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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

Reference number
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Foreword

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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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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 $\delta_{\text{SSY limit}}$ 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 to build the same level of the Weibull stress as in the fracture toughness specimen beyond $\delta_{\text{SSY limit}}$ 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 $R_Y < 0{,}8$, 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:

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

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

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

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

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:

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

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

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.

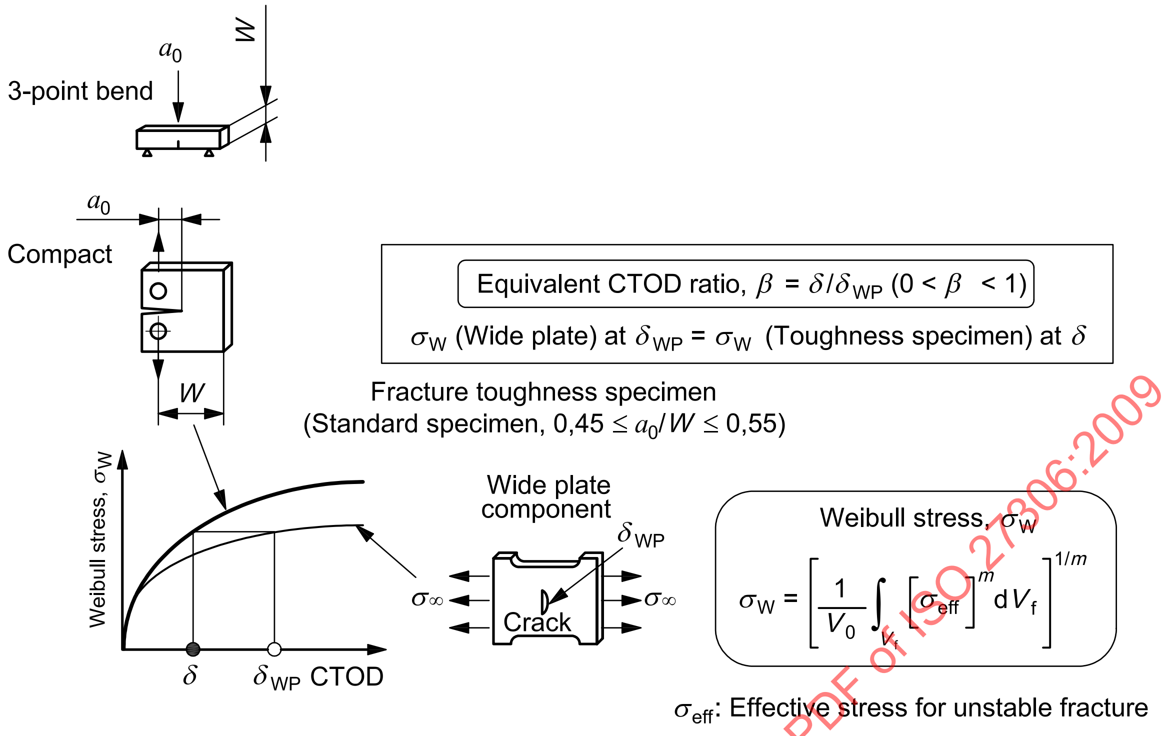


Figure 1 — Definition of the equivalent CTOD ratio, β, based on the Weibull stress fracture criterion

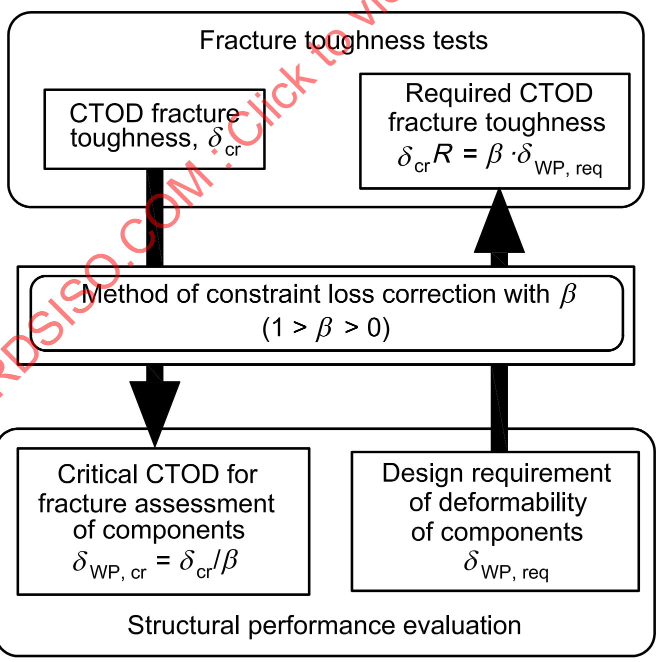


Figure 2 — Method of constraint loss correction to link fracture toughness tests and structural performance evaluation

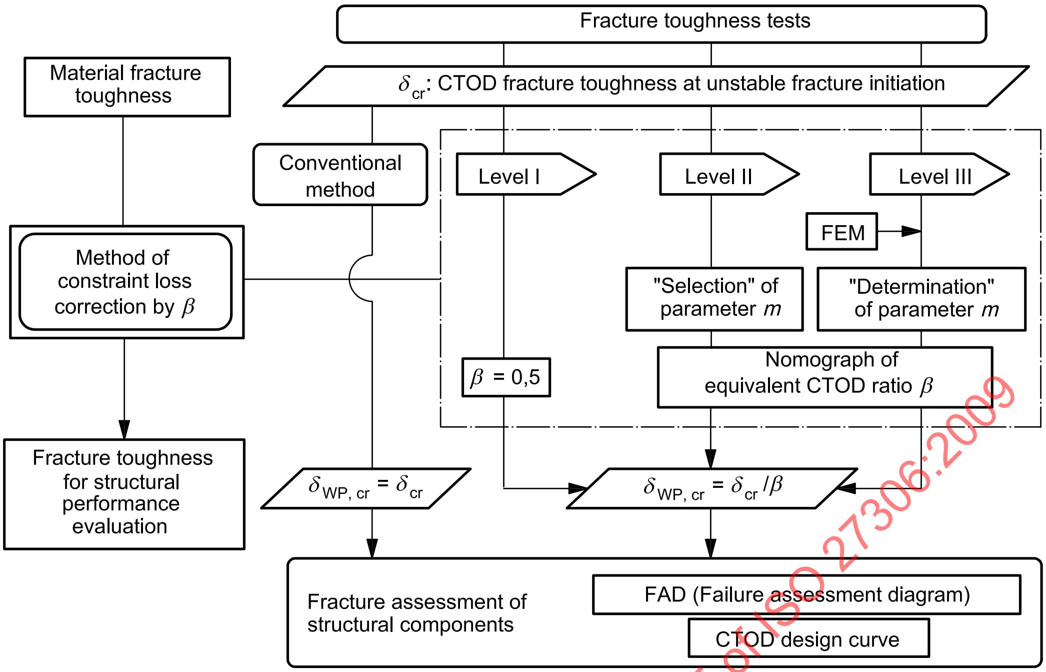


Figure 3 — Flow of fracture assessment of structural components from fracture toughness test results, where three assessment levels of the equivalent CTOD ratio, β, are included for constraint loss correction

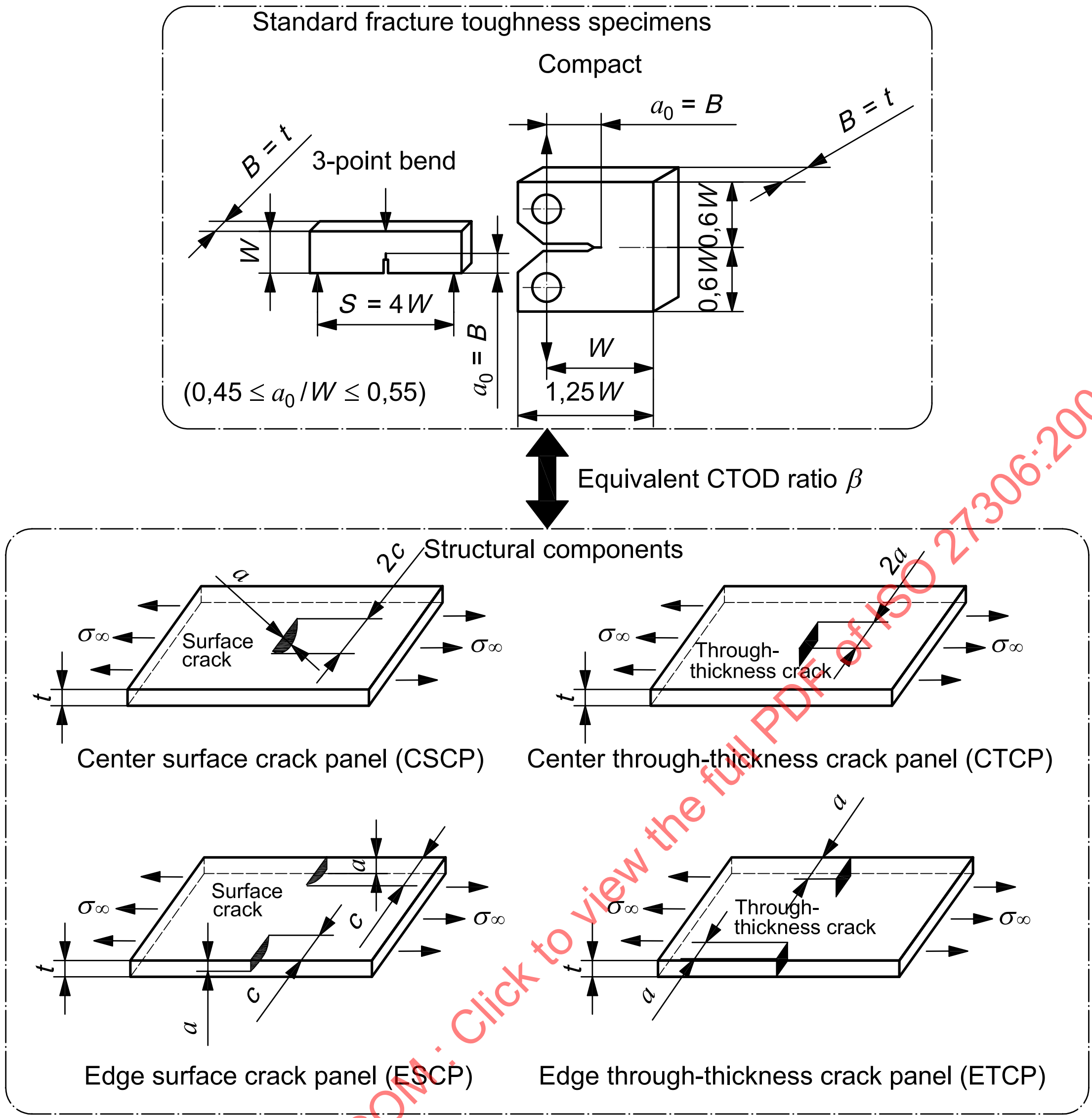
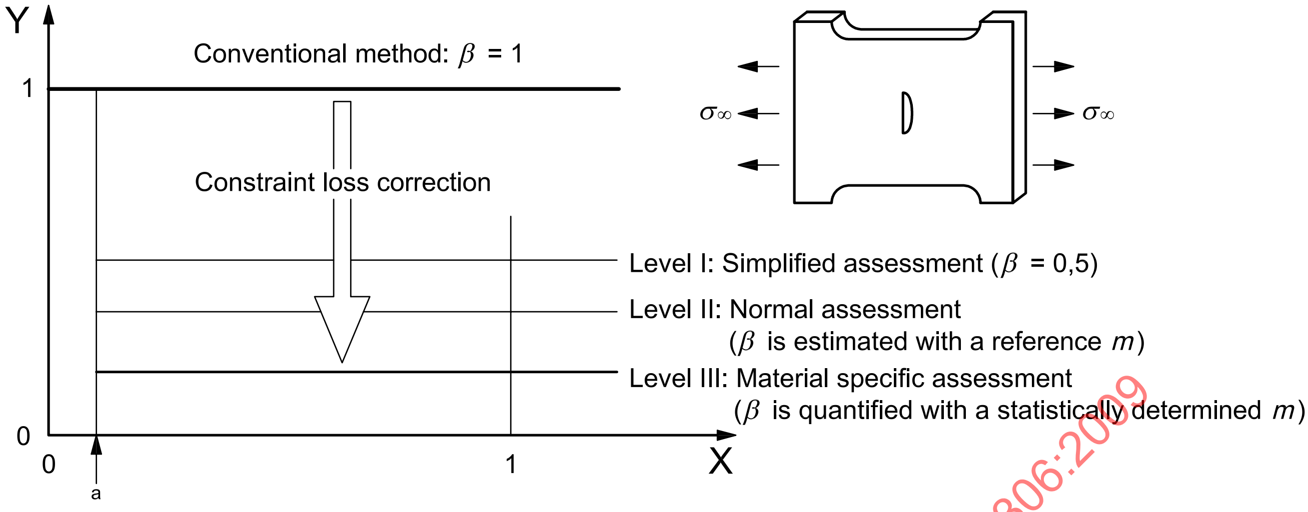


Figure 4 — Standard fracture toughness specimens and wide plate components linked with the equivalent CTOD ratio, β



Key

X applied stress $\sigma_\infty / R_{p0,2}$

Y equivalent CTOD ratio $\beta = \delta / \delta_{WP}$

a σ_∞ level corresponding to $\delta_{SSY\ limit}$ for standard fracture toughness specimen.

