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Metallic materials — Method of constraint loss correction of CTOD fracture toughness for fracture assessment of steel components

Matériaux métalliques — Méthode de correction de perte de contrainte du CTOD de la ténacité à la rupture pour l’évaluation de la rupture des composants en acier

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Contents

Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

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Metallic materials - Method of constraint loss correction of CTOD fracture toughness for fracture assessment of steel components

1. Scope

In fracture assessments of steel structures containing cracks, it has generally been assumed that the fracture resistance of fracture toughness specimens is equal to the fracture resistance of structural components. However, such an assumption often leads to excessively conservative fracture assessments. This is due to a loss of plastic constraint in structural components, which are subjected mainly to tensile loading. By contrast, fracture toughness specimens hold a constrained stress state near the crack-tip due to bending mode. The loss of constraint is significant for high strength steels with high yield-to-tensile ratios (= yield stress / tensile strength) which have been extensively developed and widely applied to structures in recent years.

This International Standard specifies a method for converting the CTOD (Crack-Tip Opening Displacement) fracture toughness obtained from laboratory specimens to an equivalent CTOD for structural components, taking constraint loss into account. This method can also apply to fracture assessment using the stress intensity factor or the *J*-integral concept (see **Clause 9**).

This International Standard deals with the unstable fracture that occurs from a crack-like defect or fatigue crack in ferritic structural steels. Unstable fracture accompanied by a significant amount of ductile crack extension and ductile fractures are not included in the scope hereof.

The CTOD fracture toughness of structural steels is measured in accordance with the established test methods, ISO 12135:2002 or BS7448-1:1999. The fracture assessment of a cracked component is done using an established method such as FAD (Failure Assessment Diagram) in the organization concerned, and reference is not made to the details thereof in this International Standard.

This International Standard can be used for eliminating the excessive conservatism frequently associated with the conventional fracture mechanics methods and accurately assessing the unstable fracture initiation limit of structural components from the fracture toughness of the structural steel. This is also used for rationally determining the fracture toughness of materials to meet the design requirements of deformability of structural components.

2. Normative references

The following referenced documents are indispensable for the application of this International Standard. For dated references, only the edition cited applies. For updated references, the latest edition of the referenced document (including any amendments) applies.

ISO 12135:2002(E), *Metallic materials – Unified method of test of the determination of quasistatic fracture toughness*

BSI, BS7448-1:1991, *Fracture mechanics toughness tests, Method for determination of* K_{Ic}*, critical CTOD and critical J values of metallic materials*

3. Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 12135:2002 and the following apply.

3.1

CTOD of standard fracture toughness specimen

crack-tip opening displacement of standard fracture toughness specimen

δ

CTOD, as the fracture driving force, for the standard fracture toughness specimen (three point bend or compact specimen) with $0{,}45 \leq a_0 / W \leq 0{,}55$, where a_0 and W are the initial crack length and specimen width, respectively

3.2

CTOD fracture toughness

crack-tip opening displacement fracture toughness

δ_{cr}

critical CTOD at the onset of brittle fracture in the standard fracture toughness specimen [δ_{c}(B) as defined in ISO 12135:2002] with $0{,}45 \leq a_0 / W \leq 0{,}55$

3.3

CTOD of structural component

crack-tip opening displacement of structural component

δ_{WP}

CTOD, as the fracture driving force, for a through-thickness crack or a surface crack existing in a structural component regarded as a wide plate

NOTE The CTOD of a surface crack is defined at the maximum crack depth.

3.4

critical CTOD of structural component

critical crack-tip opening displacement of structural component

$\delta_{\mathrm{WP,cr}}$

critical CTOD at the onset of brittle fracture in structural components

3.5

equivalent CTOD ratio

equivalent crack-tip opening displacement ratio

β

CTOD ratio defined by $\delta / \delta_{\mathrm{WP}}$, where δ and δ_{WP} are CTODs of the standard fracture toughness specimen and the structural component, respectively, at the same level of the Weibull stress σ_{W}

See Figure 1.

NOTE See Reference [1].

3.6

Weibull stress

σ_{W}

fracture driving force defined with the consideration of statistical instability of microcracks in the fracture process zone against brittle fracture

NOTE See Reference [2].

3.7

critical Weibull stress

$\sigma_{\mathrm{W,cr}}$

Weibull stress at the onset of unstable fracture

3.8

Weibull shape parameter

m

material parameter used in the definition of the Weibull stress; one of two parameters describing the statistical distribution of the critical Weibull stress, $\sigma_{W,\,cr}$

3.9
yield-to-tensile ratio

R_Y

ratio of yield strength, σ_Y, (lower yield point, R_{eL}, or 0,2% proof strength, $R_{p0,2}$) to tensile strength, R_m

4. Symbols and units

For the purposes of this document, the following symbols, units, and designations are applied in addition to those in ISO 12135:2002.

