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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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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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For an explanation on the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT) see the following URL: www.iso.org/iso/foreword.html.

The committee responsible for this document is ISO/TC 164 *Mechanical Testing of Metals,* Subcommittee SC 4, *Toughness testing — Fracture (F), Pendulum (P), Tear (T).*

This second edition cancels and replaces the first edition (ISO 27306:2009), which has been technically revised.

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

1 Scope

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

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

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

The CTOD fracture toughness of structural steels is measured in accordance with the established test methods, ISO 12135[1)] or BS 7448-1. 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 performance of structural components.

2 Normative references

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

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

BS 7448-1, *Fracture mechanics toughness tests —Part 1: Method for determination of* K_{Ic}, critical CTOD and critical J values of metallic materials

3 Terms and definitions

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

1) To be published.

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 $0{,}45 \le a_0/W \le 0{,}55$, 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] with $0{,}45 \le a_0/W \le 0{,}55$

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 1 to entry: 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

Note 1 to entry: See Figure 1.

Note 2 to entry: See Reference [1].

3.6
Weibull stress
σ_W
fracture driving force defined with the consideration of statistical instability of microcracks in the fracture process zone against brittle fracture

Note 1 to entry: 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, σ_Y, (lower yield point, R_{eL}, or 0,2% proof strength, $R_{p0,2}$) to tensile strength, R_m

4 Symbols and units

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

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

5 Principle

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

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

NOTE 2 This International Standard does not intend to address size and temperature effects nor influence of data scatter on the results. Refer to ASTM E1921-13a[3] for guidance.

The CTOD fracture toughness (critical CTOD) of the standard fracture toughness specimen is determined in accordance with the established test methods (ISO 12135 or BS 7448-1). The fracture assessment of a cracked component can be done using established methods at the user's discretion such as Failure Assessment Diagram (FAD) 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 > β > 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 of

$$\delta_{WP,cr} = \delta_{cr} / \beta \tag{1}$$

Furthermore, when the CTOD performance, $\delta_{WP,req}$, for the structural component is required, the material fracture toughness, δ_{req}, needed to meet the performance requirement is specified as

$$\delta_{req} = \beta \cdot \delta_{WP,req} \tag{2}$$

Formulae (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.

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

6 Structural components of concern

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

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

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

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

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

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

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

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

7 Conditions for use

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

— Brittle fracture beyond SSY (Small-Scale Yielding) is assessed. The assessment of brittle fracture preceded by a significant stable crack growth is not recommended;

— The fracture toughness specimen (three-point bend or compact specimen with $0{,}45 \leq a_0/W \leq 0{,}55$) shall have the same thickness as the structural component;

— No significant differences in fracture toughness through the thickness of the steel being assessed;

— β_0-nomographs for a reference crack size are presented in Clause 9, where the yield-to-tensile ratio, R_Y, Weibull shape parameter, m, are in the range $0{,}6 \leq R_Y \leq 0{,}98$ and $10 \leq m \leq 50$;

— The crack size, c and a, and the plate thickness, t, covered by this International Standard are as follows:

a) CSCP: $2c \geq 16$ mm, $0{,}04 \leq a/t \leq 0{,}24$, $12{,}5 \leq t \leq 50$ mm;

b) ESCP: $2c \geq 24$ mm, $0{,}04 \leq a/t \leq 0{,}24$, $12{,}5 \leq t \leq 50$ mm;

c) CTCP: $5 \leq 2a \leq 50$ mm;

d) ETCP: $5 \leq 2a \leq 30$ mm.

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

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

8 Assessment levels I, II, and III

8.1 General

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

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

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

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

CSCP, ESCP: Centre and edge surface crack panels

CTCP, ETCP: Centre and edge through-thickness crack panels

[a] Surface crack: $2c > 50$ mm, Through-thickness crack: $2a > 25$ mm, ($2c$: surface crack length, $2a$: through-thickness crack length, t: plate thickness, m: Weibull shape parameter).

