan, respectively, for constraint-based assessments of fracture. The IST method has been standardized as ISO 27306 in 2009 [3]. Both approaches employ the Weibull stress [4] as a driving force of brittle fracture. Nevertheless, fracture assessment results obtained by these methods are not necessarily the same [5, 6].

This paper discusses the constraint corrections provided by the FITNET FFS and IST method with attention to the similarity and dissimilarity. The FITNET FFS is based on the 2-dimensional (2D) plane-strain analysis of constraint, in terms of the T-stress or Q-parameter. By contrast, the IST method enables the constraint correction under 3D conditions. This paper puts emphasis on the 3-dimensional (3D) effect on the constraint correction. Input parameters for the assessment of constraint loss are discussed as well.

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2. Constraint Assessment by FITNET FFS and IST Method

2.1. FITNET FFS

The FITNET FFS, based on the R6 method [7], employs the failure assessment diagram (FAD), where the fracture ratio, $K_r = K_1 / K_{mat}$ ($K_1$: linear elastic stress intensity factor, $K_{mat}$: material fracture toughness) is used as the ordinate and the load ratio, $L_r = P / P_l$ ($P$: applied load, $P_l$: plastic limit load) as the abscissa. The fracture assessment curve (FAC) is represented by $K_r = f(L_r)$ for $L_r < L_{r,max}$. The fracture ratio, $f(L_r)$, on FAC is equal to 1 for $L_r = 0$ and decreases monotonically with increasing $L_r$. The $K_{mat}$ to define $K_r$ is normally measured with the deeply cracked 3-point bend or compact specimen (standard fracture toughness specimen), which leads to a conservative fracture assessment of structural components.

Two equivalent procedures are given to correct the constraint loss in structural components. Procedure I modifies the FAC for constraint, retaining the material fracture toughness, $K_{mat}$, unchanged. Procedure II modifies the fracture toughness to define $K_r$ and retains the FAC unchanged:

\[ K_r = K_1 / K_{mat} = f(L_r) \text{ for } L_r < L_{r,max} \tag{1} \]

The modified toughness, $K_{mat}^c$, for constraint loss is given as

\[ K_{mat}^c = K_{mat} \left[ 1 + \alpha (-\beta_T L_r)^k \right] \text{ for } T / \sigma_Y < 0 \tag{2b} \]

where $\alpha$ and $k$ are parameters defining constraint sensitivity of the material, $\sigma_Y$ is the yield stress, $\beta_T$ is defined as $\beta_T = T / \sigma_Y$. $T$ and $Q$ are the T-stress and Q-parameter developed in the two-parameter $K$-$T$ and $J$-$Q$ theories, respectively. As a broad guidance, Eq. (2b) is recommended for use for $L_r < 1$, because $T$-stress is derived from the elastic calculation. When plasticity becomes widespread ($L_r \geq 1$), alternative parameter $\beta_Q$ is recommended instead of $\beta_T$, where $\beta_Q$ is defined as $\beta_Q L_r = Q$.

Look-up tables for $\alpha$ and $k$ [8] are prepared for $\beta_T$ and $\beta_Q$ as a function of the material yield stress $\sigma_Y$ and the strain hardening exponent $n$. The $\alpha$- and $k$-values are obtained from 2D plane-strain FE-analysis with the modified boundary-layer (MBL) model, where the Beremin model [4] for cleavage fracture is applied to correlate $K_{mat}$ and $K_{mat}^c$ at the same level of the Weibull stress $\sigma_W$. The $\sigma_W$ is defined as

\[ \sigma_W = \left[ \frac{1}{V_0} \int_{V_T} (\sigma_{eff})^m dV \right]^{1/m} \tag{3} \]

where $V_0$: reference volume, $m$: Weibull shape parameter, $V_T$: fracture process zone, $\sigma_{eff}$: effective stress normally represented by the maximum principal stress. Thereby, $\alpha$- and $k$-values are in function of $m$. 