Figure 5 — Assessment levels I, II and III of β for correcting constraint loss in wide plate components

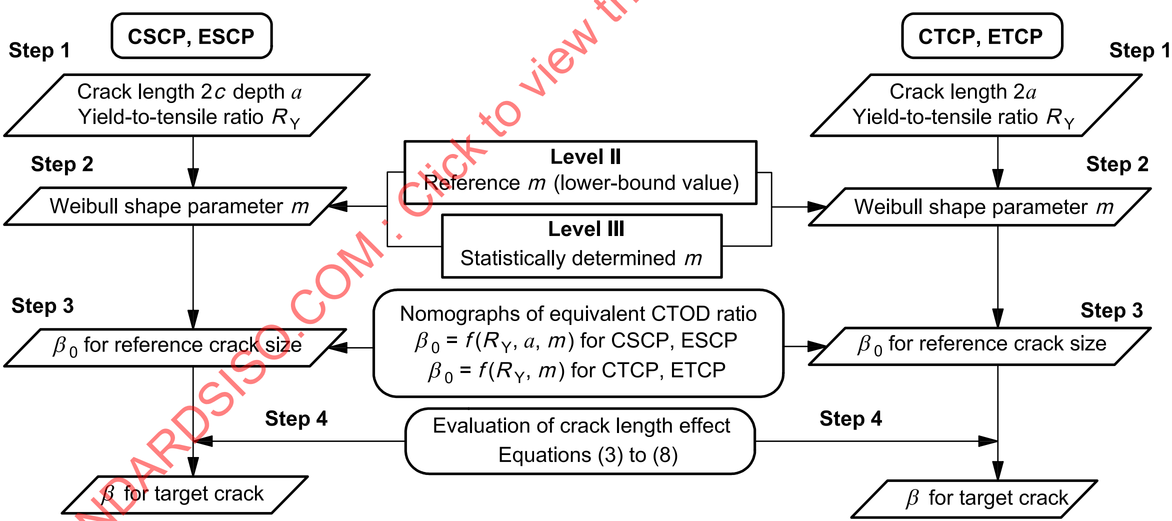
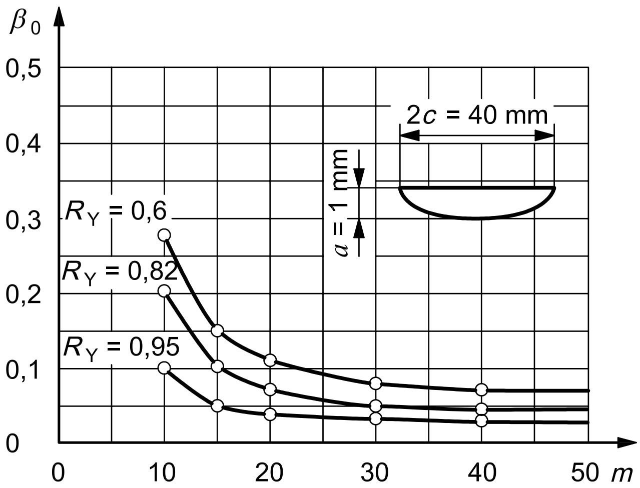
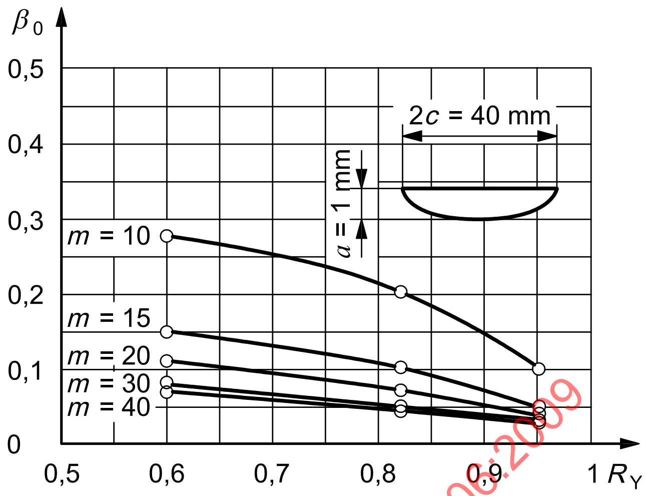


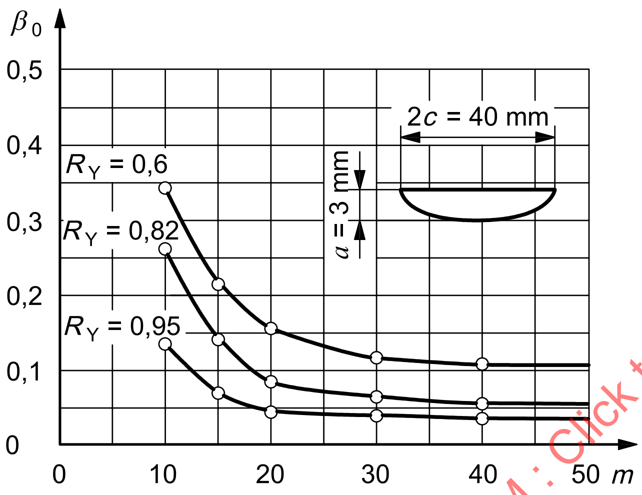
Figure 6 — Flow chart for calculating the equivalent CTOD ratio, β



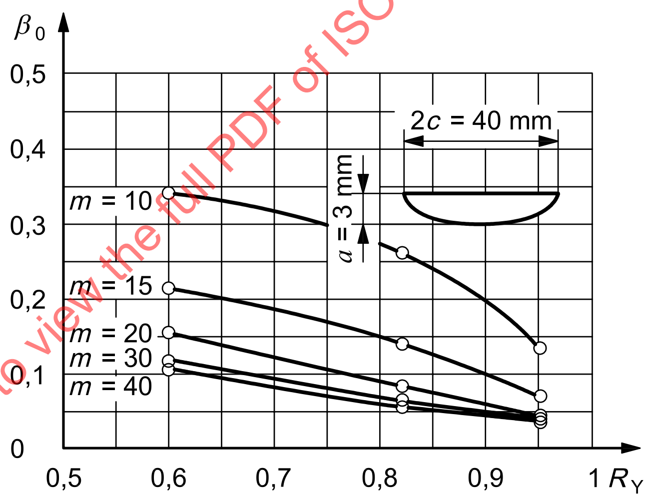
a) CSCP (a = 1 mm; $t \geqslant$ 25 mm): β_0 versus m



b) CSCP (a = 1 mm; $t \geqslant$ 25 mm): β_0 versus R_Y

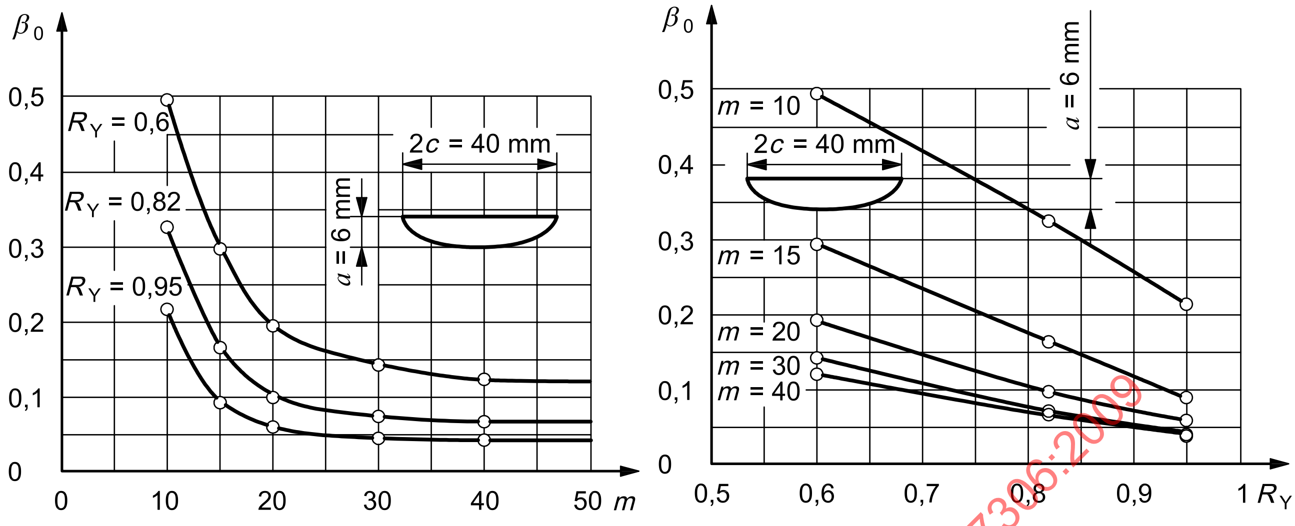


c) CSCP (a = 3 mm; $t \geqslant$ 25 mm): β_0 versus m



d) CSCP (a = 3 mm; $t \geqslant$ 25 mm): β_0 versus R_Y

Figure 7 (*continued*)



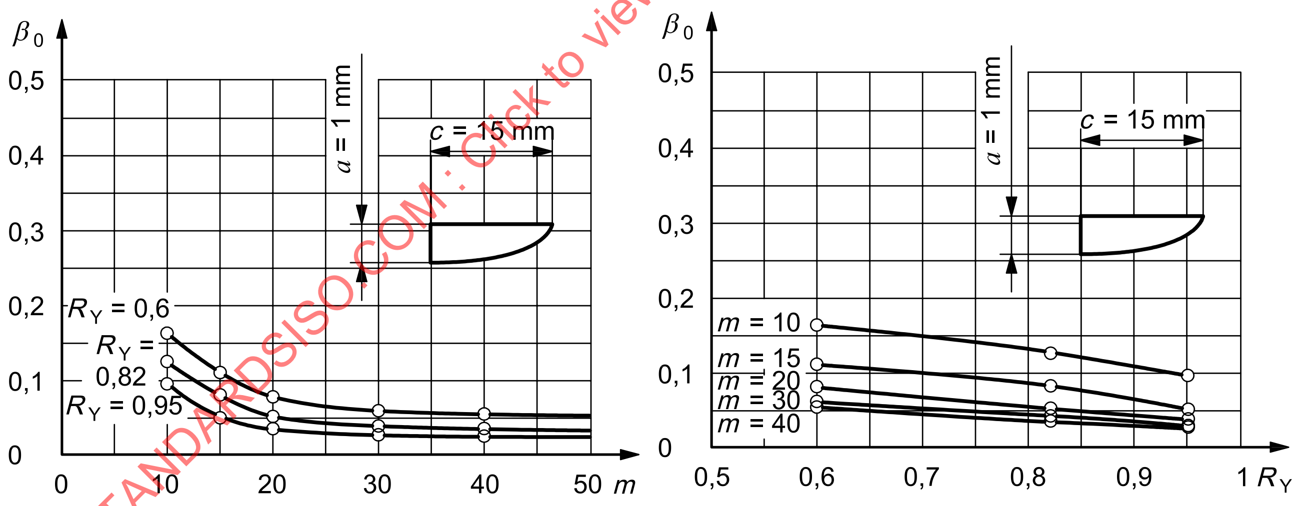
e) CSCP (a = 6 mm; $t \geqslant$ 25 mm): β_0 versus m

f) CSCP (a = 6 mm; $t \geqslant$ 25 mm): β_0 versus R_Y

Key

a	crack depth	R_Y	yield-to-tensile ratio
2c	surface crack length	t	plate thickness
m	Weibull shape parameter	β_0	equivalent CTOD ratio for reference crack size, equal to δ/δ_{WP}

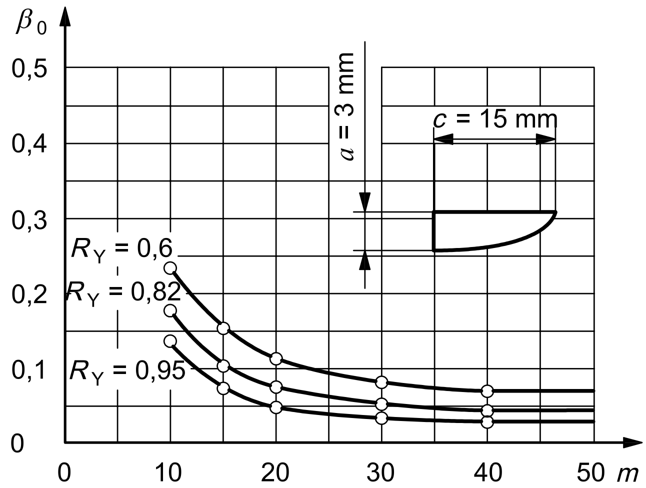
Figure 7 — Nomographs of equivalent CTOD ratio, β_0, for centre surface crack panel (CSCP)



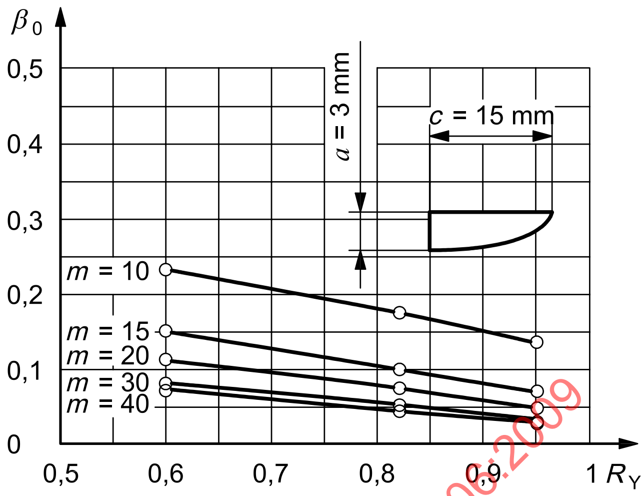
a) ESCP (a = 1 mm; $t \geqslant$ 25 mm): β_0 versus m

b) ESCP (a = 1 mm; $t \geqslant$ 25 mm): β_0 versus R_Y

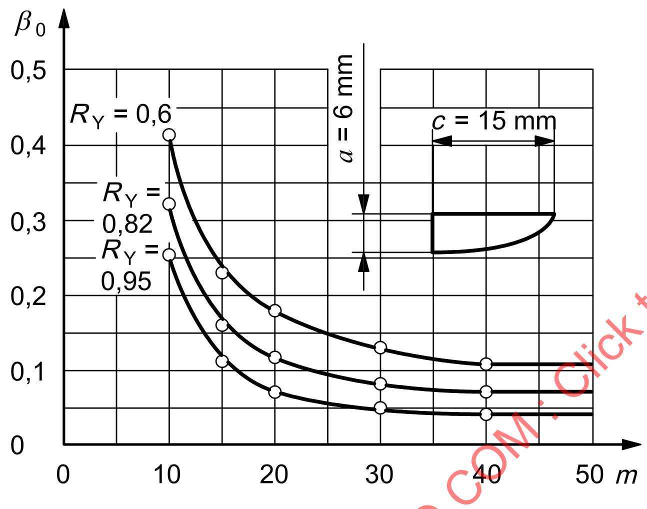
Figure 8 (*continued*)