8.2 Level I: Simplified assessment

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

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

8.3 Level II: Normal assessment

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

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

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

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

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

$$m = 10 \tag{4}$$

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

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

8.4 Level III: Material specific assessment

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

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

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

9 Equivalent CTOD ratio, β

9.1 General

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

9.2 Factors influencing the equivalent CTOD ratio, β

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

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

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

— yield-to-tensile ratio, R_Y, of the material;

— crack type (CSCP, ESCP, CTCP, ETCP) and crack size (crack depth of surface crack and crack length of through-thickness crack);

— plate thickness, t;

b) factor exerting a volumetric effect:

— length of surface crack.

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

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

9.3.1 General

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

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

— ESCP: $2c \geq 24$ mm, $0{,}04 \leq a/t \leq 0{,}24$, $12{,}5 \leq t \leq 50$ mm

— CTCP: $5 \leq 2a \leq 50$ mm

— ETCP: $5 \leq 2a \leq 30$ mm

9.3.2 Surface crack cases (CSCP and ESCP)

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

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

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

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

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

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

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

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

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

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

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

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

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

9.3.3 Through-thickness crack cases (CTCP and 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 yield-to-tensile ratio, R_{Y}.

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

Step 3: Determine the equivalent CTOD ratio, β_0, for a reference length of the through-thickness crack from the nomographs shown in Figures 9 and 10 as a function of m and R_{Y}.

Step 4: Calculate the equivalent CTOD ratio, β_{2a}, for the target crack length, $2a$, with Formula (8) or (9), depending on the type of crack:

$$\beta_{2a(\mathrm{CTCP})} = \beta_{0(\mathrm{CTCP})} \cdot \left(2a/13{,}8\right)^{0.4} \tag{8}$$

$$\beta_{2a(\mathrm{ETCP})} = \beta_{0(\mathrm{ETCP})} \cdot \left(2a/11\right)^{k_{\mathrm{ETCP}}(m,R_{\mathrm{Y}})},\quad k_{\mathrm{ETCP}}\left(m,R_{\mathrm{Y}}\right) = \frac{-0{,}57+3{,}1R_{\mathrm{Y}}-1{,}45R_{\mathrm{Y}}^{\,2}}{\exp\left\{-0{,}35\left(m-10\right)\right\}+1} \tag{9}$$

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

$$\beta_{a(\mathrm{ETCP})} = \beta_{2a(\mathrm{ETCP})}/\sqrt{2} \tag{10}$$

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 Formulae (5), (6), (8), and (9), 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 Failure Assessment Diagram (FAD)[6] or CTOD design curve[7], which have been duly authorized in the organization concerned, may be used.