Nomenclature:

- $K_{mat}$: material fracture toughness measured in terms of stress intensity factor $K$
- $K_{mat}^c$: constraint corrected fracture toughness
- $K_r$: ratio of stress intensity factor $K$ to material fracture toughness $K_{mat}$
- $L_r$: ratio of net section stress to yield or proof stress
- $\beta$: equivalent CTOD ratio, defined by $\delta / \delta_{WP}$, that links CTODs of standard fracture toughness specimen and structural component at the same Weibull stress level
- $\beta_T$: normalized measure of structural constraint defined by $T/(L_r \sigma_Y)$ ($T$: T-stress, $\sigma_Y$: yield stress)
- $\delta$: CTOD of standard fracture toughness specimen with crack depth ratio of $a_0/W = 0.5$
- $\delta_{mat}$: material fracture toughness measured in terms of CTOD
- $\delta_{c,mat}$: constraint corrected CTOD fracture toughness
- $\delta_r$: ratio of elastic component of CTOD to material fracture toughness $\delta_{mat}$
2.2. IST method

The IST method, developed as ISO 27306, is purely based on the Beremin model [4]. On the basis of the Weibull stress criterion, the IST method implements the equivalent CTOD ratio, $\beta$, defined as

$$\beta = \frac{\delta}{\delta_{WP}} \quad (0 < \beta < 1) \quad (4)$$

where $\delta$ and $\delta_{WP}$ are CTODs of the standard fracture toughness specimen and the structural component, respectively, at the same Weibull stress $\sigma_W$. Note that $\sigma_W$ in the IST method is computed by 3D FEM. At early stage of loading, $\beta$ decreases rapidly with CTOD, $\delta$, of the toughness specimen. Beyond small-scale yielding (SSY), however, its dependence on $\delta$ becomes rather weak. The IST method provides a constant correction of constraint, independent of the load level, using $\beta$ at such turning point on the $\beta - \delta$ curve [2].

When assessing on FAD, the IST method modifies the CTOD fracture toughness $\delta_{mat}$ to define the fracture ratio, $\sqrt{\delta r} = \sqrt{\delta_{WP}^e / \delta_{mat}^e}$, and retains the FAC unchanged:

$$\sqrt{\delta r} = \sqrt{\delta_{WP}^e / \delta_{mat}^e} = \sqrt{\delta_{WP}^e / (\delta_{cr} / \beta)} = f (L_t) \quad (5)$$

where $\delta_{WP}^e$ is the elastic CTOD of the component and $\delta_{cr}$ is the critical CTOD of the standard fracture toughness specimen. The modified toughness, $\delta_{mat}^e = \delta_{cr} / \beta$, indicates the critical CTOD of the component.

The structural components concerned in the IST method are wide plates under tensile loading; CSCP, ESCP, CTCP and ESCP (C: centre, E: edge, S: surface, T: through-thickness, C: crack, P: panel).

Three assessment levels (Level I, II and III) for $\beta$ are specified in the IST method. The assessment level to be applied depends upon the agreement of the parties concerned.

- Level I (simplified assessment): $\beta$ has a default value of 0.5 as a converative approximation.
- Level II (normal assessment): this is applied to those cases where the mechanical properties and crack geometry are known, but the Weibull parameter $m$ is not available. Two default (lower-bound) values for $m$ are proposed: $m = 10$ when $\delta_{cr} \leq 0.05 \text{ mm}$; and $m = 20$ when $\delta_{cr} > 0.05 \text{ mm}$, where $\delta_{cr}$ is an average CTOD toughness under thickness $= 25 \text{ mm}$. Once $m$ is selected, $\beta$ is obtained from nomographs as a function of the component crack type, the yield-to-tensile ratio $YR (= \sigma_y / \sigma_T)$ and the parameter $m$.
- Level III (material specific assessment): this is applicable to those cases where the information for assessing of $\beta$ is fully known. The parameter $m$ is determined statistically from a sufficient number of toughness data. The $\beta$-nomographs at Level II and Level III are common. $\beta$ (Level III) $\leq \beta$ (Level II).

The IST method provides $\beta_0$-nomographs for wide plates including a reference size of crack. Figure 1 shows $\beta_0$ for CSCP and CTCP. It can be seen that $\beta_0$ decreases with increasing $YR$ and $m$. The equivalent CTOD ratio, $\beta$, has a crack length effect [2]. For CTCP, it is formulated as

$$\text{CTCP: } \beta(2a) = \beta_0 \cdot (2a / 13.8)^{0.4} \quad \text{for } 5 \leq 2a \leq 50 \text{ mm} \quad (6)$$

![Fig. 1. Nomographs of equivalent CTOD ratio, $\beta_0$, for CSCP and CTCP with a reference size of crack. (a) CSCP with crack length $2c = 40 \text{ mm}$ and depth $a = 6 \text{ mm}$, (b) CTCP with crack length $2a = 13.8 \text{ mm}$.](image-url)
3. Comparison between FITNET and IST Methodologies