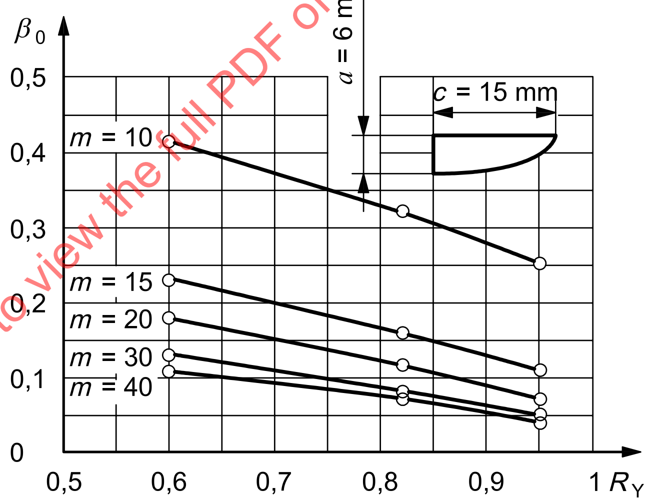
c) ESCP (a = 3 mm; $t \geqslant$ 25 mm): β_0 versus m



d) ESCP (a = 3 mm; $t \geqslant$ 25 mm): β_0 versus R_Y



e) ESCP (a = 6 mm; $t \geqslant$ 25 mm): β_0 versus m



f) ESCP (a = 6 mm; $t \geqslant$ 25 mm): β_0 versus R_Y

Key

a crack depth

c length of edge surface crack

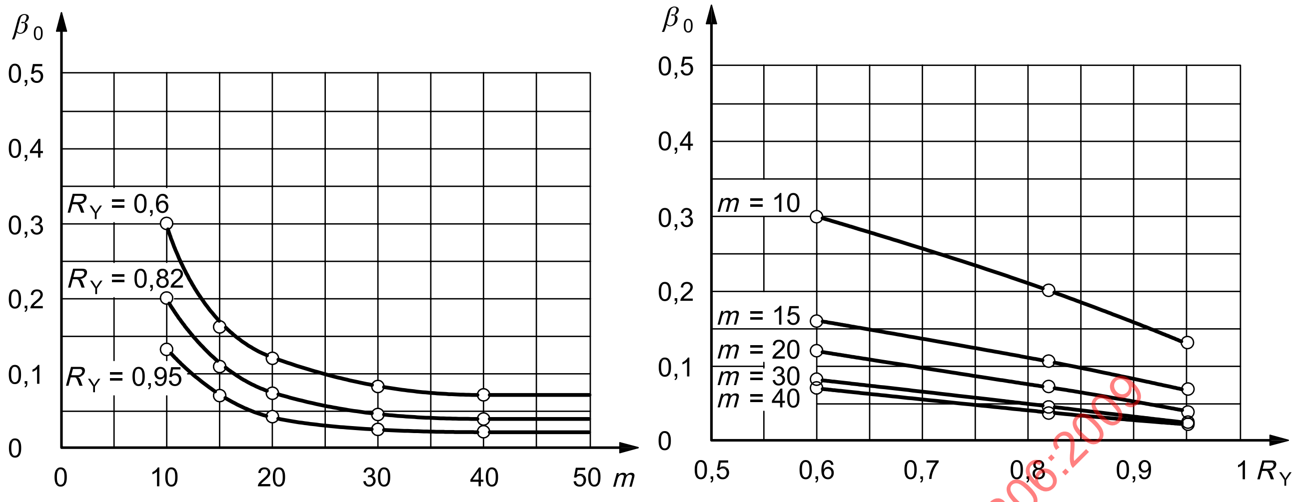
m Weibull shape parameter

R_Y yield-to-tensile ratio

t plate thickness

β_0 equivalent CTOD ratio for reference crack size, defined as δ/δ_{WP}

Figure 8 — Nomographs of equivalent CTOD ratio, β_0, for edge surface crack panel (ESCP)



a) CTCP ($2a$ = 13,8 mm): β_0 versus m

b) CTCP ($2a$ = 13,8 mm): β_0 versus R_Y

Key

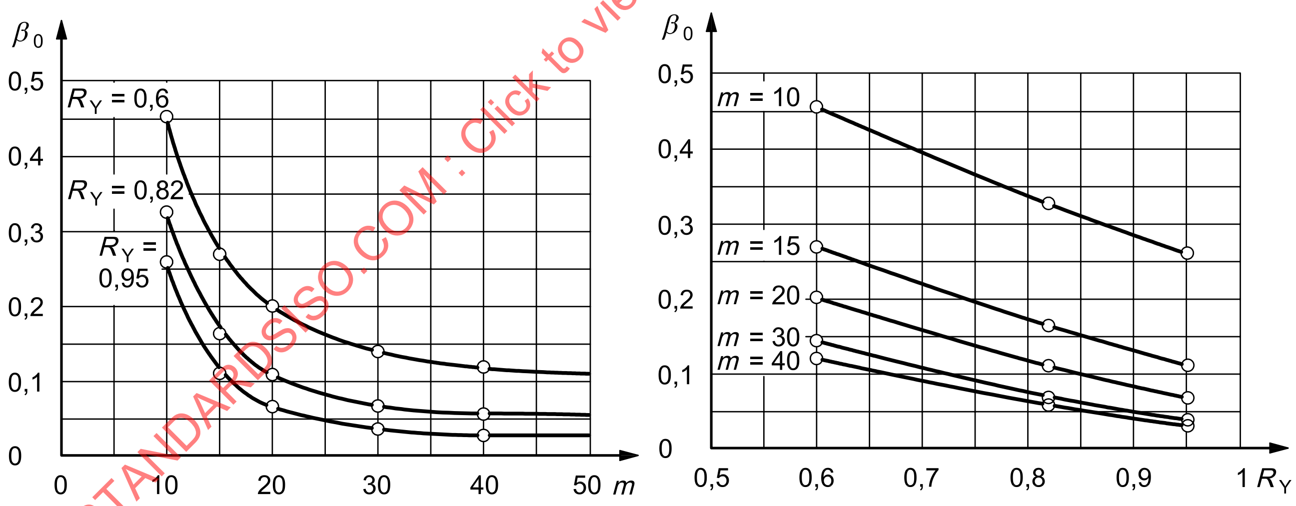
$2a$ through-thickness crack length

m Weibull shape parameter

R_Y yield-to-tensile ratio

β_0 equivalent CTOD ratio for reference crack size, defined as δ/δ_{WP}

Figure 9 — Nomographs of equivalent CTOD ratio, β_0, for centre through-thickness crack panel (CTCP)



a) ETCP ($2a$ = 11 mm): β_0 versus m

b) ETCP ($2a$ = 11 mm): β_0 versus R_Y

Key

a length of edge through-thickness crack

m Weibull shape parameter

R_Y yield-to-tensile ratio

β_0 equivalent CTOD ratio for reference crack size, defined as δ/δ_{WP}

Figure 10 — Nomographs of equivalent CTOD ratio, β_0, for edge through-thickness crack panel (ETCP)

Annex A
(informative)

Procedure for the selection of Weibull parameter m at level II assessment

A.1 General

The procedure for the selection of the Weibull shape parameter m at level II assessment is described. The shape parameter m is selected in the light of the average CTOD fracture toughness at the assessment temperature.

A.2 Determination of average CTOD fracture toughness

In selecting the shape parameter m, the average (arithmetic mean) value of the CTOD fracture toughness $\delta_{\text{cr,ave}}$ at the assessment temperature obtained with 25 mm thick test specimens shall be used.

In cases where no test data with 25 mm thick test specimens are available, the CTOD fracture toughness for a 25 mm thick specimen $\delta_{\text{cr,ave-25}}$, which is calculated using Equations (A.1) and (A.2) [3], [8], may be used.

$$\delta_{\text{cr,ave-25}} = \left\{ \sqrt{\delta_{\text{min}}} + \left(\sqrt{\delta_{\text{cr,ave-}B}} - \sqrt{\delta_{\text{min}}} \right) \cdot \left(\frac{B}{25} \right)^{1/4} \right\}^2 \qquad \text{(A.1)}$$

$$\delta_{\text{min}} = \frac{500 \cdot \left(1 - \nu^2\right)}{R_{\text{p0,2}} \cdot E} \cdot K_{\text{min}}{}^2 \qquad \text{(A.2)}$$

where

B is the test specimen thickness (mm);

$\delta_{\text{cr,ave-}B}$ is the average CTOD fracture toughness with test specimen thickness B (mm);

$R_{\text{p0,2}}$ is the yield strength (MPa);

ν is Poisson's ratio;

K_{min} is equal to 20 $(\text{MPa}\sqrt{\text{m}})$.

Note that Equations (A.1) and (A.2) are valid for the CTOD fracture toughness at brittle fracture initiation without a significant amount of stable crack extension.

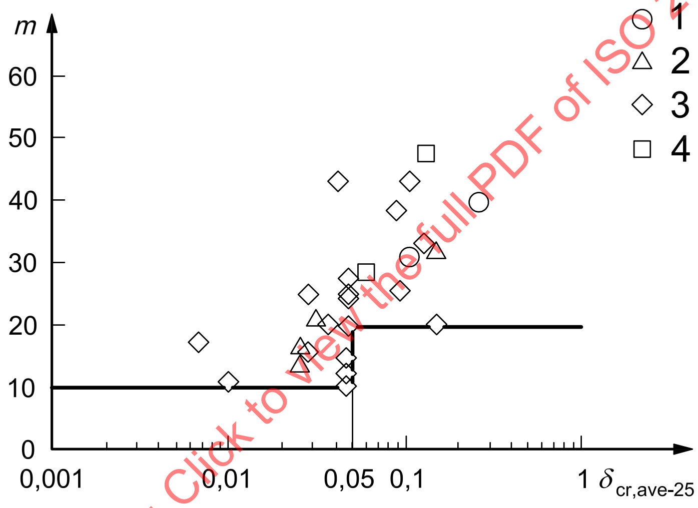
A.3 Determination of Weibull shape parameter m

A.3.1 Assessment of brittle fracture initiation of steel structure components from fracture toughness of structural steel

In cases where the brittle fracture limit of steel components is to be assessed based on the fracture toughness of the structural steel, the shape parameter m is selected as shown in Equation (A.3) depending on the average CTOD fracture toughness, $\delta_{\text{cr,ave-25}}$.

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

In Equation (A.3), the shape parameter m is selected provisionally as the lower-bound value of m so as to lead to a conservative failure assessment in the light of a diagram for m and $\delta_{\text{cr,ave -25}}$ (Figure A.1) based on data from Reference [1] and References [9] to [19].



Key

1 mild steel ($R_{p0,2} < 295$ MPa)

2 HT500 class (295 MPa $\leqslant R_{p0,2} <$ 440 MPa)

3 HT600 class (440 MPa $\leqslant R_{p0,2} <$ 685 MPa)

4 HT800 class (685 MPa $\leqslant R_{p0,2} <$ 885 MPa)

m Weibull shape parameter

$\delta_{\text{cr,ave-25}}$ CTOD fracture toughness for a 25 mm thick specimen, expressed in millimetres

Figure A.1 — Relationship between Weibull parameter, m, and average CTOD fracture toughness, $\delta_{\text{cr,ave-25}}$

A.3.2 Determination of fracture toughness needed to meet design requirement of deformability of structural components

In cases where the fracture toughness needed to meet the design requirement of deformability of structural components is to be determined, the use of the lower-bound value in Equation (A.4) is recommended for estimation of the required fracture toughness.

$$m = 10 \qquad \text{(A.4)}$$

In cases where the level of CTOD fracture toughness of the material can be estimated from the Charpy impact test results or other properties, m may be selected as shown in Equation (A.3).

For additional information on the relationship between the Weibull parameter and the fracture toughness of structural steels, see Reference [20].

Annex B
(informative)

Analytical method for the determination of Weibull parameter m at level III assessment

B.1 General

This annex describes the analytical procedure for the determination of the Weibull shape parameter m that is needed at level III failure assessment. A common procedure [9] is shown in Figure B.1, and the recommended methods in the Steps 1 to 3 are described in the following.

B.2 Fracture toughness test (Step 1)

Fracture toughness tests shall be performed using the three-point bend test specimen or the compact specimen in accordance with ISO 12135. However, the initial crack length of the test specimen shall be within the range of $0{,}45 \leqslant (a_0/W) \leqslant 0{,}55$. The toughness tests (Table B.1) shall be performed with an adequate number of specimens to determine the parameter m, and statistical data of the critical CTOD shall be obtained. After testing, the fracture surface shall be observed, and the fact that brittle fracture occurred without stable crack extension larger than 0,2 mm shall be confirmed.

NOTE 1 In R/H/R6 Revision 3 – Appendix 17, a minimum number of 30 tests is recommended [21], [22].

NOTE 2 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 $a_0/W > 0{,}55$ [23].