Symbol	Unit	Designation
a	mm	Depth of surface crack or half length of through-thickness crack in structural component
c	mm	Half length of surface crack in structural component
m	1	Weibull shape parameter
t	mm	Plate thickness
V_0	mm^3	Reference volume defined for Weibull stress
V_f	mm^3	Volume of fracture process zone
R_Y	-	Yield-to-tensile ratio (=σ_Y / R_m)
β	-	Equivalent CTOD ratio
β_0	-	Equivalent CTOD ratio for reference crack length (In cases of surface crack panel, β_0 is defined for plate thickness $t = 25$ mm.)
$\beta_{2c,\,t}$	-	Equivalent CTOD ratio for target length of centre surface crack or double-edge surface crack on target plate thickness
β_{2a}	-	Equivalent CTOD ratio for target length of centre through-thickness crack or double-edge through-thickness crack
$\beta_{c,\,t}$	-	Equivalent CTOD ratio for target length of single-edge surface crack on target plate thickness
β_a	-	Equivalent CTOD ratio for target length of single-edge through-thickness crack
δ	mm	CTOD of standard fracture toughness specimen
δ_{cr}	mm	Critical CTOD of standard fracture toughness specimen at onset of brittle fracture (CTOD fracture toughness)
$\delta_{SSY\ limit}$	mm	CTOD at small-scale yielding limit for standard fracture toughness specimen
δ_{WP}	mm	CTOD of structural component
$\delta_{WP,\,cr}$	mm	Critical CTOD of structural component at onset of brittle fracture
σ_{eff}	MPa	Effective stress used for the calculation of Weibull stress
σ_Y	MPa	Lower yield point, R_{eL}, or 0,2 % proof strength, $R_{p0,2}$
σ_W	MPa	Weibull stress
$\sigma_{W,\,cr}$	MPa	Critical Weibull stress at onset of brittle fracture

5. Principle

This International Standard deals with the initiation of unstable fracture due to cleavage of structural steels. It presents a method for converting the CTOD fracture toughness obtained from the standard fracture toughness specimen [three-point bend or compact specimen with $0,45 \leq a_0 / W \leq 0,55$ and B (specimen thickness) = t (plate thickness of structural component)], which are characterized by an extremely severe plastic constraint in the vicinity of the crack-tip, to an equivalent critical CTOD for structural components, which are generally characterized by less constraint. The reverse procedure is also possible with this method. Thus, this method links fracture toughness tests and fracture performance assessments of structural components by taking account of loss of plastic constraint in structural components, as shown in Figure 2.

NOTE 1 The fracture toughness specimen with a deep crack such as $a_0 / W = 0,7$ presents somewhat higher constraint near the crack- tip than that with $0,45 \leq a_0 / W \leq 0,55$. The equivalent CTOD ratio β defined in this International Standard leads to a conservative fracture assessment, if the user employs a deep cracked specimen with $a_0 / W > 0,55$.

NOTE 2 This International Standard does not intend to address size and temperature effects nor influence of data scatter on the results. Refer to ASTM E1921 [3] for guidance.

The CTOD fracture toughness (critical CTOD) of the standard fracture toughness specimen is determined in accordance with the established test methods, ISO 12135:2002 or BS7448-1:1991. The fracture assessment of a cracked component can be done using established methods at the user's discretion such as FAD (Failure Assessment Diagram) and CTOD design curve in the organization concerned.

The critical CTOD of the standard fracture toughness specimen is converted to the critical CTOD of the structural component using the equivalent CTOD ratio, β. The equivalent CTOD ratio, β, is defined as a CTOD ratio, $\delta / \delta_{\mathrm{WP}}$, where δ and δ_{WP} are CTODs of the standard fracture toughness specimen and the structural component, respectively, at the same level of the Weibull stress σ_{W}. The equivalent CTOD ratio, β, is in the range $1 > \beta > 0$.