The similarity and dissimilarity between the FITNET FFS and IST method are summarizes in Table 1. Both methodologies are two-parameter approaches, coupling a conventional fracture mechanics parameter with a toughness correction parameter. From the relationship between $K$ and CTOD, the FITNET parameter and the IST parameter for toughness correction will be equivalent in the form [5]

$$K_{mat} / K_{mat}^c = 1 / \left[ 1 + \alpha(-\beta_T L_T)k^k \right] = \sqrt{\delta_{mat}} / \delta_{mat}^c$$

The FITNET toughness correction, $1/[1+\alpha(-\beta_T L_T)k^k]$, is based on 2D plane-strain FE-analysis with the MBL model, taking $T$-stress = 0 for the standard fracture toughness specimen. These boundary conditions do not necessarily match the actual condition of specimens, and besides, the FITNET parameter does not consider the volume effect on the Weibull stress. On the other hand, the equivalent CTOD ratio, $\beta$, in the IST method is obtained from 3D FEM. The IST method employs a constant correction of constraint ($\beta$: independent of the load level) for simplicity, although the specified $\beta$ is applicable beyond SSY.

Figure 2 shows the change in the toughness correction ratio with the load ratio $L_r$ for CTCP ($2a/2W = 50/400$). The load ratio $L_r$ is represented by the net section average stress $\sigma_{ref}$ over the yield stress $\sigma_Y$. It can be seen that the FITNET correction, $1/[1+\alpha(-\beta_T L_T)k^k]$, decreases monotonically with the load ratio $L_r$. On the other hand, the IST correction, $\sqrt{\beta}$, is nearly constant for $L_r > 0.4$. Considering these properties, the IST method adopts a constant $\beta$ that is valid in a load range beyond SSY. The inconsistency between the FITNET and IST toughness corrections are attributed to 2D vs. 3D formulation.

The toughness correction for constraint loss is associated with the mechanical properties and Weibull parameter $m$ of the material. The FITNET FFS employs the yield stress $\sigma_Y$ and the strain hardening exponent $n$ as the input mechanical properties. By contrast, the IST method uses a single parameter, yield-to-tensile ratio, $YR$, and does not inquire the material strength. Figure 3 shows the FITNET toughness correction ratio for CTCP with different sets of $\sigma_Y$ and $n$. Each combination of $\sigma_Y$ and $n$ leads to a certain $YR (= 0.8$ in this case). It is found that $1/[1+\alpha(-\beta_T L_T)k^k]$ does not depend on $\sigma_Y$ and $n$, provided that they hold the same $YR$. Hence, it is concluded that $YR$ controls the toughness correction ratio.

As shown in Figs. 1 and 3, a low $m$-value provides a high toughness correction ratio. This is related to the property of the Weibull stress $\sigma_W$: the volume term includes $m$ in the form, $(V_f)^{1/m}$. The fracture process zone $V_f$ develops to a larger extent in the structural component than in the standard fracture toughness specimen, which makes a small difference between $\sigma_W$-values for them. In the FITNET procedure, look-up tables for $\alpha$ and $k$ are prepared for $m = 5$ to 20 [1]. The estimation of $m$ for the material being assessed is an important issue. In the IST method, default values for $m$ are provided at Level II assessment as shown in Table 1.

| Table 1. Comparison between FITNET FFS and IST method. | FITNET FFS | IST method (ISO 27306) |
|-------------------|------------|------------------------|
| Fracture mechanics parameter | $K$ | $\delta$ |
| Two-parameter approach | Toughness correction ratio | $K_{mat} / K_{mat}^c = 1 / \left[ 1 + \alpha(-\beta_T L_T)k^k \right]$ | $\delta_{mat} / \delta_{mat}^c$ |
| 2D versus 3D formulation | FE-analysis | 2D plane-strain | 3D |
| $T$-stress, $Q$-parameter analysis | Volume effect | Not included | Included |
| Input material parameters | Mechanical properties | $\sigma_Y$ and $n$ | $YR (= \sigma_Y / \sigma_Y)$ |
| | Weibull shape parameter $m$ | No guideline | Level II: $m = 10$ for $\delta_{cr} \leq 0.05mm$
| | | | $m = 20$ for $\delta_{cr} > 0.05mm$ |
4. Fracture Assessment with FITNET and IST Constraint Corrections