NOTE 3 One set of fracture toughness data obtained by the above specimen may give a non-unique m-value, if the stress field near the crack-tip shows the singularity controlled by K or by the HRR (Hutchinson, Rice and Rosengren) field within the range of the fracture toughness level measured. This non-uniqueness is related to the statistical characteristics of toughness values, which follow a two-parameter Weibull distribution with a constant shape parameter (= 2 for the critical CTOD), under the singular stress fields. In such a case, the use of two sets of specimens with high and low constraints, e.g. deep-cracked and shallow-cracked specimens, is recommended to get a unique solution for m. The details of the calibration procedure for m using two data sets is described in Reference [24].

Table B.1 — Fracture toughness testing

Number of test specimens	Large enough for determination of Weibull parameter m with statistical reliability
Items measured	Force, P, and crack mouth opening displacement, V_g
Fracture toughness parameter	Critical CTOD, δ_{cr}

B.3 FE-analysis of stress fields ahead of crack-tip in fracture toughness specimen (Step 2)

B.3.1 General

The stress fields ahead of the crack-tip in the fracture toughness specimen shall be analysed by a finite element method (FEM) that incorporates large deformation analysis. A guideline for obtaining sound FE-results in terms of the stress-strain curve of material used and the FE-model is described in the following subclauses.

B.3.2 Stress-strain curve for FE-analysis

B.3.2.1 Round-bar tensile testing

In order to obtain the stress-strain curve of the material for use in the FE-analysis, a round-bar tensile test shall be performed in accordance with established International Standards for testing, such as the following:

ISO 6892:1998, *Metallic materials — Tensile testing at ambient temperature;*

ISO 15579:2000, *Metallic materials — Tensile testing at low temperature.*

The test shall be performed at the same temperature as that of the fracture toughness test in Step 1. During the test, force and elongation between gauge marks shall be measured and recorded.

B.3.2.2 Equivalent stress-equivalent plastic strain curve for FE-analysis

Based on the results of the round-bar tensile test, the relationship between equivalent stress and equivalent plastic strain to be used in the FE-analysis shall be determined in accordance with the following procedure.

a) Calculate the nominal stress-nominal plastic strain relationship, excluding the elastic strain component, from the nominal stress-nominal strain curve measured in the strain range up to uniform elongation.

b) Convert the nominal stress-nominal plastic strain relationship to the true stress-true plastic strain relationship (equivalent stress-equivalent plastic strain relationship) using the following equations.

$$s = \sigma(1 + \varepsilon) \qquad \text{(B.1)}$$

$$e = \ln(1 + \varepsilon) \qquad \text{(B.2)}$$

where

s is the true stress;

e is the true strain;

σ is the nominal stress;

ε is the nominal strain.

NOTE Lüder's strain, if observed in the round-bar tension test, would be included in Equations (B.1) and (B.2).

c) Constitute the equivalent stress-equivalent plastic strain relationship beyond uniform elongation ε_T in the form:

$$\bar{\sigma} = R_{p0,2}\left(1 + \bar{\varepsilon}_p / \alpha\right)^n \qquad \text{(B.3)}$$

where

$\bar{\sigma}$ is the equivalent stress;

$\bar{\varepsilon}_p$ is the equivalent plastic strain (plastic component of equivalent strain);

$R_{p0,2}$ is the yield stress;

α and n are material constants (n being the strain hardening coefficient).

It is recommended that the material constants α and n should be determined using test data between $\varepsilon_T/2$ and ε_T, where ε_T is the uniform elongation (= nominal strain at the maximum load).

B.3.3 FE-model of fracture toughness specimen

A three-dimensional model shall be used in the FE-analysis. In the FE-mesh, the minimum element size and the region covered by the minimum element ahead of the crack-tip shall be well defined so that the stress/strain fields can be obtained with sufficient accuracy. Reference conditions for mesh design are shown in Table B.2. It is recommended that the minimum element size does not exceed the element size given in Table B.2. It is also recommended that a fine mesh region at the crack-tip divided with the minimum element is not smaller than the size indicated in Table B.2.

Table B.2 — Mesh design in FE-model

Element type	Isoparametric hexahedron element (8 Gaussian points)
Minimum element size	0,03 mm × 0,03 mm (in 2-dimensional plane)
Minimum mesh region	0,3 mm × 0,3 mm (in 2-dimensional plane)

The force P and crack mouth opening displacement V_g relation obtained by the FE-analysis shall be consistent with that measured in the test.

B.4 Method for determining Weibull shape parameter, m (Step 3)

B.4.1 General

A recommended procedure for determining the Weibull shape parameter m is described in the following, which is based on the Beremin cleavage fracture models.

B.4.2 Effective stress for the definition of Weibull stress

The Weibull stress, σ_W, is defined by Equation (B.4).

$$\sigma_W = \left\{ \frac{1}{V_0} \int_{V_f} \sigma_{eff}{}^m \mathrm{d}V_f \right\}^{\frac{1}{m}} \tag{B.4}$$

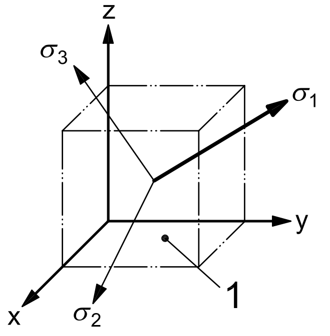
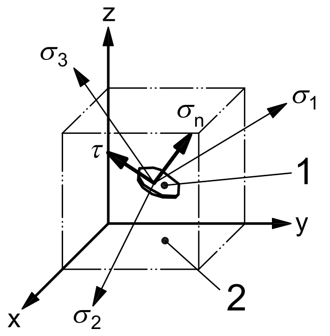
where

σ_{eff} is the effective stress for cleavage fracture initiation;

V_f is the fracture process zone that almost corresponds to the plastic zone ahead of the crack tip.

Methods for defining σ_{eff} can be based on two fracture criteria – one being based on the maximum principal stress criterion [2], and the other based on the fracture energy criterion [25, 26]. The stress, σ_{eff}, is given as shown in Table B.3 depending on which fracture criterion is selected. Either may be adopted for the determination of the Weibull shape parameter, m.

Table B.3 — Definitions of effective stress, σ_{eff}

Type 1 [2]	Maximum principal stress criterion	 **Key** 1 unit volume V_0	$\sigma_{eff} = \sigma_1$
Type 2 [25], [26]	Fracture energy criterion	 **Key** 1 micro-crack 2 unit volume V_0	$\sigma_{eff} = \left[\frac{1}{2\pi}\int_0^{\pi}\int_0^{\pi}\left\{\sigma_n^2 + \frac{4}{(2-\nu)^2}\tau^2\right\}^{m/2}\sin\theta\,d\theta\,d\phi\right]^{1/m}$ where σ_n is the normal stress acting on micro-crack; τ is the maximum shear stress acting on micro-crack; m is the Weibull shape parameter; ν is Poisson's ratio; θ, ϕ are angles of micro-crack relative to direction of maximum principal stress.

B.4.3 Calculation of Weibull stress

In the Beremin model, the reference volume, V_0, is defined as the microscopic fracture unit of the material concerned. However, the volume, V_0, does not affect the Weibull parameter, m, therefore, any volume size may be adopted provided it is within the scope of the Beremin model. Here, $V_0 = 1$ mm^3 is recommended for convenience.

The Weibull stress can be calculated by the method shown in Table B.4, using either the maximum principal stress, σ_1, or effective stress, σ_{eff}, defined in References [25] and [26].

An initial Weibull parameter, m_0, is assumed in this step.

Table B.4 — Method for numerical calculation of Weibull stress

	Stresses at 8 Gaussian points		Average stress of element
Maximum principal stress σ_1	Numerical integration (Gaussian integration) $\int_{V_f}\int_{Element} \sigma_1{}^m dV\, dV_f$	$\sum_{\ln V_f}\sum_{j=1}^{8}\left(\sigma_{1,j}{}^m \cdot \frac{V_i}{8}\right)$ (V_i: Volume of each element)	$\sum_{\ln V_f} \sigma_1{}^m \cdot V_i$ (V_i: Volume of each element)
Effective stress σ_{eff}	Numerical integration (Gaussian integration) $\int_{V_f}\int_{Element} \sigma_{eff}{}^m dV\, dV_f$	$\sum_{\ln V_f}\sum_{j=1}^{8}\left(\sigma_{eff,j}{}^m \cdot \frac{V_i}{8}\right)$ (V_i: Volume of each element)	$\sum_{\ln V_f} \sigma_{eff}{}^m \cdot V_i$ (V_i: Volume of each element)

B.4.4 Determination of critical Weibull stress

It is recommended that the critical Weibull stress shall be linked with the critical CTOD at brittle fracture initiation, using CTOD as a "linking parameter". An alternative index can be used as a linking parameter provided the force-deformation behaviour in the FE-analysis shows good agreement with that measured in the experiment.

The CTOD in the FE-analysis shall be calculated by the same procedure as used in determining the critical CTOD in the toughness test.

B.4.5 Statistical determination of Weibull shape parameter, m

For the analysis of toughness data, two-parameter Weibull failure distribution is assumed.

The Weibull parameter shall be determined by the maximum likelihood estimation method from the statistical set of the critical Weibull stress corresponding to the critical CTOD measured. The data necessary for the use of the maximum likelihood method are the total number of specimens tested and each toughness value. The maximum likelihood method is explained in detail in Reference [9]. Iteration shall be conducted until the Weibull parameter m converges to a stationary value that satisfies Equation (B.5) (Figure B.1).

$$|m_i - m_{i-1}|/m_i < 1\ \% \qquad \text{(B.5)}$$

where m_i and m_{i-1} are the m-values obtained in the ith and (i-1)th step, respectively.

It should be confirmed that the final m value should converge to the same value for either initial assumed m_0 that is larger than or smaller than the final m value.

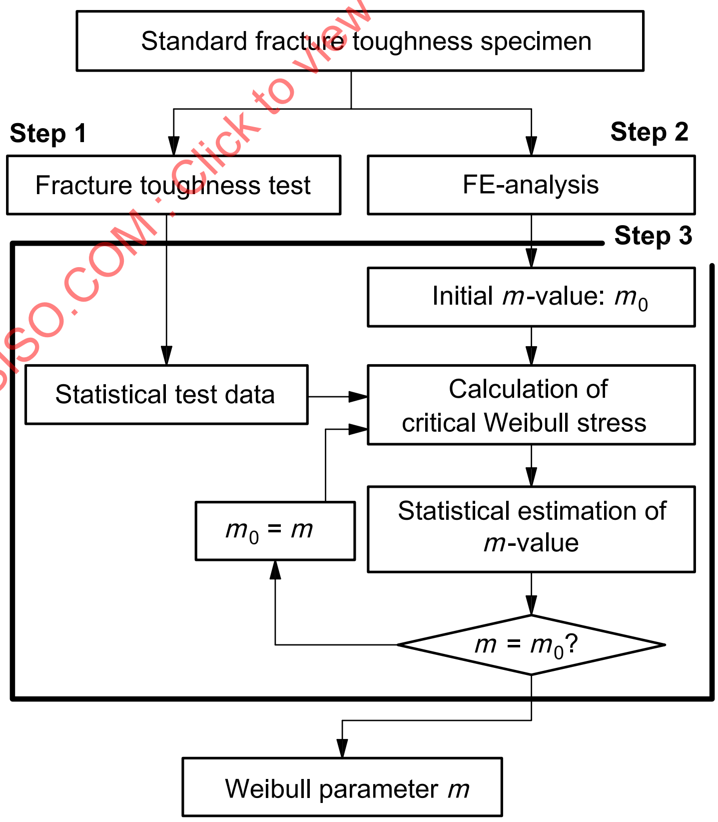


Figure B.1 — Procedure for determination of Weibull shape parameter, m [9], [21]

Annex C
(informative)

Guidelines for the equivalent CTOD ratio, β

C.1 General

C.1.1 Overview

This annex describes guidelines for the determination of β at three assessment levels [23].

C.1.2 Fracture toughness specimen

The equivalent CTOD ratio, β, adopted in this International Standard is the CTOD ratio, δ/δ_{WP}, which is determined in such a way that the Weibull stress of the standard fracture toughness specimen is equal to that of the structural component containing a crack. The standard fracture toughness specimens applicable in this International Standard have the following characteristics, which provide no significant differences in the Weibull stress:

a) type of specimen: three-point bend specimen or compact specimen;

b) range of crack length: $0{,}45 \leqslant a_0/W \leqslant 0{,}55$, where a_0 is the initial crack length and W is the specimen width.

C.1.3 Equivalent CTOD ratio, β

The equivalent CTOD ratio, β, in this International Standard is applicable beyond the CTOD level of $\delta_{\text{SSY limit}}$, below which the standard fracture toughness specimen exhibits a small-scale yielding deformation.

$$\delta_{\text{SSY limit}} = \frac{a_0 R_{p0,2}\left(1-\nu^2\right)}{5E} \tag{C.1}$$

where

a_0 is the initial crack length;

$R_{p0,2}$ is the 0,2 % offset yield strength, in MPa;

ν is Poisson's ratio;

E is Young's modulus of elasticity, in MPa.

