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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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Foreword

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ISO 27306 was prepared by Technical Committee ISO/TC 164, *Mechanical testing of metals*, Subcommittee SC 4, *Toughness testing — Fracture(F), Pendulum(P), Tear(T)*.

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 loading. 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 toughness assessment using the stress intensity factor or the J-integral concept (see Clause 8).

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 is not included in the scope hereof.

The CTOD fracture toughness of structural steels is measured in accordance with any one of the established test methods, ISO 12135:2002, BS 7448-1:1991 or ASTM E1290-99. 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 document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 12135:2002, *Metallic materials — Unified method of test for the determination of quasistatic fracture toughness*

BS 7448-1:1991, *Fracture mechanics toughness tests — Method for determination of KIc, critical CTOD and critical J values of metallic materials*

ASTM E1290-99[1)], *Standard Test Method for Crack-Tip Opening Displacement (CTOD) Fracture Toughness measurement*

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 $\leqslant (a_0/W) \leqslant$ 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 $\leqslant a_0/W \leqslant$ 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
$\delta_{WP,cr}$
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 δ/δ_{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].

1) The procedure for calculating CTOD in ASTM E1290-08 is different from the one in ASTM E1290-1999. The new ASTM E1290 procedure gives a somewhat different CTOD value compared to those calculated by ISO 12135:2002 and BS 7448-1:1991. This International Standard employs ASTM E1290-99, which specifies the CTOD calculation procedure similar to ISO 12135:2002 and BS 7448-1:1991.

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
$\sigma_{W,cr}$
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 (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.

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 ($= R_{p0,2}/R_m$)
β	—	Equivalent CTOD ratio
β_0	—	Equivalent CTOD ratio for reference crack size
β_{2c}	—	Equivalent CTOD ratio for target size of centre surface crack or double-edge surface crack
β_{2a}	—	Equivalent CTOD ratio for target size of centre through-thickness crack or double-edge through-thickness crack
β_c	—	Equivalent CTOD ratio for target size of single-edge surface crack
β_a	—	Equivalent CTOD ratio for target size of single-edge through-thickness crack

Symbol	Unit	Designation
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_{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 specimens [three-point bend or compact specimens with $0,45 \leqslant a_0/W \leqslant 0,55$ 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 a higher constraint near the crack- tip than that with $0,45 \leqslant a_0/W \leqslant 0,55$. The equivalent CTOD ratio β defined in this International Standard leads to a conservative fracture assessment, if the user employs the deep cracked specimen with $a_0/W > 0,55$.

NOTE 2 This International Standard does not intend to address size and temperature effects nor the 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 any one of the established test methods, ISO 12135:2002, BS 7448-1:1991 or ASTM E1290-99. 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, δ/δ_{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, $\delta_{WP,cr}$, of the structural component using β in the form

$$\delta_{WP,cr} = \delta_{cr} / \beta \qquad (1)$$

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

$$\delta_{req} = \beta \cdot \delta_{WP,req} \qquad (2)$$

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, and 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. The nomographs are presented in Clause 8, where the yield-to-tensile ratio, R_Y, and the Weibull shape parameter, m, are in the range $0{,}6 \leqslant R_Y \leqslant 0{,}95$ and $10 \leqslant m \leqslant 50$ (R_Y and m for structural steels are generally in this range). They are prepared on the conditions that the thickness, B, of the fracture toughness specimen is equal to the plate thickness, t, of the structural component, and that there are no significant differences in fracture toughness through the thickness of the steel being assessed. This procedure may also be applicable in cases where the crack size, yield-to-tensile ratio, R_Y, etc. of the structural component concerned are not within the range of the nomographs, provided that, β, is obtained by an appropriate procedure.

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 7. 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, undercut, cold cracking (hydrogen-induced cracking) 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 uniaxial 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 Assessment levels I, II and III

7.1 General

This International Standard proposes three levels for the assessment of the equivalent CTOD ratio, β. Applicable assessment levels can be selected by agreement of the parties concerned. The details of the assessments and required information are summarized in Table 1.