The critical CTOD, δ_{cr}, of the fracture toughness specimen is converted to the critical CTOD, $\delta_{\mathrm{WP,cr}}$, of the structural component using β in the form

$$d_{\mathrm{WP,cr}} = d_{\mathrm{cr}} / b \qquad (1)$$

Furthermore, if the deformability, $\delta_{\mathrm{WP,req}}$, required for the structural component is given, the material fracture toughness needed to meet the deformability requirement, δ_{req}, can be calculated as

$$d_{\mathrm{req}} = b \cdot d_{\mathrm{WP,req}} \qquad (2)$$

Equations (1) and (2) transfer the CTOD fracture toughness to the equivalent CTOD of the structural component at the same fracture probability. The CTOD fracture toughness to be used for fracture assessments shall be determined by agreement of the parties concerned, for instance, a minimum of three test results.

The equivalent CTOD ratio, β, is dependent on the yield-to-tensile ratio, R_{Y}, of the material, the Weibull shape parameter m, the type and size of a crack in the structural component. In addition, β also depends on the deformation level of the structural component, but its dependence is rather small in the deformation range beyond small-scale yielding (SSY). The equivalent CTOD ratio, β, in this International Standard is specified in this large deformation range, and given in nomographs. The β-nomographs are physically effective in cases where both the standard fracture toughness specimen and the structural component show unstable fracture.

Three assessment levels (level I, level II and level III) for β are included in this method, as shown in Figure 3. The details are described in **Clause 8.** The assessment level to be applied depends upon the agreement of the parties concerned.

6. Structural components of concern

The structural components concerned in this International Standard are of the following four types regarded as wide plates under tensile loading, as shown in Figure 4. The crack in the components should be sufficiently small in comparison with the component dimensions (length, width) so as to ensure that the plate width effect on the stress intensity factor is negligibly small.

CSCP (Centre surface crack panel): Wide plate component with a surface crack at the centre of the plate under tensile loading

ESCP (Edge surface crack panel): Wide plate component with double-edge or single-edge surface crack at the edge of the plate under tensile loading

CTCP (Centre through-thickness crack panel): Wide plate component with a through-thickness crack at the centre of the plate under tensile loading

ETCP (Edge through-thickness crack panel): Wide plate component with double-edge or single-edge through-thickness crack at the edge of the plate under tensile loading

NOTE These represent some important structural configurations. For instance, CSCP represents a shell or pipe component with a flaw induced by crane scratch. ESCP is related to a beam or box component including a crack originated from geometrical discontinuity by fatigue or seismic loading. CTCP and ETCP may correspond to an extreme case of CSCP and ESCP where the surface crack grows in thickness direction to a large extent. Weld cracks such as lack of fusion, incomplete penetration, undercut, cold crack (hydrogen induced crack) and slag inclusion etc. are more likely in weldments. But this International Standard does not deal with the welded joints, because further investigation is necessary on the effects of strength mismatch, residual stress and the crack-tip location with respect to welds. Embedded cracks are not considered in this International Standard on the ground that embedded cracks are less likely in normal structural components than surface cracks.

The loading condition is assumed to be substantially uni-axial and perpendicular to the crack plane. The surface crack is assumed to be semi-elliptical, and the half-length, c, of the crack should be larger than the crack depth, a (shallow surface crack). Surface cracks existing in structural components are not necessarily of semi-elliptical type, but they should be idealized as semi-elliptical cracks by flaw assessment methods duly authorized in the organization concerned.

Other components can be assessed if the equivalent CTOD ratio β is derived by a suitable method.

7. Range of use

This International Standard allows β to be applied for the fracture assessment of ferritic steel components under the following conditions:

- Brittle fracture beyond SSY is assessed. The assessment of brittle fracture preceded by a significant stable crack growth is not recommended;
- The fracture toughness specimen (three-point bend or compact specimen with $0{,}45 \le a_0 / W \le 0{,}55$) shall have the same thickness as the structural component;
- No significant differences in fracture toughness through the thickness of the steel being assessed;
- β_0-nomographs for a reference crack size are presented in Clause **9**, where the yield-to-tensile ratio, R_Y, Weibull shape parameter, m, are in the range, $0{,}6 \le R_Y \le 0{,}98$ and $10 \le m \le 50$;
- The crack size, c *and* a, and the plate thickness, t, covered by this International Standard are as follows:

CSCP: $2c \ge 16$ mm, $0{,}04 \le a/t \le 0{,}24$, $12{,}5 \le t \le 50$ mm
ESCP: $2c \ge 24$ mm, $0{,}04 \le a/t \le 0{,}24$, $12{,}5 \le t \le 50$ mm
CTCP: $5 \le 2a \le 50$ mm
ETCP: $5 \le 2a \le 30$ mm

R_Y and m for ferritic structural steels are generally in the above range. The constraint correction by β may also be effective in cases where R_Y, m and the crack size are not within the above range, provided that, β, is obtained by an appropriate procedure.