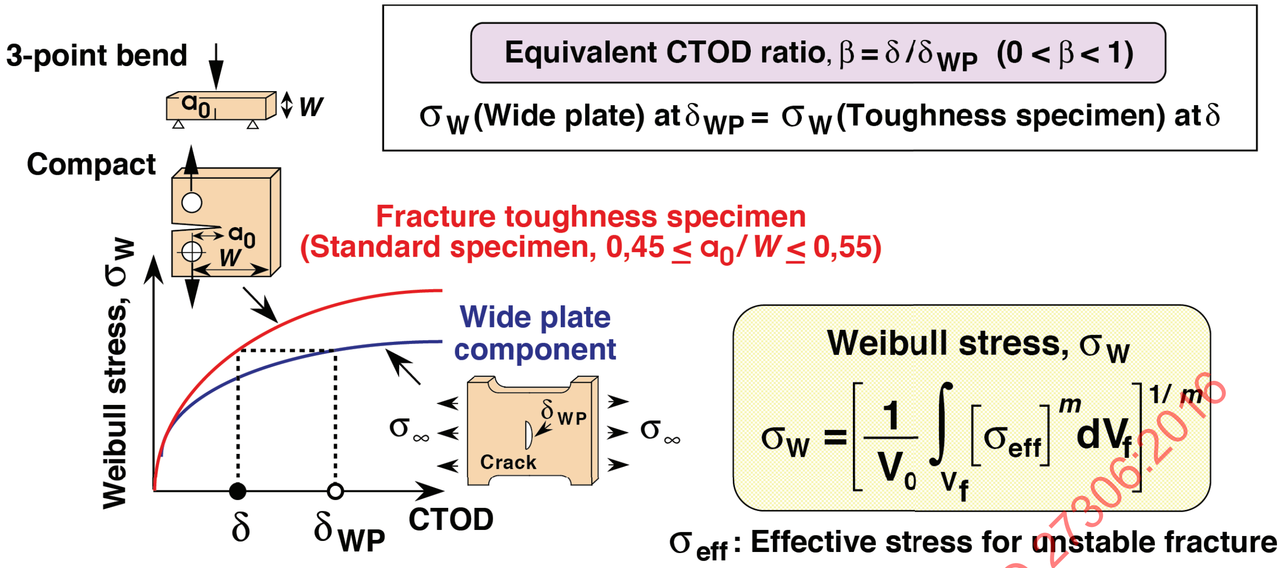


Figure 1 — Definition of the equivalent CTOD ratio, *β*, based on the Weibull stress fracture criterion

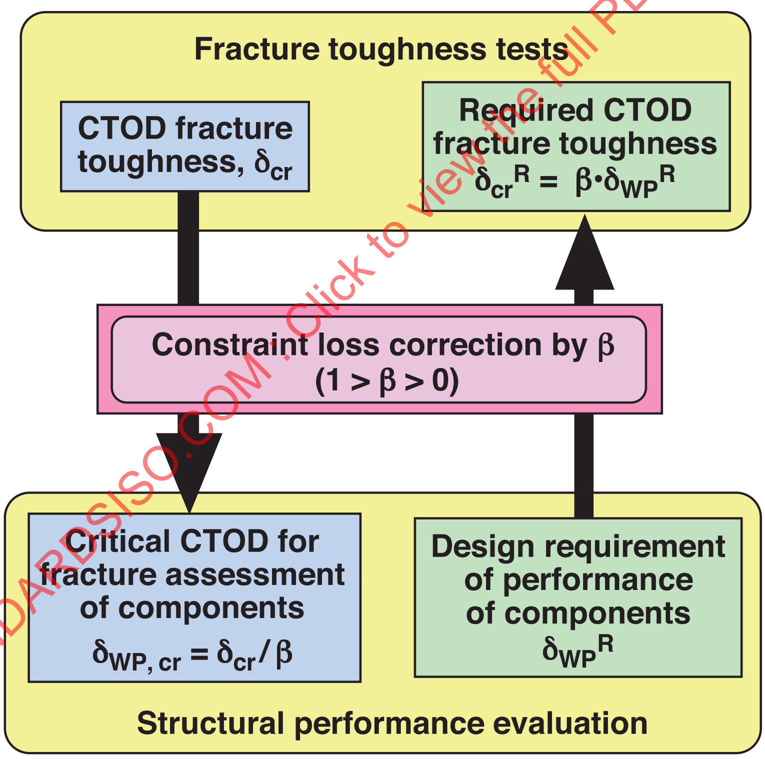


Figure 2 — Method of constraint loss correction to link fracture toughness tests and structural performance evaluation