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) — Reference m-value (lower-bound value)	— Yield-to-tensile ratio, R_Y — Crack type in structural component — Crack size (length, depth) — Stress-strain curve for finite element (FE) analysis — Statistically determined m-value
Equivalent CTOD ratio β	$\beta = 0,5$	$0 < \beta < 1$ (in most cases, $0 < \beta < 0,5$) $\beta = f(R_Y, a, c, m)$ for CSCP, ESCP $\beta = f(R_Y, a, m)$ for CTCP, ETCP	$0 < \beta$ (Level III) $< \beta$ (Level II) $\beta = f(R_Y, a, c, m)$ 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; m: Weibull shape parameter

Assessment levels I to III are applied in loading conditions beyond small-scale yielding (SSY). The $\delta_{SSY\ limit}$ 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 to build the same level of the Weibull stress as in the fracture toughness specimen beyond $\delta_{SSY\ limit}$ are considered in a wide plate structural component, constraint loss can be significant in the structural component. This International Standard presents the equivalent CTOD ratio, β, under such loading conditions.

7.2 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, $\beta = 0,5$ is used as an upper-bound engineering approximation.

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

7.3 Level II: Normal assessment

Level II assessment is applicable to cases where the mechanical properties (yield-to-tensile ratio, R_{Y}) of the structural component being assessed and the type and size of the assumed crack are known, but the Weibull shape parameter, m, is unknown. A lower-bound value for m is assumed for the assessment of β.

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

The use of a lower-bound m-value may lead to an excessive overestimation of β for cases where the yield-to-tensile ratio $R_{\mathrm{Y}} < 0{,}8$, and the surface crack length $2c > 50$ mm or the through-thickness crack length $2a > 25$ mm. Level III assessment is recommended in such cases.

7.4 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.

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

8 Equivalent CTOD ratio, β

8.1 General

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

8.2 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 mainly controlling 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 (in the case of a deep surface crack);

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.

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

8.3.1 General

The procedure for calculating the equivalent CTOD ratio, β, at assessment levels I to III is described below. Equations (3), (4), (6) and (7) are applicable for the following crack sizes:

CSCP: $2c \geqslant 16$ mm, $1 \leqslant a \leqslant 6$ mm, $t \geqslant 25$ mm

ESCP: $2c \geqslant 24$ mm, $1 \leqslant a \leqslant 6$ mm, $t \geqslant 25$ mm

CTCP: $5 \leqslant 2a \leqslant 50$ mm

ETCP: $5 \leqslant 2a \leqslant 30$ mm

8.3.2 Surface crack case (CSCP or 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) and the material yield-to-tensile ratio, R_Y.

Step 2: Set the reference value (lower-bound value) of the shape parameter, m. Annex A can be referred to when selecting the lower-bound m-value.

Step 3: Determine the equivalent CTOD ratio, β_0, for a reference crack size from the nomographs shown in Figures 7 and 8 as a function of the m-value, crack depth, a, and the yield-to-tensile ratio, R_Y.

Step 4: Calculate the equivalent CTOD ratio, $\beta = \beta_{2c}$, for the target crack length, $2c$, using Equation (3) or Equation (4), depending on the type of crack:

$$\beta_{2c(\text{CSCP})} = \beta_{0(\text{CSCP})} \cdot (2c/40)^{k_{\text{CSCP}}(m)/2}, \quad k_{\text{CSCP}}(m) = \frac{1}{\exp\left[0{,}1(m-33)\right]+1} \tag{3}$$

$$\beta_{2c(\text{ESCP})} = \beta_{0(\text{ESCP})} \cdot (2c/30)^{k_{\text{ESCP}}(m)/2}, \quad k_{\text{ESCP}}(m) = \frac{1}{\exp\left[0{,}1(m-40)\right]+1} \tag{4}$$

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

$$\beta_{c(\text{ESCP})} = \beta_{2c(\text{ESCP})} \cdot (1/2)^{k_{\text{ESCP}}(m)/2} \tag{5}$$

For $t \geqslant 25$ mm and $1 \leqslant a \leqslant 6$ mm, the equivalent CTOD ratio, β, shows virtually no dependence on the plate thickness, t.

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

8.3.3 Through-thickness crack case (CTCP or ETCP)

The procedure for calculating the equivalent CTOD ratio, β, for the through-thickness 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 length, $2a$, and the material yield-to-tensile ratio, R_Y.

Step 2: Set the reference value (lower-bound value) of the shape parameter, m. Annex A can be referred to when selecting the lower-bound m-value.

Step 3: Determine the equivalent CTOD ratio, β_0, for a reference crack size from the nomographs shown in Figures 9 and 10 as a function of the m-value and the yield-to-tensile ratio R_Y.