R_Y and m at the temperature of the target component shall be employed for the determination of β.

8. Assessment levels I, II, and III

8.1 General

This International Standard proposes three levels for the assessment of the equivalent CTOD ratio, β. The choice of level depends on the agreement of the parties concerned. The detail of the assessments and required information are summarized in Table 1.

Assessment levels I to III are applied in loading conditions beyond small-scale yielding (SSY). The $\delta_{\text{SSY limit}}$ described in Figure 5 is the crack-tip opening displacement, δ, of the standard fracture toughness specimen corresponding to the SSY limit specified in ISO 12135. When stress fields in a wide plate structural component are focused to build the same level of the Weibull stress as in the fracture toughness specimen beyond $\delta_{\text{SSY limit}}$, constraint loss can be significant in the structural component. This International Standard provides the equivalent CTOD ratio, β, under such stress conditions.

Table 1 – Assessment levels I, II and III of β and required information

	Level I (Simplified assessment)	Level II (Normal assessment)	Level III (Material specific assessment)
Information needed for assessment	None	- Yield-to-tensile ratio, R_Y - Crack type in structural component - Crack size (length, depth) - lower-bound m-value	- Yield-to-tensile ratio, R_Y - Crack type in structural component - Crack size (length, depth) - Stress-strain curve for FE-analysis - Statistically determined m-value
Equivalent CTOD ratio β	β = 0,5	$0 < \beta < 1$ (in most case, $0 < \beta < 0{,}5$) $\beta = f(R_Y, a, c, t, m)$ for CSCP, ESCP $\beta = f(R_Y, a, m)$ for CTCP, ETCP	$0 < \beta$ (Level III) $< \beta$ (Level II) $\beta = f(R_Y, a, c, t, m)$ for CSCP, ESCP $\beta = f(R_Y, a, m)$ for CTCP, ETCP
Remarks	For a long crack[a], level II is recommended.	For a long crack[a] and $R_Y < 0{,}8$, level III is recommended.	Constitutive equation and finite element size ahead of the crack-tip should be well defined in FE-analysis.

CSCP, ESCP: Centre and edge surface crack panels
CTCP, ETCP: Centre and edge through-thickness crack panels
[a] : Surface crack: $2c > 50$ mm, Through-thickness crack: $2a > 25$mm,
$2c$: Surface crack length, $2a$: Through-thickness crack length, t: Plate thickness, m: Weibull shape parameter

8.2 Level I: Simplified assessment

Level I assessment is applicable to cases where the information necessary for calculating β, such as the mechanical properties of the structural component being assessed, the type and size of the assumed crack, etc. is not fully available. At level I assessment, β =0,5 is used as an upper-bound engineering approximation.

However, for a structural component that potentially includes a long crack (surface crack length $2c$ > 50mm or through-thickness crack length $2a$ > 25mm), level II assessment is recommended because β may exceed 0,5 with a low shape parameter, m.

8.3 Level II: Normal assessment

Level II assessment is applicable to cases where the yield-to-tensile ratio, R_Y, of the material and the type and size of the crack being assessed are known, but the Weibull shape parameter, m, is unknown. A lower-bound value for m is assumed for the assessment of β.

In cases of fracture assessment of structural components from fracture toughness results:

$$\left.\begin{array}{l} m = 10 \quad \text{for } \delta_{\text{cr,ave-25}} \le 0{,}05 \ \text{(mm)} \\ m = 20 \quad \text{for } \delta_{\text{cr,ave-25}} > 0{,}05 \ \text{(mm)} \end{array}\right\} \qquad (3)$$

where $\delta_{\text{cr,ave-25}}$ is the average CTOD fracture toughness at the assessment temperature obtained with 25 mm thick specimen, in mm. **Annex A** can be referred to when selecting the lower-bound m-value depending on the CTOD toughness level, $\delta_{\text{cr,ave-25}}$. **Annex A** includes a procedure for estimating $\delta_{\text{cr,ave-25}}$, when the thickness of the fracture toughness specimen is not 25 mm.

In cases of fracture toughness determination needed to meet design requirement of deformability of structural components:

$$m = 10 \qquad (4)$$

At level II, β-values are derived from nomographs as a function of the yield-to-tensile ratio, R_Y, and the Weibull parameter m of the material.

The use of a lower-bound m-value may lead to an excessive overestimation of β for a long crack (surface crack length $2c$ > 50 mm or through-thickness crack length $2a$ > 25 mm) with R_Y < 0,8. Level III assessment is recommended in such cases.

8.4 Level III: Material specific assessment

Level III assessment is applicable to cases where the information for the assessment of β is fully known.