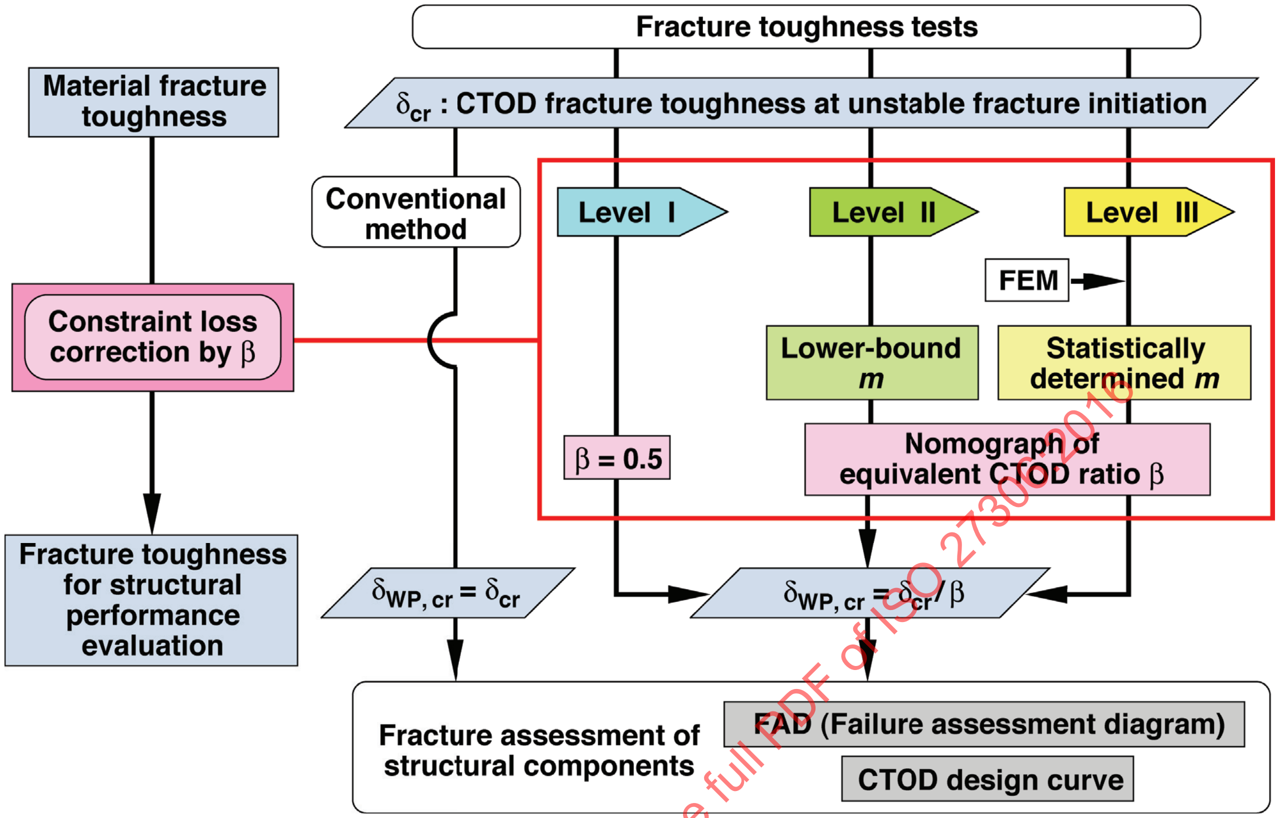


Figure 3 — Flow of fracture assessment of structural components from fracture toughness test results, where three assessment levels of the equivalent CTOD ratio, *β*, are included for constraint loss correction