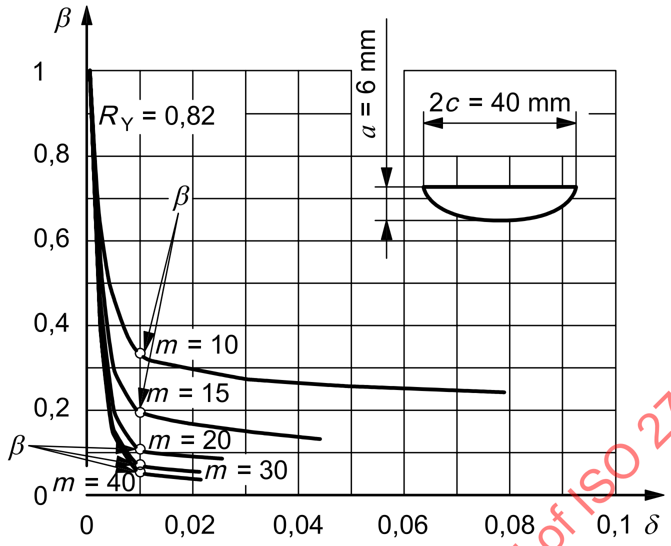
This CTOD value corresponds to the stress intensity factor, $K_{\text{SSY limit}}$, defining the small-scale yielding (SSY) limit of the fracture toughness specimen in ISO 12135:2002.

$$K_{\text{SSY limit}} = \left(\frac{a_0 R_{p0,2}{}^2}{2{,}5}\right)^{1/2} \tag{C.2}$$

Equation (C.1) is derived from Equation (C.2) using

$$\delta = \frac{K^2\left(1-\nu^2\right)}{2ER_{p0,2}} \tag{C.3}$$

In general, the equivalent CTOD ratio, β, depends on the load level (CTOD level), and decreases with increasing CTOD. However, beyond a certain load level, the load level has only a slight effect on β as shown in Figure C.1.



Key

a crack depth

$2c$ surface crack length

m Weibull shape parameter

R_Y yield-to-tensile ratio

t plate thickness

β equivalent CTOD ratio adopted in this method, defined as δ/δ_{WP}

δ CTOD of standard fracture toughness specimen, in millimetres

Figure C.1 — CSCP (a = 6 mm; $t \geqslant$ 25 mm)**: Equivalent CTOD ratio, β, adopted in this International Standard**

Thus, from an engineering viewpoint, the value of β at the sudden change point in the derivative of β with respect to CTOD in Figure C.1, is adopted for constraint loss correction of CTOD of structural components. The CTOD of the standard fracture toughness specimen at this point is approximately 0,01 mm, which almost corresponds to $\delta_{SSY\ limit}$ for a 25 mm thick toughness specimen. This International Standard uses such β in the whole CTOD range beyond $\delta_{SSY\ limit}$, which provides conservative fracture assessment of structural components.

C.2 Guidelines for the selection of assessment levels I, II and III

C.2.1 General

Guidelines for applying the fracture assessment levels I, II and III are given in the following subclauses.

C.2.2 Level I: Simplified assessment

Assessment level I 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. have not all been obtained. At level I assessment, $\beta = 0{,}5$ is used as an upper-bound engineering approximation.

As shown in Figures C.2 a) and b), the equivalent CTOD ratio, β, may exceed 0,5, in a very few cases, when m is as small as 10. This tends to occur more frequently for long cracks. In order to avoid this risk, level II assessment is recommended instead of level I, particularly for cases where the long cracks given below may exist.

a) Surface crack length: $2c > 50$ mm (CSCP, ESCP)

b) Through-thickness crack length: $2a > 25$ mm (CTCP, ETCP)

C.2.3 Level II: Normal assessment

Assessment level II 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.

The equivalent CTOD ratio, β, is calculated using the nomographs of the equivalent CTOD ratio, β_0, for the reference crack size (Figures 7 to 10) and the conversion equations for the crack length [Equations (3) to (8)]. The reference crack size for each crack type is shown in Table C.1, which gives an identical stress intensity factor, K.

Table C.1 — Reference crack size for wide plate components

	Reference crack size ($K = \sigma_\infty \sqrt{6,9\pi}$)	
	Length	**Depth**
CSCP	$2c = 40$ mm	$a = 6$ mm
ESCP	$2c = 30$ mm	$a = 6$ mm
CTCP	$2a = 13,8$ mm	—
ETCP	$2a = 11$ mm	—

Equations (3) to (8), used to convert the equivalent CTOD ratio, β_0, for the reference crack size to β for the target crack size, are derived from numerical analyses, examples of which are shown in Figure C.3. It should be noted that these conversion equations are applicable within the crack size range shown in Table C.2, because the numerical analysis was performed in this range.

Table C.2 — Range of crack size used for the formulation of crack size effect on β

	Range of FE-analysis	
	Crack size	**Plate thickness**
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	—

At level II assessment, the Weibull shape parameter, m, is set equal to a lower-bound value of m.

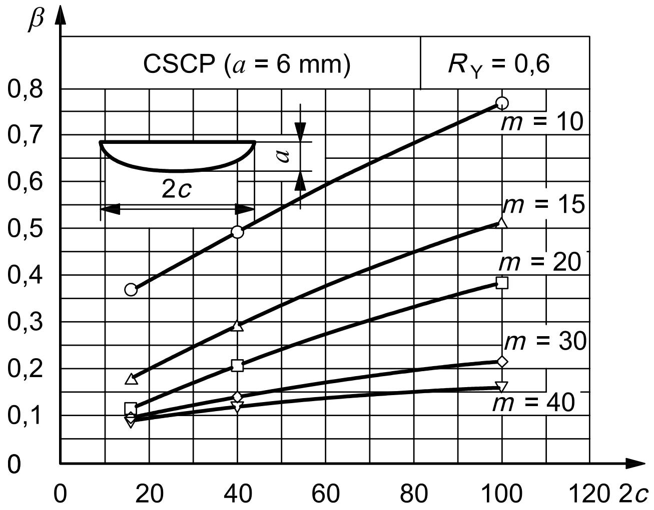
It is also noted that, as shown in Figure C.2, there is a possibility that the use of a lower bound m-value may give an excessive over-estimation of β in the following cases:

a) $R_Y < 0,8$ and

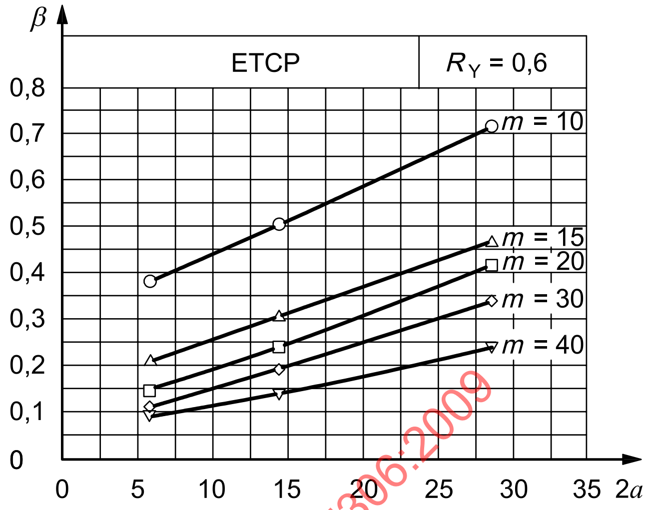
b) surface crack length: $2c > 50$ mm (CSCP, ESCP) or

c) through-thickness crack length: $2a > 25$ mm (CTCP, ETCP).

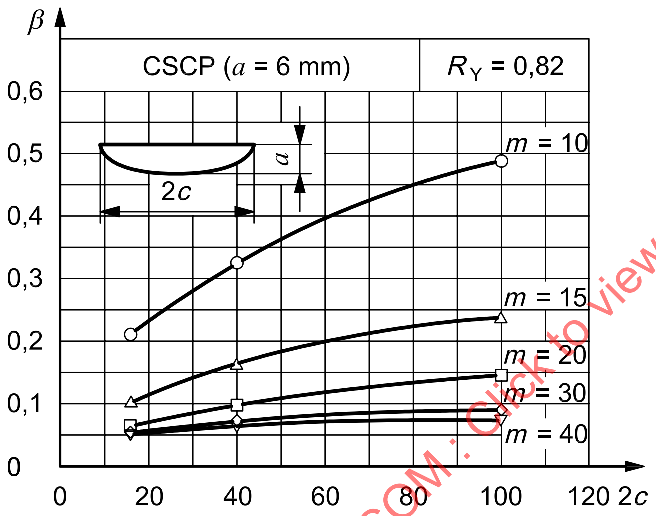
In such cases, level III assessment is recommended.



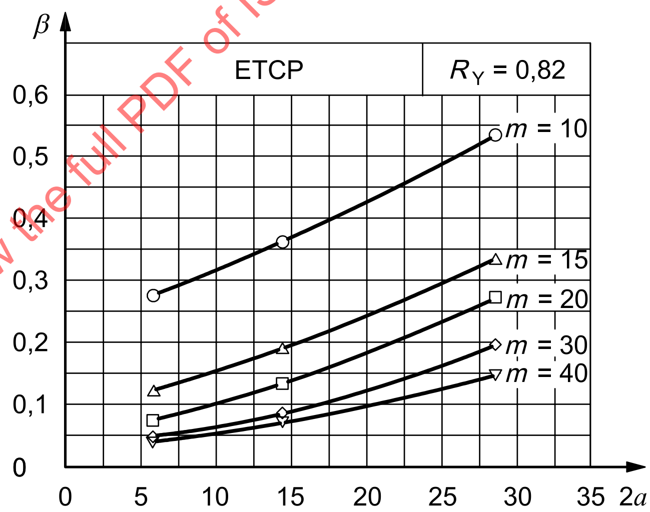
a) CSCP (R_Y = 0,60)



b) ETCP (R_Y = 0,60)

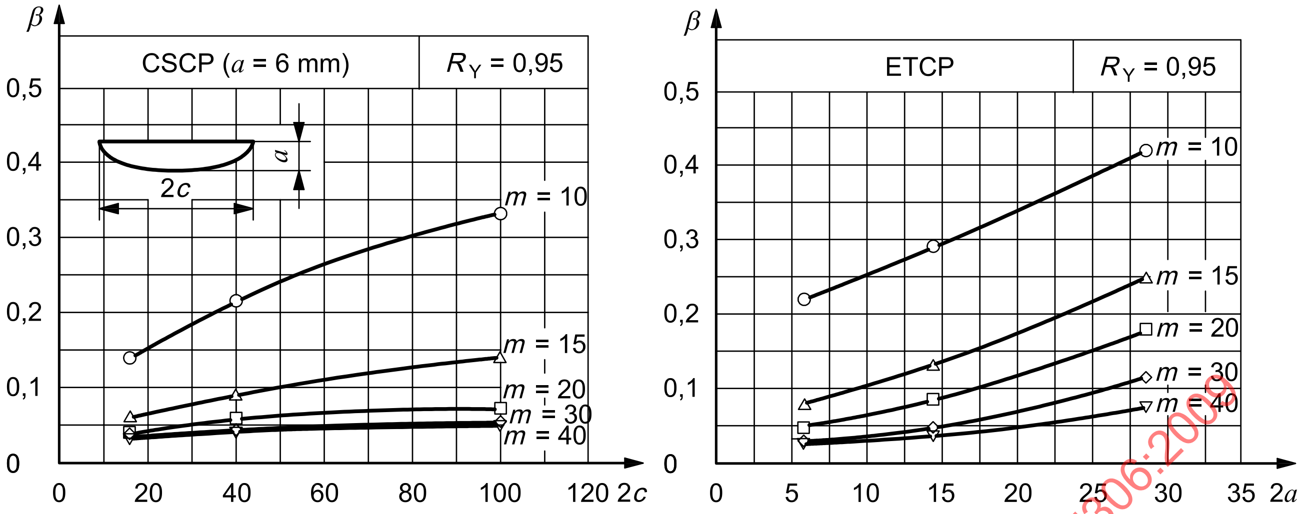


c) CSCP (R_Y = 0,82)



d) ETCP (R_Y = 0,82)

Figure C.2 (*continued*)



e) CSCP (R_Y = 0,95) **f)** ETCP (R_Y = 0,95)

Key

2a through-thickness crack length, in millimetres

2c surface crack length, in millimetres

m Weibull shape parameter

R_Y yield-to-tensile ratio

β equivalent CTOD ratio, defined as δ/δ_{WP}

NOTE β is elevated to a large extent in the case of a lower-bound m-value for a long crack.

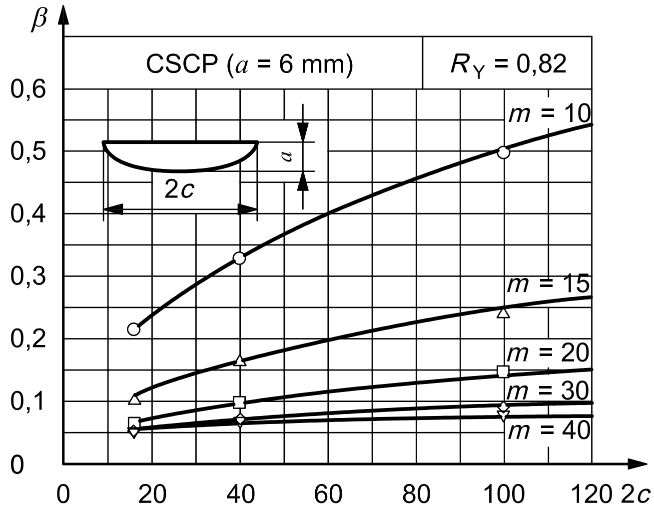
Figure C.2 — Effect of Weibull parameter, m, on β

C.2.4 Level III: Material specific assessment

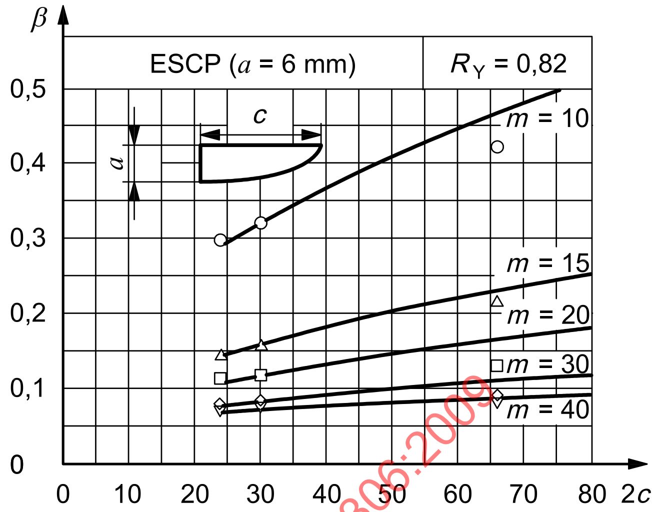
Assessment level III is applicable to cases where the information for the assessment of β is fully known. At level III, the equivalent CTOD ratio, β, is determined using the Weibull shape parameter, m, specific to the material concerned.