Step 4: Calculate the equivalent CTOD ratio, $\beta = \beta_{2a}$, for the target crack length $2a$ with Equation (6) or (7), depending on the type of crack:

$$\beta_{2a(\text{CTCP})} = \beta_{0(\text{CTCP})} \cdot (2a/13{,}8)^{0{,}4} \tag{6}$$

$$\beta_{2a(\text{ETCP})} = \beta_{0(\text{ETCP})} \cdot (2a/11)^{k_{\text{ETCP}}(m,\, R_Y)}, \quad k_{\text{ETCP}}(m, R_Y) = \frac{-0{,}57 + 3{,}1 R_Y - 1{,}45 {R_Y}^2}{\exp\left[-0{,}35(m-10)\right] + 1} \tag{7}$$

In the case of single-edge through-thickness crack of length a, the equivalent CTOD ratio, $\beta = \beta_a$, is given in the form

$$\beta_{a(\text{ETCP})} = \beta_{2a(\text{ETCP})} \big/ \sqrt{2} \tag{8}$$

The equivalent CTOD ratio, β, of through-thickness cracks shows no dependence on the plate thickness.

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

In the case of the fracture assessment using the stress intensity factor K, $\beta^{1/2}$ can be used for the constraint loss correction. For the assessment based on the J-integral, β may be used as it is.

FE analysis of the Weibull stress for the fracture toughness specimen is required for determining the m-value at level III assessment. A recommended procedure for the analytical determination of the m-value is described in Annex B.

Annex C describes the guidelines for application of the equivalent CTOD ratio, β, at assessment levels I to III. In cases where the crack size in structural components, yield-to-tensile ratio, R_Y and the shape parameter, m of the material being assessed are not in the range of the nomographs in Figures 7 to 10, and are also outside the applicable range of Equations (3), (4), (6) and (7), an equivalent CTOD ratio, β, obtained by a suitable method, e.g. FE analysis of the target component, may be used.

Annex D presents examples of fracture assessments of structural components using the equivalent CTOD ratio, β. Fracture assessment methods, such as FAD (Failure Assessment Diagram) [6] or CTOD design curve [7], which have been duly authorized in the organization concerned, may be used.

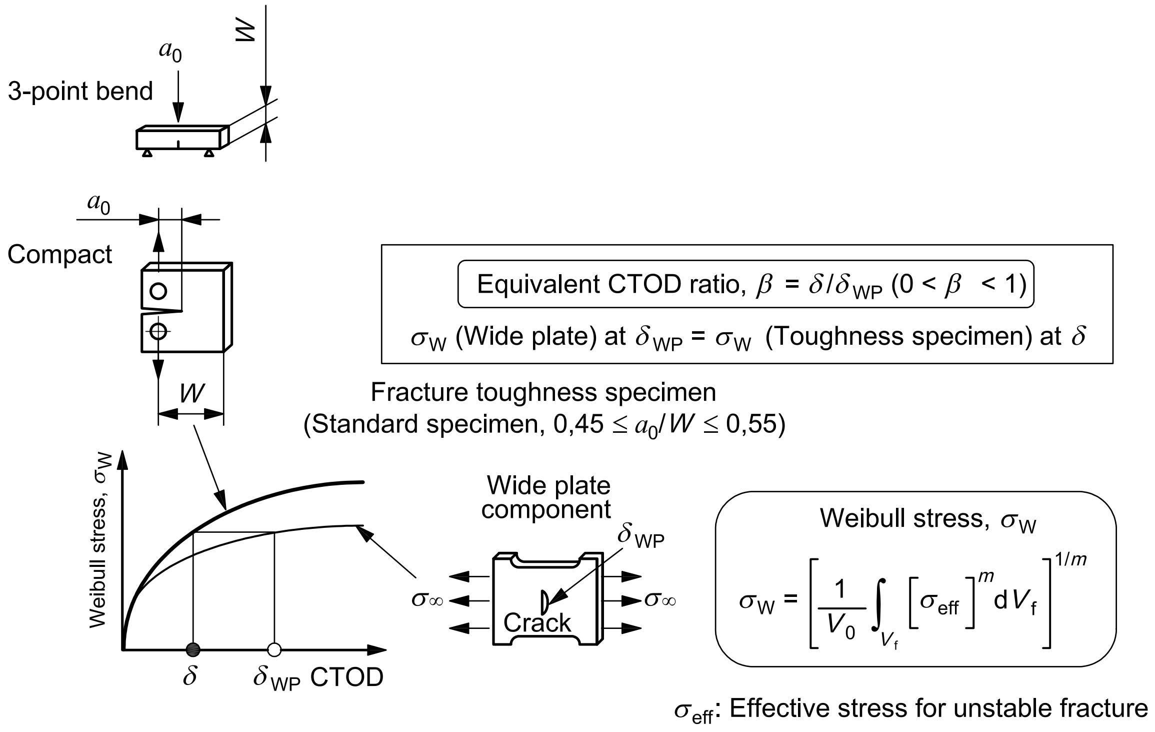

Figure 1 — Definition of the equivalent CTOD ratio, β, based on the Weibull stress fracture criterion