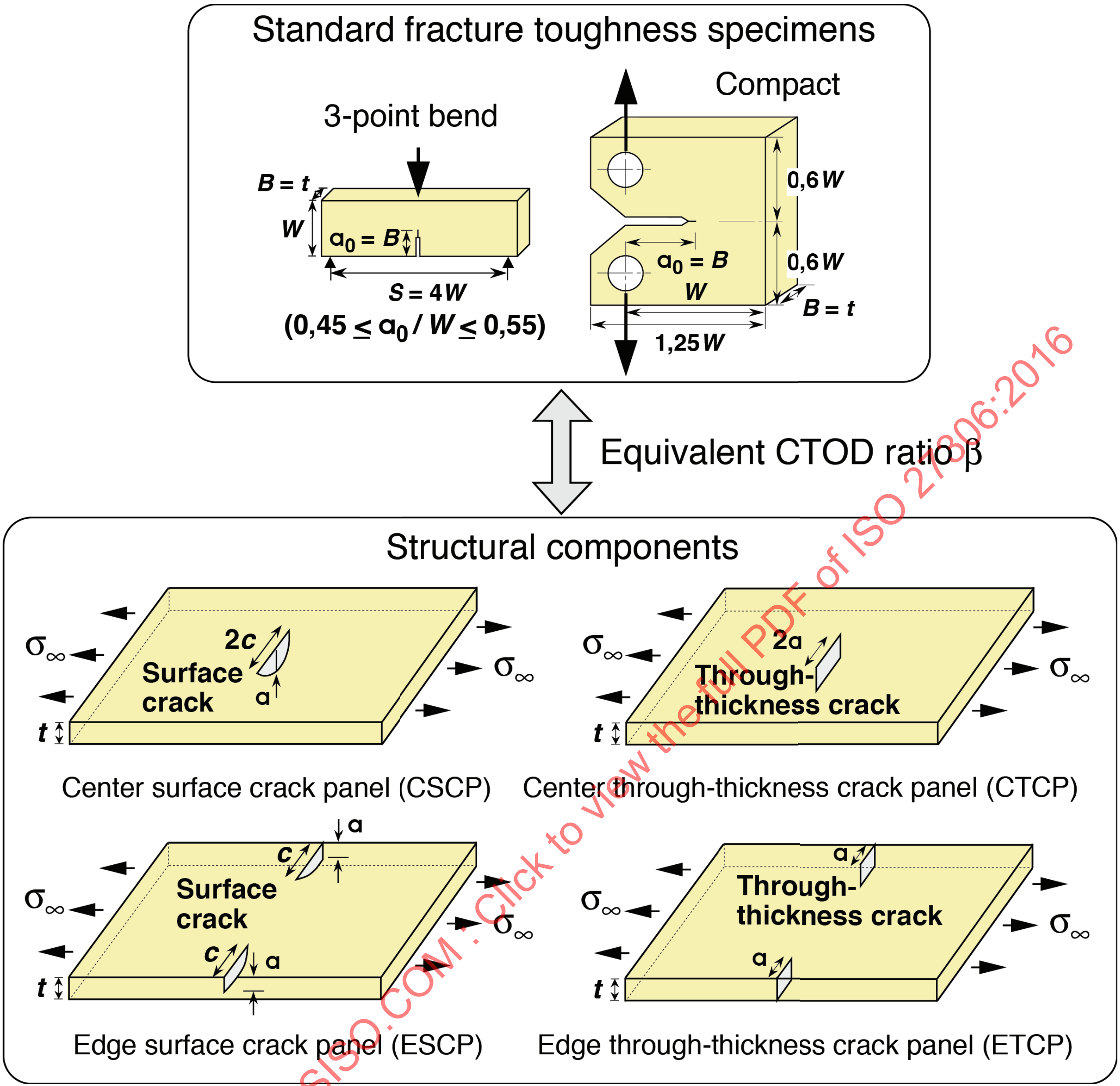


Figure 4 — Standard fracture toughness specimens and wide plate components linked by the equivalent CTOD ratio, *β*