Using the FITNET and IST methodologies, the fracture assessment of CTCP is conducted within the context of the failure assessment diagram (FAD). The failure assessment curves (FAC) at Level 2A and 2B specified in BS7910 [9] are employed. In the conventional approach the critical CTOD, \( \delta_{cr} \), measured with the standard fracture toughness specimen is directly used as \( \delta_{mat} \), which often leads to excessively conservative fracture assessment. The IST method applies the modified fracture toughness, \( \delta_{mat}^{c} = \delta_{cr} / \beta \), and retains the FAC unchanged (Eq. (5)). When the FITNET parameter is applied, it follows that

\[
\frac{1}{\sqrt{1 + \alpha(-\beta T L_r)^k}} = f(L_r)
\]

(8)

The fracture performance of CTCP (crack length \( 2a = 50 \) mm, panel width \( 2W = 250 \) mm) in tension is assessed. The material was 25mm thick SM490YB steel and tests were conducted at –100°C. The yield stress and tensile strength at –100°C were 530 MPa and 646 MPa, hence YR = 0.82 (\( n = 12.4 \)). The CTOD results at –100°C were 0.011 mm in average toughness (\( \delta_{cr} \)) and 0.068 mm for 0.2MOTE (min. of 3 equivalent). 0.2MOTE toughness is commonly employed in the fracture assessment, if more than 3 toughness data are available [9]. The net section fracture stresses of the CTCP were 534 and 560 MPa for two tests. The toughness correction ratios provided by the IST method and FITNET FFS are as follows:

\( \beta \) at Level II: \( m = 20 \) was selected, because \( \delta_{cr} > 0.05 \) mm. \( \beta_0 \) for the reference crack size obtained from Fig. 1(b) is 0.074 for YR = 0.82 and \( m = 20 \). Hence, \( \beta = \beta_0 \times (50/13.8)^0.4 = 0.120 \). (\( \sqrt{\beta} = 0.35 \)).

\( \beta \) at Level III: The Weibull parameter \( m \) statistically determined with 25 toughness test results was 36. \( \beta_0 \) for YR = 0.82 and \( m = 36 \) is 0.04. Hence, \( \beta = \beta_0 \times (50/13.8)^{0.4} = 0.067 \) (\( \sqrt{\beta} = 0.26 \)).

1/[1+\alpha(-\beta T L_r)^k] : \( \beta_T = -0.952 \) for CTCP with \( 2a/2W = 0.2 \). \( \alpha = 6.84 \) and \( k = 2.06 \) for \( \sigma_Y = 530 \) MPa, \( n = 12.4 \) and \( m = 20 \). 1/[1+\alpha(-\beta T L_r)^k] at the fracture load level was 0.13 ~ 0.15 for two tests.

Figure 4(a) shows the loading paths (change in \( \sqrt{\delta_{cr}} \) with \( L_r \)) for the CTCP. Compared with the conventional method (\( \beta = 1 \)), both FITNET FFS and IST method give a lower \( \sqrt{\delta_{cr}} \). The IST method predicts the incidence of brittle fracture at the intersection of the loading path and FAC. By contrast, the FITNET FFS predicts a plastic collapse, because \( \sqrt{\delta_{cr}} - L_r \) relation does not cross the FAC. In fact, the CTCP failed in a brittle mode. Figure 4(b) indicates the fracture ratio, \( \sqrt{\delta_{cr}} \), at the fracture load level. It is found that excessive conservatism in the conventional method is reasonably reduced by the IST method and the assessment results are almost on the Level 2A or 2B FAC.
5. Conclusion

This paper discussed the similarity and dissimilarity between the FITNET FFS and IST method for constraint correction in the fracture assessment of structural components. Both FITNET FFS and IST method are two-parameter approaches, coupling a conventional fracture mechanics parameter with a toughness correction for constraint loss. Toughness correction parameters are derived from the Beremin model for cleavage fracture. The FITNET and IST parameters are equivalent: \( \frac{1}{1+\alpha(-T_Lr)^k} = \sqrt[3]{\beta} \). The toughness correction ratios provided by the FITNET FFS and IST method are not necessarily the same, which is due to a difference between 2D (FITNET) and 3D (IST) approaches. It is shown that the mechanical property controlling toughness correction is the yield-to-tensile ratio, \( YR \). With the IST method, an excessive conservatism in the conventional method is reasonably reduced.

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