The Weibull shape parameter m is determined in accordance with the method in Annex B based on a sufficient number of fracture toughness test results and the FE-analysis of stress fields ahead of the crack-tip in fracture toughness specimens.

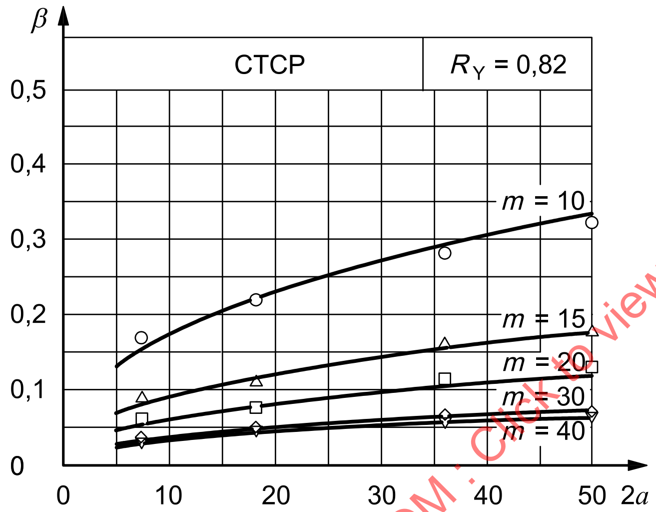
A complimentary explanation of Annex C is given in Reference [23].



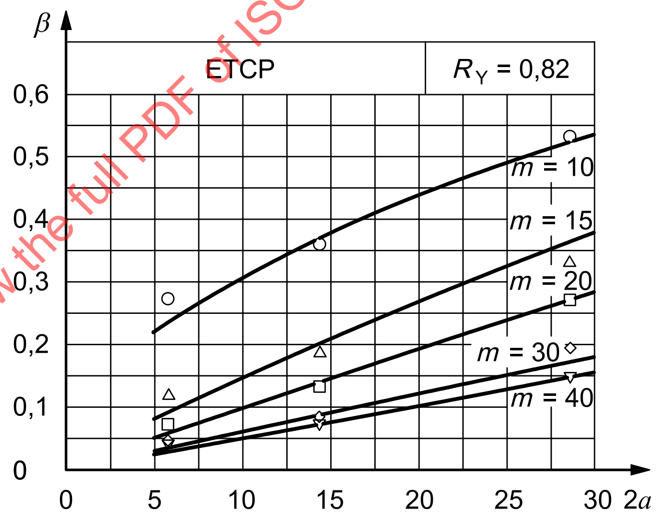
a) CSCP [See Equation (3)]



b) ESCP [See Equation (4)]



c) CTCP [See Equation (6)]



d) ETCP [See Equation (7)]

Key

2a through-thickness crack length, in millimetres

2c surface crack length, in millimetres

m Weibull shape parameter

R_Y yield-to-tensile ratio

β equivalent CTOD ratio, equal to δ/δ_{WP}

Figure C.3 — Evaluation of crack length effect on equivalent CTOD ratio, β

Annex D
(informative)

Examples of fracture assessment using the equivalent CTOD ratio, β

D.1 General

The equivalent CTOD ratio, β, proposed in this International Standard enables more accurate fracture assessment of structural components with crack, in comparison with conventional fracture mechanics methods. In this annex, the procedure for application of the equivalent CTOD ratio, β, to the FAD (Failure Assessment Diagram) as specified in BS 7910:2005 [6] is presented, and practical examples are exhibited.

D.2 Application of the equivalent CTOD ratio, β, to FAD (Failure Assessment Diagram)

D.2.1 General

The procedure of fracture assessment based on the FAD (Failure Assessment Diagram) in BS 7910:2005 [6] using the equivalent CTOD ratio, β, is schematically illustrated in Figure D.1. The detailed procedure is described in Figure D.2 as follows.

D.2.2 Determination of CTOD toughness of material, δ_{cr}

The critical CTOD of the standard fracture toughness test specimens shall be obtained in accordance with ISO 12135. A minimum of three test results (critical CTODs) is generally chosen as the CTOD fracture toughness of the material [6], [27]. If more than three toughness test results are available, the use of a minimum of three equivalent results (MOTE) [28] is recommended [6], [27].

D.2.3 Calculation of the equivalent CTOD ratio, β

The equivalent CTOD ratio, β, is calculated according to the procedure at fracture assessment levels I, II and III as described in this International Standard. The assessment level to be applied shall be decided by agreement among the parties concerned.

D.2.4 Fracture assessment of structural component based on FAD

D.2.4.1 Construct the FAD curve in BS 7910:2005 [6]

According to BS 7910:2005, FAD curves at level 2A and level 2B are given as

$$\text{Level 2A: } f(L_r) = \sqrt{\delta_r} = \left(1 - 0{,}14 L_r^{\,2}\right)\left[0{,}3 + 0{,}7\exp\left(-0{,}65 L_r^{\,6}\right)\right] \qquad \text{(D.1)}$$

where $L_r = \sigma_{ref}/R_{p0,2}$ and σ_{ref} is the average stress at net section.

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

where E is Young's modulus and ε_{ref} is the true strain corresponding to σ_{ref}.

The maximum value for L_r is defined as

$$L_{r,\max} = \left(R_{p0,2} + R_m\right)/2R_{p0,2} \tag{D.3}$$

where R_m is the ultimate tensile strength perpendicular to the crack plane.

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

D.2.4.2 Calculate the stress intensity factor, K, of the structural component

The stress intensity factor, K, is calculated by the following methods, assuming elastic stress conditions regardless of the load level:

— refering to K-value handbook [29];

— analysing by the finite element method (FEM).

D.2.4.3 Calculate the elastic component of CTOD, δ_{WP}^{e}, of the structural component

$$\delta_{WP}^{e} = \frac{K^2}{XR_{p0,2}E'} \quad \begin{cases} E' = E & \text{(plane stress)} \\ E' = E/\left(1-\nu^2\right) & \text{(plane strain)} \end{cases} \tag{D.4}$$

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.

D.2.4.4 Convert the CTOD toughness, δ_{cr}, of the material to the critical CTOD of the structural component, $\delta_{WP,cr}$, using the equivalent CTOD ratio, β

$$\delta_{WP,cr} = \delta_{cr}/\beta \tag{D.5}$$

D.2.4.5 Calculate the loading path of the structural component

The loading path of the structural component is calculated as

$$f\left(L_r\right) = \sqrt{\delta_r} = \sqrt{\frac{\delta_{WP}^{e}\left(L_r\right)}{\delta_{mat}}} = \sqrt{\frac{\delta_{WP}^{e}\left(L_r\right)}{\delta_{WP,cr}}} = \sqrt{\frac{\delta_{WP}^{e}\left(L_r\right)}{\delta_{cr}/\beta}} \tag{D.6}$$

where δ_{mat} is the material fracture toughness.

D.2.4.6 Determine the failure load

The failure load, $L_{r,cr}$, for the structural component of interest is given as the point where the loading path [Equation (D.6)] crosses the FAD curve [Equation (D.1) or Equation (D.2)].

Figure D.3 shows the procedure for determining the CTOD fracture toughness needed to meet design requirements of deformability of structural components, using the FAD with constraint loss correction by β.

D.3 Examples of fracture assessments using the equivalent CTOD ratio, β

D.3.1 Fracture assessment of CTCP (1)

D.3.1.1 General

An example of the fracture assessment of a wide plate component with the equivalent CTOD ratio, β, is presented here, in the case of the CTCP subjected to uniaxial tension (Figure D.4). The steel used was SM490YB (JIS G 3106 [30]) with the plate thickness $t = 25$ mm. Two CTCP components were tested at –100°C. Fracture net-stresses, $\sigma_{ref,cr}$, were 534 MPa and 560 MPa.

The fracture assessment of the test results is described in the following subclauses.

D.3.1.2 Determination of CTOD toughness of material, δ_{cr}

Fracture toughness tests were conducted in accordance with ISO 12135 at –100°C, the same temperature for the wide plate tests. Twenty-five three-point bend specimens of standard type ($a_0/W = 0{,}5$) were tested. The critical CTODs, δ_{cr}, at brittle fracture initiation for the specimens are summarized in Table D.1.

Table D.1 — CTOD fracture toughness of SM490YB steel tested at –100 °C

	CTOD fracture toughness δ_{cr} mm
Minimum	0,027
Maximum	0,37
0,2 MOTE	0,068
$\delta_{cr,ave\text{-}25}$	0,11
NOTE 0,2 MOTE is the minimum of three equivalent results at 20 % fracture probability.	

D.3.1.3 Calculation of the equivalent CTOD ratio, β

The equivalent CTOD ratio, β, is calculated as shown in Figure 6 in Clause 8.

Step 1: Define the crack length, $2a$, and the material yield-to-tensile ratio, R_Y.

— Target crack length $2a = 50$ mm

— Yield-to-tensile ratio, $R_Y = R_{p0,2}/ R_m = 0{,}82$ ($R_{p0,2} = 530$ MPa, $R_m = 646$ MPa at –100 °C)

Step 2: Set the reference value (lower-bound value) of the Weibull shape parameter, m.

— At level II assessment, Annex A is referred to to determine the reference m-value (lower-bound value). Since the CTOD fracture toughness $\delta_{cr,ave\text{-}25} = 0{,}11$ mm is larger than 0,05 mm, the reference m-value is set as

$$m = 20 \text{ (at level II)}$$

— At level III assessment, the shape parameter, m, is statistically determined from the Weibull stress analysis described in Annex B. The result is

$$m = 36 \text{ (at level III)}$$

Step 3: Determine the equivalent CTOD ratio, β_0, for reference crack size.

— From the nomograph (Figure 9 in Clause 8), the β_0-values for the reference crack size at level II and level III are given as

$$\beta_0 = 0{,}074 \text{ (at level II for } m = 20 \text{ and } R_Y = 0{,}82)$$

$$\beta_0 = 0{,}040 \text{ (at level III for } m = 36 \text{ and } R_Y = 0{,}82)$$

Step 4: Calculate the equivalent CTOD ratio, β, for the target crack length.

— The equivalent CTOD ratio, β, for the target crack length is calculated using Equation (6) as follows:

$$\beta = 0{,}5 \text{ (at level I)}$$

$$\beta = 0{,}12 \text{ (at level II)} \qquad (\beta = \beta_0 (2a/13{,}8)^{0{,}4} = 0{,}074(50/13{,}8)^{0{,}4} = 0{,}12)$$

$$\beta = 0{,}067 \text{(at level III)} \qquad (\beta = \beta_0 (2a/13{,}8)^{0{,}4} = 0{,}04(50/13{,}8)^{0{,}4} = 0{,}067)$$

D.3.1.4 Fracture assessment of structural component based on FAD

D.3.1.4.1 Construct the FAD curve in BS 7910:2005

The FAD curves at level 2A [Equation (D.1)] and level 2B [Equation (D.2)] are used here. The FAD curve at level 2B in Figure D.5 is constructed with the true stress-true strain curve of SM490YB (JIS G 3106) steel at the test temperature.

D.3.1.4.2 Calculate the stress intensity factor K of the structural component

The stress intensity factor, K, for CTCP is given as follows [29]:

$$K = \sigma_\infty \sqrt{\pi a} \cdot F(2a/W)$$

$$F(2a/W) = F(\xi) = \left(1 - 0{,}025\xi^2 + 0{,}06\xi^4\right)\sqrt{\sec(\pi\xi/2)} \approx 1{,}024 \qquad (\xi = 2a/W = 0{,}2)$$

D.3.1.4.3 Calculate the elastic component of the CTOD, $\delta_{\mathrm{WP}}^{\mathrm{e}}$, of the structural component

$$\delta_{\mathrm{WP}}^{\mathrm{e}} = \frac{K^2}{XER_{\mathrm{p0,2}}} = \frac{\pi a F^2}{ER_{\mathrm{p0,2}}} \sigma_\infty^2 \; (X{=}1)$$

D.3.1.4.4 Convert the CTOD toughness, δ_{cr}, of the material to the critical CTOD of CTCP, $\delta_{\mathrm{WP,cr}}$, using the equivalent CTOD ratio, β

Since a number of toughness data were available, 0,2 MOTE toughness was adopted here as the material fracture toughness.

$$\delta_{\mathrm{WP,cr}} = \delta_{\mathrm{cr}} / \beta$$

— $= 0{,}068/0{,}5 \quad = 0{,}136$ mm ····· at level I

— $= 0{,}068/0{,}12 \quad = 0{,}567$ mm ····· at level II

— $= 0{,}068/0{,}067 = 1{,}015$ mm ····· at level III

D.3.1.4.5 Calculate the loading path of the structural component

$$f(L_r)=\sqrt{\delta_r}=\sqrt{\frac{\delta_{WP}^e}{\delta_{mat}}}=\sqrt{\frac{\delta_{WP}^e}{\delta_{WP,cr}}}=\sqrt{\frac{\pi a F^2}{E R_{p0,2}\delta_{WP,cr}}}\sigma_\infty=\sqrt{\frac{\pi a F^2 R_{p0,2}}{E\delta_{WP,cr}}}\left(\frac{W-2a}{W}\right)L_r$$

— $= 1{,}00 L_r$ ·····at level I

— $= 0{,}49 L_r$ ·····at level II

— $= 0{,}37 L_r$ ·····at level III

D.3.1.4.6 Determine the failure load

The critical load ratio and critical fracture ratio calculated are summarized in Table D.2.