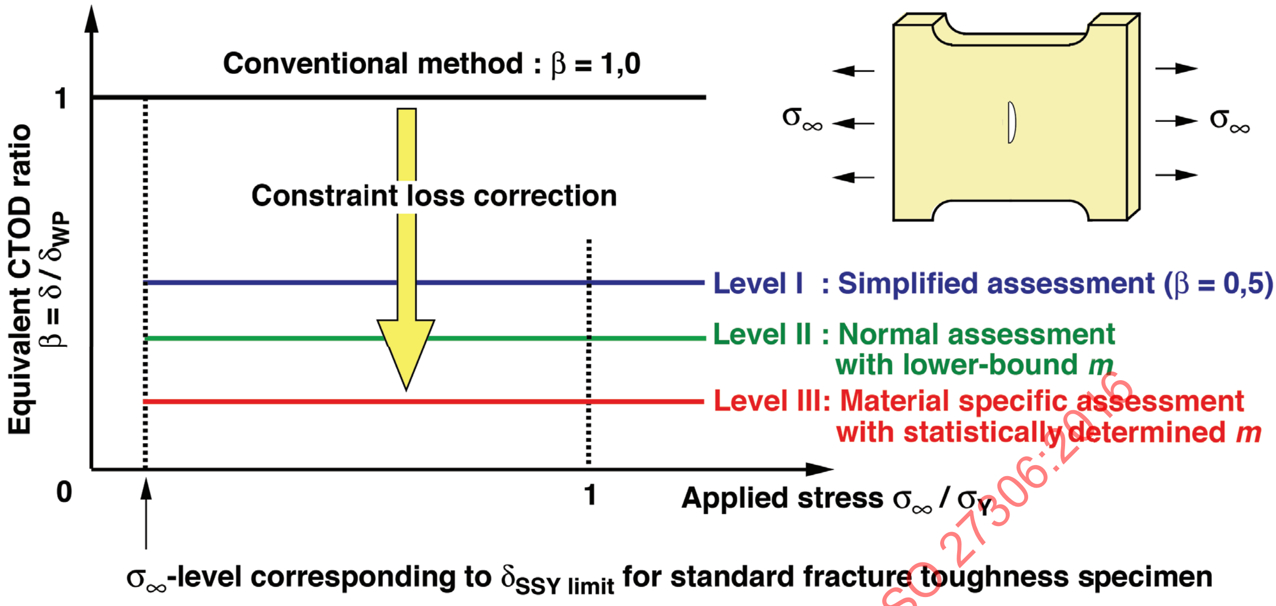


Figure 5 — Assessment levels I, II and III of β for correcting constraint loss in wide plate components

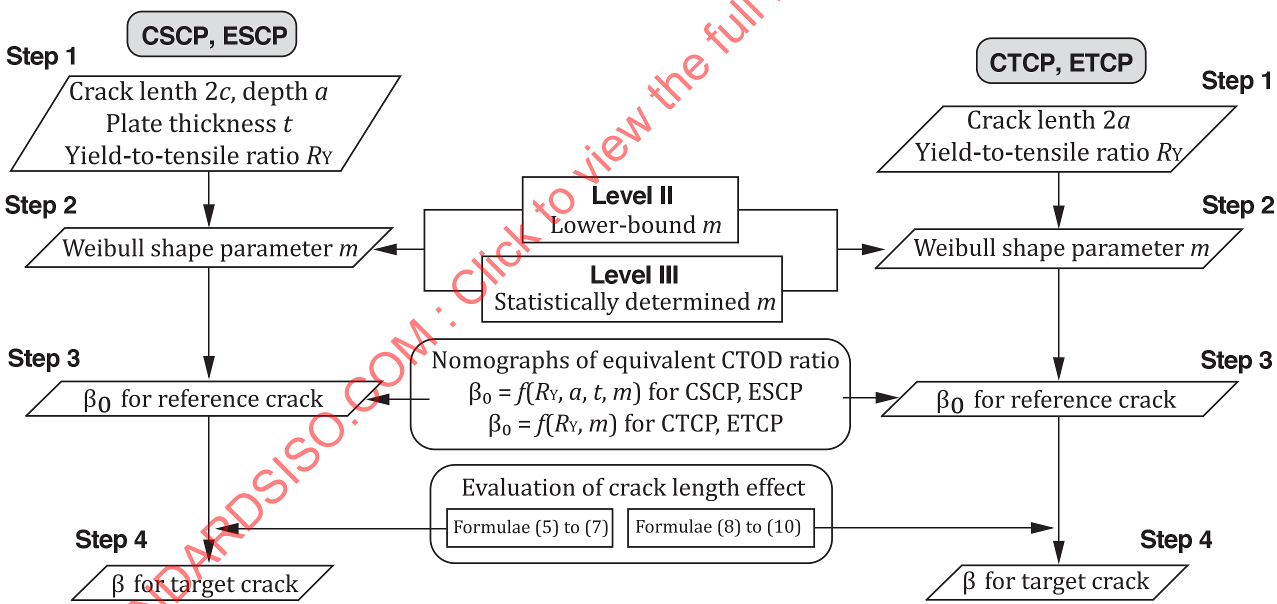
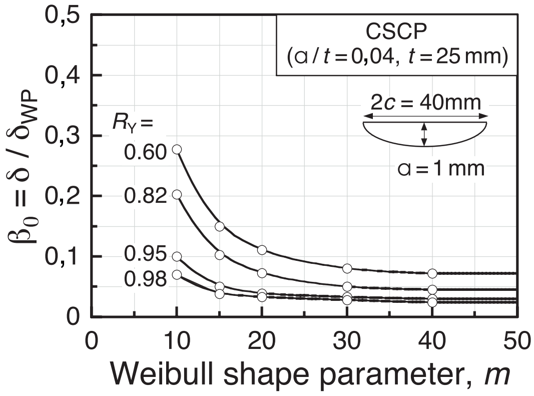
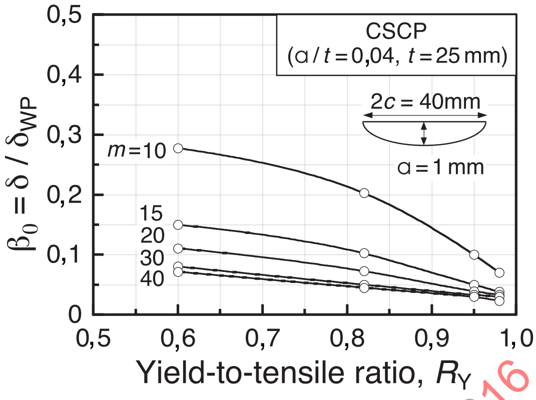