At level III, β-values are also derived from nomographs, but with a statistically determined m-value from a sufficient number of fracture toughness test results. A recommended procedure for the determination of the m-value is described in **Annex B**.

Generally, β at level III is smaller than that at level II.

9. Equivalent CTOD ratio, β

9.1 General

This section describes a method for converting the CTOD of the standard fracture toughness specimen to the equivalent CTOD of structural components by using the equivalent CTOD ratio, β [4].

9.2 Factors influencing the equivalent CTOD ratio, β

The equivalent CTOD ratio, β, based on the Weibull stress criterion, depends on the shape parameter, m, of the material.

In addition, β is also influenced by the following factors, although the strength class and uniform elongation of the material have virtually no influence on β [4], [5]:

a) factors affecting plastic constraint in the vicinity of the crack-tip:

- yield-to-tensile ratio, R_Y, of the material;
- crack type (CSCP, ESCP, CTCP, ETCP) and crack size (crack depth of surface crack and crack length of through-thickness crack);

- plate thickness, t.

b) factor exerting a volumetric effect:

- length of surface crack.

NOTE The equivalent CTOD ratios, β, for CTCP and ETCP do not depend on the plate thickness, because the plate thickness plays the same role in the evolution of the Weibull stresses for the CTCP (ETCP) and the fracture toughness specimen, where the crack is of through-thickness type.

9.3 Procedure for calculating the equivalent CTOD ratio, β, at assessment levels I to III

9.3.1 General

The procedure for calculating the equivalent CTOD ratio, β, at assessment levels I to III is described below. Equations (5) to (9) are applicable for the following crack sizes:

CSCP: $2c \geq 16$ mm, $0{,}04 \leq a/t \leq 0{,}24$, $12{,}5 \leq t \leq 50$ mm
ESCP: $2c \geq 24$ mm, $0{,}04 \leq a/t \leq 0{,}24$, $12{,}5 \leq t \leq 50$ mm
CTCP: $5 \leq 2a \leq 50$ mm
ETCP: $5 \leq 2a \leq 30$ mm

9.3.2 Surface crack cases (CSCP and ESCP)

The procedure for calculating the equivalent CTOD ratio, β, for the surface crack is as follows.

Level I: $\beta = 0{,}5$

Level II: β is calculated, as shown in Figure 6, according to the following steps.

Step 1 Define the crack size (crack length $2c$, depth a), plate thickness, t, and the yield-to-tensile ratio, R_{Y}.

Step 2 Set a lower-bound value of the shape parameter, m: 10 or 20 depending on the material toughness level and cases of the fracture assessment [Equations (3) and (4)].

Step 3 Determine the equivalent CTOD ratio, β_0, for a reference size of the surface crack on 25 mm thick plate from the nomographs shown in Figures 7 and 8 as a function of m and R_{Y}. Figures 7 and 8 provide β_0 for the crack depth ratios, $a/t = 0{,}04$, 0,12 and 0,24 ($a = 1$, 3 and 6 mm and $t = 25$ mm).

Step 4 Calculate the equivalent CTOD ratio, $\beta_{2c,\,t}$, for the target length, $2c$, and the target plate thickness, t, with Equation (5) or (6), depending on the type of crack:

$$b_{2c,\,t\,(\mathrm{CSCP})} = b_{0(\mathrm{CSCP})} \cdot \sqrt{25/t} \cdot \left(2c/40\right)^{k_{\mathrm{CSCP}}(m)/2},\ k_{\mathrm{CSCP}}(m) = \frac{1}{\exp\left\{0{,}1\left(m-33\right)\right\}+1} \tag{5}$$

$$b_{2c,\,t\,(\mathrm{ESCP})} = b_{0(\mathrm{ESCP})} \cdot \sqrt{25/t} \cdot \left(2c/30\right)^{k_{\mathrm{ESCP}}(m)/2},k_{\mathrm{ESCP}}(m) = \frac{1}{\exp\left\{0{,}1\left(m-40\right)\right\}+1} \tag{6}$$

NOTE Equations (5) and (6) hold under a given crack depth ratio, a/t.

In the case of single-edge surface crack of length c, the equivalent CTOD ratio, $\beta = \beta_{c,\,t}$, is given in the form

$$b_{c,\,t\,(\mathrm{ESCP})} = b_{2c,\,t\,(\mathrm{ESCP})} \cdot \left(1/2\right)^{k_{\mathrm{ESCP}}(m)/2} \tag{7}$$

Level III: β is calculated, as shown in Figure 6, with a statistically determined m-value.