Table D.2 — Calculated results of load ratio and fracture ratio at brittle fracture initiation

TP-No.[a]	Critical load ratio $L_{r,cr}$ $(=\sigma_{ref,cr}/R_{p0,2})$	Critical fracture ratio $\sqrt{\delta_{r,cr}}$		
		Level I	Level II	Level III
UT-1	1,06 (560/530)	1,06	0,52	0,39
UT-2	1,01 (534/530)	1,01	0,49	0,37

[a] TP-No.: Test piece number.

The results of fracture assessments, $L_{r,cr}-\sqrt{\delta_{r,cr}}$ relationships, using the equivalent CTOD ratio, β, give better agreement with the FAD curve as shown in Figure D.6. The fracture assessments of the CTCP are summarized in Table D.3.

D.3.2 Fracture assessment of CTCP (2)

SM400B (JIS G 3106) with the plate thickness $t = 20$ mm was used. The CTCP components with a crack of length $2a = 160$ mm and the fracture toughness tests were conducted at –85 °C, –80 °C and –70 °C. One specimen was employed in each test at each temperature. $R_Y = R_{p0,2}/R_m$ in the temperature range –85 °C to –70 °C was 0,7.

Annex A was referred to to determine the reference m-value (lower-bound value) at level II assessment. The CTOD fracture toughness, $\delta_{cr\text{-}20}$, for a 20 mm thick specimen was converted to $\delta_{cr\text{-}25}$ for a 25 mm thick specimen using Equations (A.1) and (A.2) as follows.

$$\delta_{cr-25}=\left\{\sqrt{\delta_{min}}+\left(\sqrt{\delta_{cr-20}}-\sqrt{\delta_{min}}\right)\cdot\left(\frac{20}{25}\right)^{1/4}\right\}^2$$

$$=0{,}11 \text{ mm at } -85\,°C,\ \ 0{,}14 \text{ mm at } -80\,°C,\ \ 0{,}17 \text{ mm at } -70\,°C$$

Since $\delta_{cr\text{-}25}$ at each temperature was larger than 0,05 mm, the reference m-value was set as $m = 20$.

The equivalent CTOD ratio, β, was computed by the FE-analysis with $m = 20$ because the crack length $2a = 160$ mm was beyond the size range of Equation (6). Nevertheless, the numerically obtained $\beta = 0{,}29$ was almost equal to that calculated by Equation (6). Namely, β_0 for $R_Y = 0{,}7$ and $m = 20$ is 0,1 (Figure 9 in Clause 8), hence $\beta = \beta_0(160/13{,}8)^{0{,}4} = 0{,}27$.

The results of fracture assessments using β are summarized in Table D.4.

D.3.3 Fracture assessment of CTCP (3)

HW685 (WES 3001 [31]) with the plate thickness $t = 20$ mm was used. The CTCP tests and fracture toughness tests were conducted at –80 °C and –60 °C. The crack length $2a$ in the CTCP components was 160 mm. Two CTCPs were tested at –80 °C and one at –60 °C. $R_Y = R_{p0,2}/R_m$ was 0,95 at –80 °C and –60 °C.

Annex A was referred to to determine the reference m -value (lower-bound value) at level II assessment. The CTOD fracture toughness converted to $\delta_{cr\text{-}25}$ for a 25 mm thick specimen was:

$$\delta_{cr,\ ave\text{-}25} = \left[\sqrt{\delta_{min}} + \left(\sqrt{\delta_{cr,\ ave\text{-}20}} - \sqrt{\delta_{min}}\right) \cdot \left(\frac{20}{25}\right)^{1/4}\right]^2$$
$$= 0{,}16 \text{ mm at } -80\ °\text{C},\quad 0{,}19 \text{ mm at } -70\ °\text{C}$$

Since $\delta_{cr,ave\text{-}25}$ at each temperature was larger than 0,05 mm, the reference m-value was set as $m = 20$.

The equivalent CTOD ratio, β, was computed by the FE-analysis with $m = 20$, because the crack length $2a = 160$ mm was beyond the range of the crack size in Equation (6). The results of fracture assessments are summarized in Table D.5.

D.3.4 Fracture assessment of CSCP

The steel used was SM490YB (JIS G 3106)[30], the same steel as in D.3.1. Fracture toughness results are given in Table D.1. The m-values determined from fracture toughness results were $m = 20$ at level II assessment and $m = 36$ at level III assessment (see D.3.1).

The CSCP components employed included a surface crack of length $2c = 47$ mm and depth $a = 9$ mm. Three CTCP components were tested at –100 °C. Fracture net-stresses, $\sigma_{ref,cr}$, were in the range 511 MPa to 528 MPa.

The crack depth $a = 9$ mm was beyond the crack size range in Equation (6), hence the equivalent CTOD ratio, β, was computed by the FE-analysis with $m = 20$ (at level II) and $m = 36$ (at level III). Numerically computed β-values were 0,123 and 0,078 at level II and level III, respectively.

The stress intensity factor, K, for the CSCP was evaluated at the bottom of the surface crack using the K-value handbook [29].

Since a number of toughness data were available, 0,2 MOTE toughness was adopted as the material fracture toughness. The results of fracture assessments are summarized in Table D.6.

D.3.5 Fracture assessment of ESCP with crack in stress concentration area

The steel used in the tests was SM490B (JIS G 3106) class steel with a plate thickness of 25 mm. Twenty three-point bend fracture toughness specimens (standard specimens of $B\times 2B$ type with $a_0/W = 0{,}5$) were tested at –100 °C. The critical CTOD values, δ_{cr}, were in the range 0,01 mm to 0,16 mm. The m-value at level II assessment given by the procedure in Annex A was $m = 20$, that was equal to the m-value at level III assessment determined from fracture toughness results.

The configuration and dimensions of the ESCP are shown in Table D.7. The ESCP had two corner cracks of 20 mm (surface length) × 6 mm (depth), which were located at the geometrical discontinuities. The cracks were originally cut by machine and then extended by fatigue loading. Six tensile tests were conducted at –100 °C. Fracture net-stresses, $\sigma_{ref,cr}$, of the ESCP were in the range of 391 MPa to 414 MPa.

At level II and level III assessments, β_0 was read from Figure 8 in this International Standard with $m = 20$ and $R_Y = 0{,}71$, and β was calculated using Equation (4), giving $\beta = 0{,}17$.

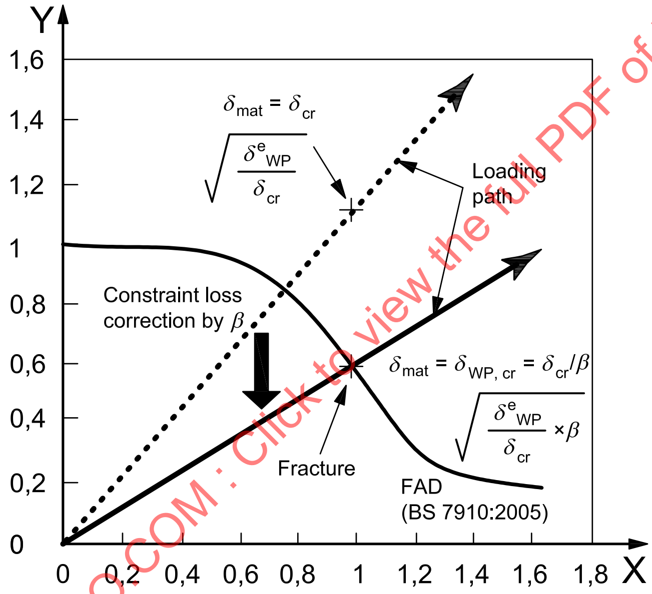
The elastic component of the CTOD, δ^{e}_{WP}, at the bottom of the surface crack was calculated by FE-analysis.

Since a number of toughness data were available, 0,2 MOTE toughness was adopted as the material fracture toughness. The results of fracture assessments are summarized in Table D.7.

Applications of the equivalent CTOD ratio, β, to fracture assessments of these wide plate components are described in Reference [32].

D.4 Application of the equivalent CTOD ratio, β, to fracture assessments of steel structures and components

Practical applications of the equivalent CTOD ratio, β, to the fracture assessments of steel structures and components are given in References [33] and [34]. The fracture performance of beam-to-column connections that are subjected to cyclic loading is evaluated with β in Reference [33]. A large welded component with a crack at the location of geometrical discontinuity is assessed on the basis of the equivalent CTOD concept in Reference [34].

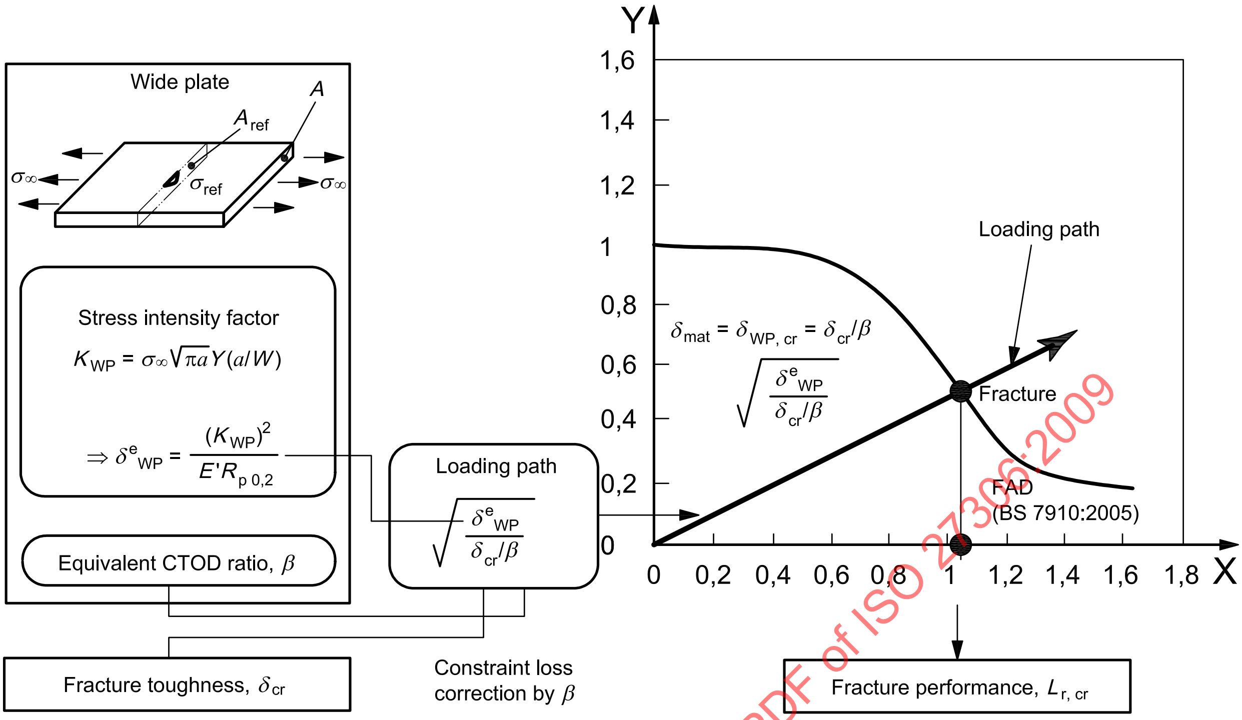


Key

X load ratio, $L_r = \sigma_{ref}/R_{p0,2}$

Y fracture ratio, $\sqrt{\delta_r} = \sqrt{\dfrac{\delta^{e}_{WP}}{\delta_{mat}}}$

Figure D.1 — Application of the equivalent CTOD ratio, β, to the failure assessment diagram (FAD) in BS 7910:2005

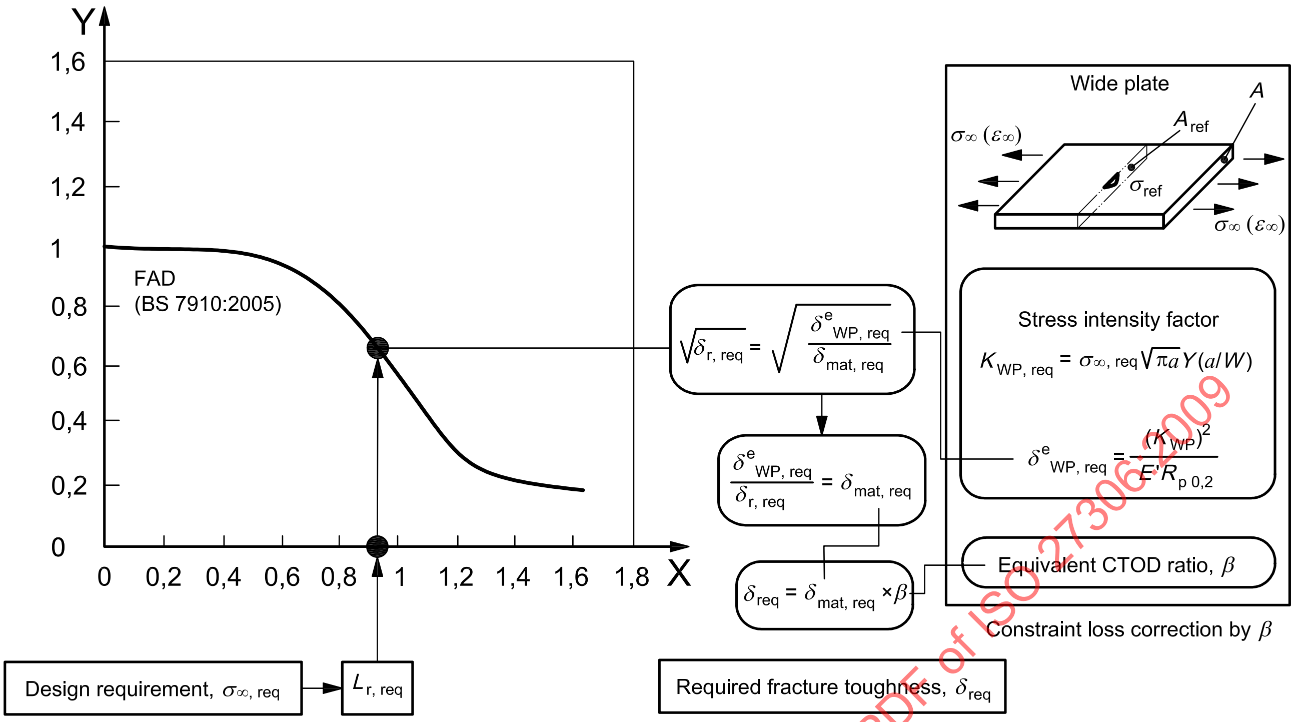


Key

X load ratio, $L_r = \sigma_{ref}/R_{p0,2}$

Y fracture ratio, $\sqrt{\delta_r} = \sqrt{\frac{\delta^e_{WP}}{\delta_{mat}}}$

Figure D.2 — Procedure for failure assessment by FAD approach with equivalent CTOD ratio, β