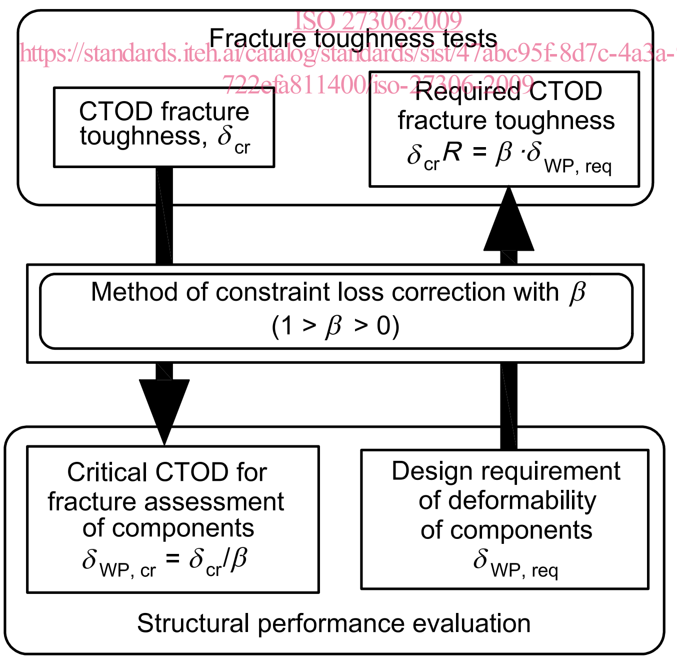

Figure 2 — Method of constraint loss correction to link fracture toughness tests and structural performance evaluation

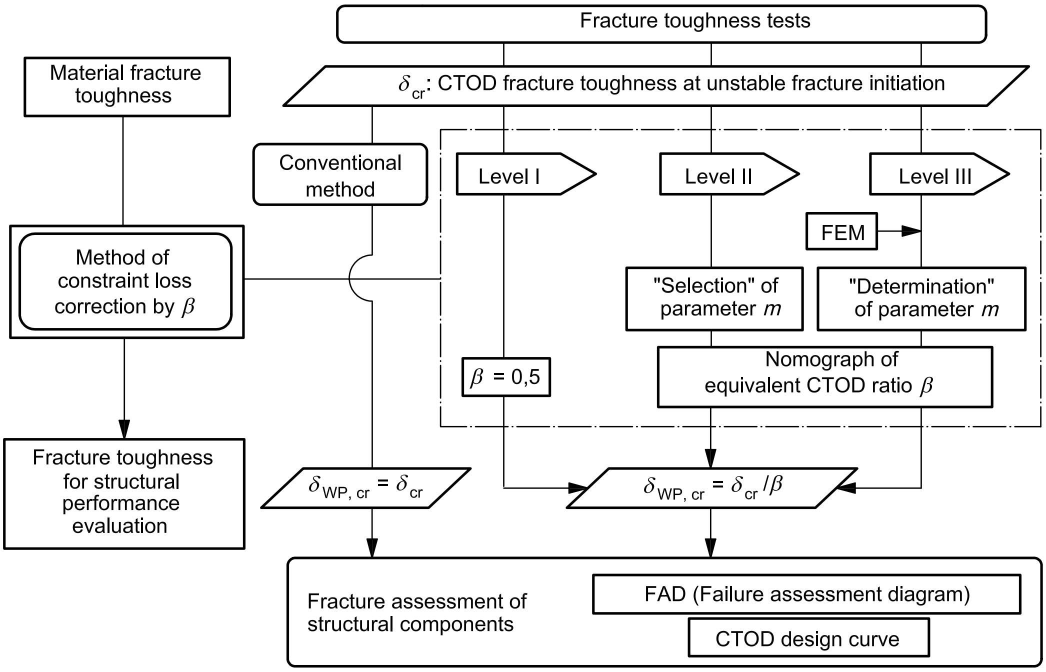

Figure 3 — Flow of fracture assessment of structural components from fracture toughness test results, where three assessment levels of the equivalent CTOD ratio, β, are included for constraint loss correction