$$\sqrt{\delta_{r,\,req}} = \sqrt{\frac{\delta^{e}_{WP,\,req}}{\delta_{mat,\,req}}}$$

$$K_{WP,\,req} = \sigma_{\infty,\,req}\sqrt{\pi a}\,Y(a/W)$$

$$\delta^{e}_{WP,\,req} = \frac{(K_{WP})^2}{E'R_{p\,0,2}}$$

$$\frac{\delta^{e}_{WP,\,req}}{\delta_{r,\,req}} = \delta_{mat,\,req}$$

$$\delta_{req} = \delta_{mat,\,req} \times \beta$$

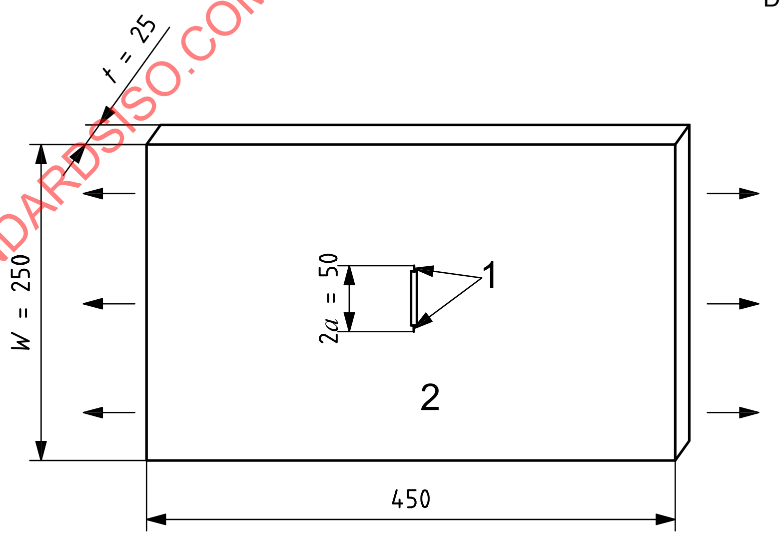
Key

X load ratio, $L_r = \sigma_{ref}/R_{p0,2}$

Y fracture ratio, $\sqrt{\delta_r} = \sqrt{\frac{\delta^{e}_{WP}}{\delta_{mat}}}$

Figure D.3 — Procedure for determining CTOD fracture toughness required to meet design requirements of deformability of components

Dimensions in millimetres

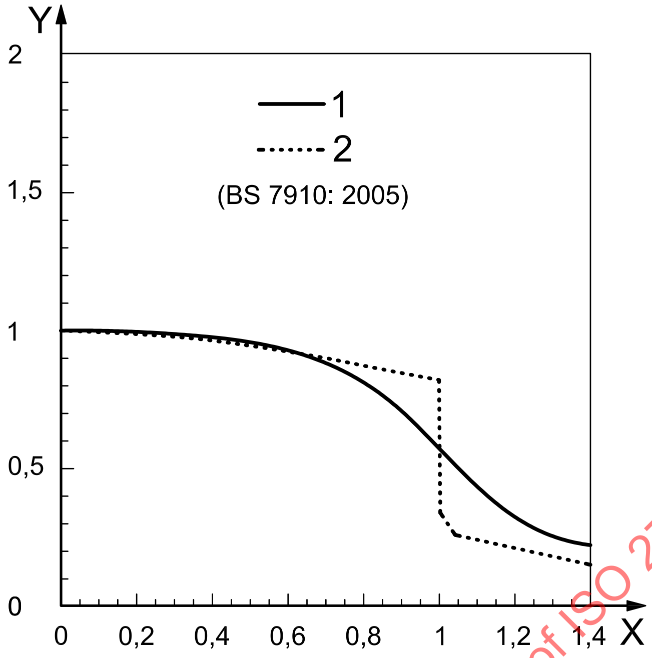


Key

1 fatigue pre-crack

2 through-thickness crack

Figure D.4 — Configuration of CTCP used in the case study D.3.1



Key

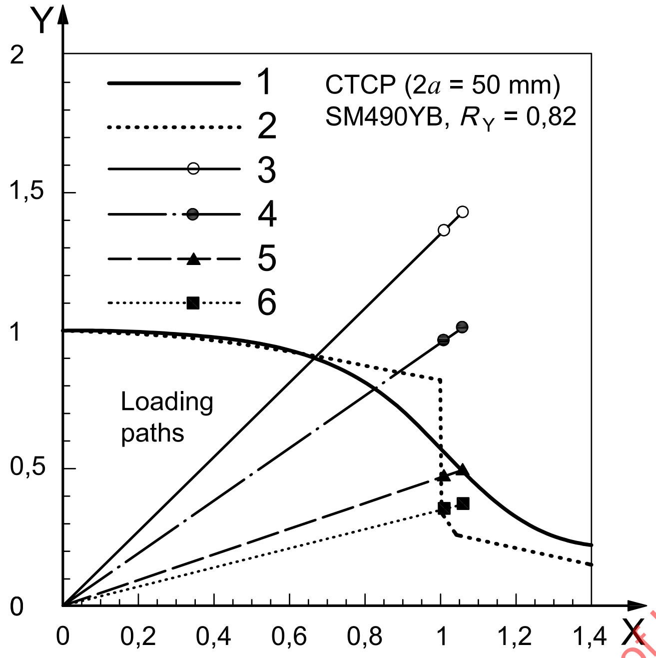
X load ratio, $L_r = \sigma_{ref}/R_{p0,2}$

Y fracture ratio, $\sqrt{\delta_r}$

1 level 2A-FAD

2 level 2B-FAD

Figure D.5 — FAD curves at level 2A and level 2B in BS 7910:2005



Key

X load ratio, $L_r = \sigma_{ref}/R_{p0,2}$

Y fracture ratio, $\sqrt{\delta_r}$

1 level 2A-FAD

2 level 2B-FAD

3 no-correction ($\beta = 1$)

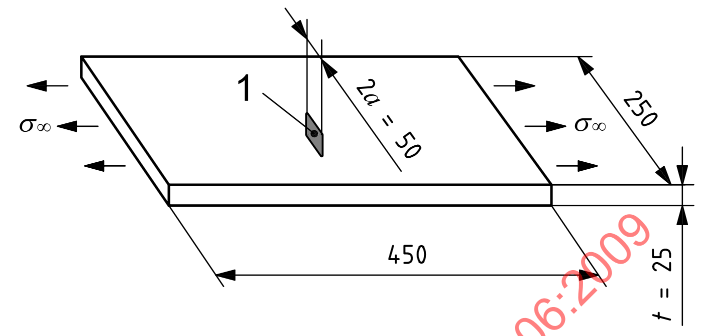
4 level I ($\beta = 0,5$)

5 level II ($\beta = 0,12$)

6 level III ($\beta = 0,067$)

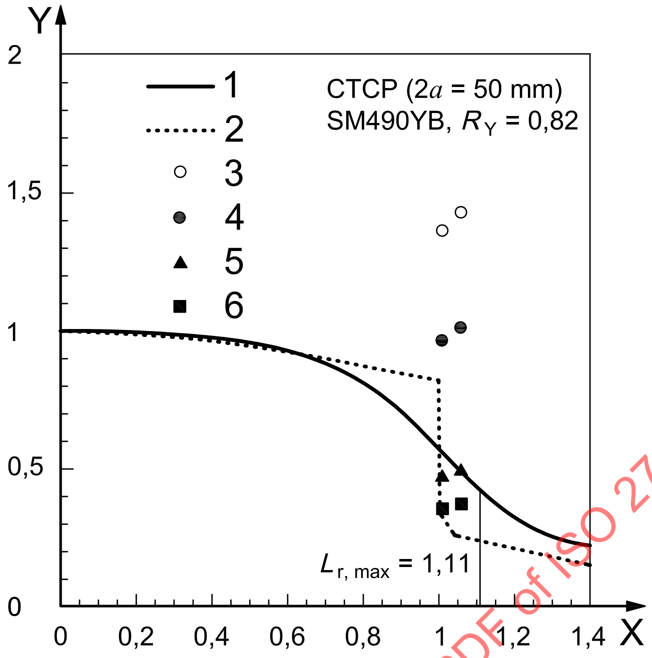
Figure D.6 — Comparison between fracture assessment results using different β-values

Table D.3 — Fracture assessment of CTCP (1)

<table>
<tr><td colspan="2"></td><td colspan="3">CTCP (Centre through-thickness crack panel)</td></tr>
<tr><td colspan="2"></td><td colspan="3">Dimensions in millimetres


Key
1 crack</td></tr>
<tr><td colspan="2">Loading mode</td><td colspan="3">Uniaxial tension</td></tr>
<tr><td colspan="2">Test temperature</td><td colspan="3">−100 °C</td></tr>
<tr><td colspan="2" rowspan="4">Material</td><td colspan="3">SM490YB (JIS G 3106)</td></tr>
<tr><td colspan="3">Yield stress: $R_{p0,2}$ = 530 MPa (at test temperature)</td></tr>
<tr><td colspan="3">Tensile strength: R_m = 646 MPa (at test temperature)</td></tr>
<tr><td colspan="3">Yield-to-tensile ratio: R_Y = 0,82 (at test temperature)</td></tr>
<tr><td>Fracture net-stress</td><td>$\sigma_{ref,cr}$
(MPa)</td><td colspan="3"><table><tr><td>TP-No.</td><td>UT-1</td><td>UT-2</td></tr><tr><td>$\sigma_{ref,cr}$ (MPa)</td><td>560</td><td>534</td></tr></table></td></tr>
<tr><td>Critical CTOD</td><td>δ_{cr} (mm)
$\delta_{WP,cr}$ (mm)</td><td colspan="3"><table><tr><td>TP-No.</td><td>UT-1</td><td>UT-2</td></tr><tr><td>$\delta_{WP,cr}$ (mm)</td><td>0,62</td><td>0,51</td></tr></table><table><tr><td>Range</td><td>Max.</td><td>Min.</td><td>Ave.</td><td>0,2 MOTE</td></tr><tr><td>δ_{cr} (mm)</td><td>0,37</td><td>0,027</td><td>0,11</td><td>0,068</td></tr></table></td></tr>
<tr><td colspan="2">Assessment level</td><td>Level I</td><td>Level II</td><td>Level III</td></tr>
<tr><td>Weibull shape parameter</td><td>m</td><td>—</td><td>20 (see Annex A)</td><td>36</td></tr>
<tr><td>Equivalent CTOD ratio</td><td>β</td><td>0,5</td><td>0,120</td><td>0,067</td></tr>
<tr><td>Elastic component of CTOD of wide plate</td><td>δ_{WP}^{e}</td><td colspan="3">$\delta_{WP}^{e} = \frac{K^2}{E R_{p0,2}}, \quad K = \sigma_\infty \sqrt{\pi a}\, F(2a/W)$</td></tr>
</table>

Table D.3 (*continued*)

<table>
<tr>
<td rowspan="2">Results of fracture assessment</td>
<td>


Key

X load ratio, $L_r = \sigma_{ref}/R_{p0,2}$

Y fracture ratio, $\sqrt{\delta_r}$

1 level 2A-FAD

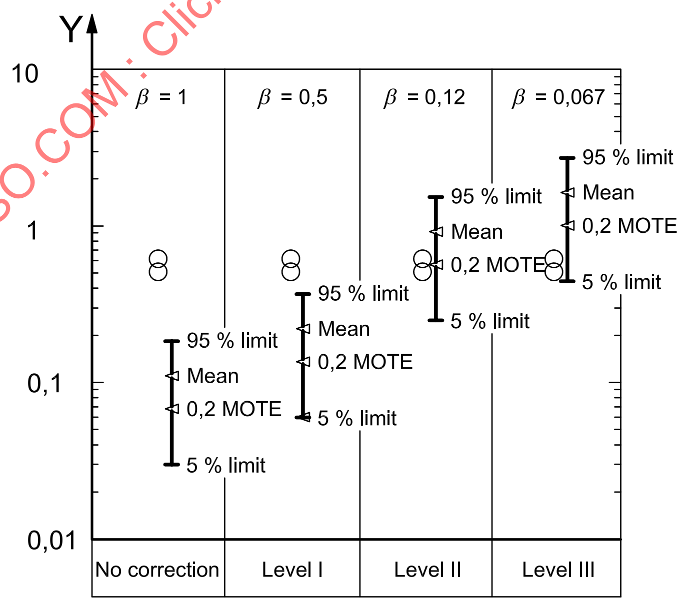
2 level 2B-FAD

3 no correction ($\beta = 1$)

4 level I ($\beta = 0,5$)

5 level II ($\beta = 0,12$)

6 level III ($\beta = 0,067$)

Fracture assessment using FAD
</td>
</tr>
<tr>
<td>


Comparison between wide plate critical CTODs measured and estimated with β from CTOD test results

Key

Y critical CTOD, $\delta_{WP,cr}$ (mm)
</td>
</tr>
</table>