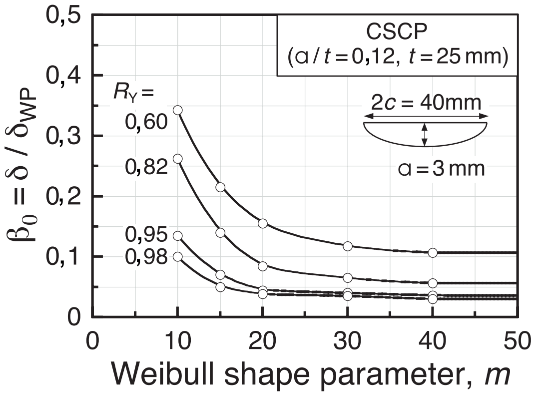
Figure 6 — Flow chart for calculating the equivalent CTOD ratio, β



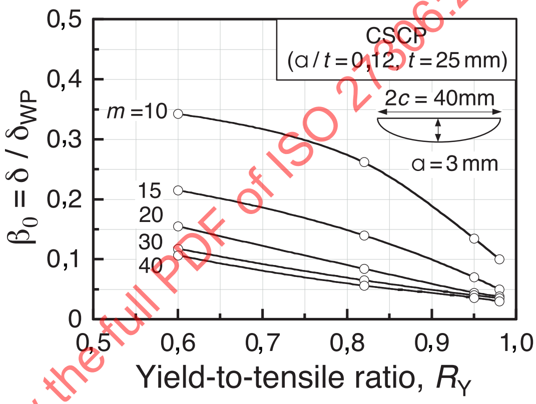
a) CSCP (a/t = 0,04; t = 25 mm): β_0 versus m



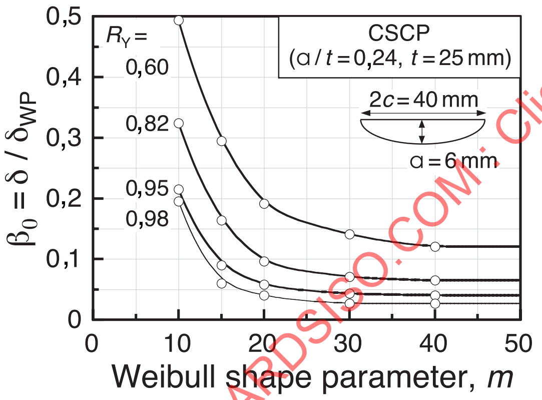
b) CSCP (a/t = 0,04; t = 25 mm): β_0 versus R_Y



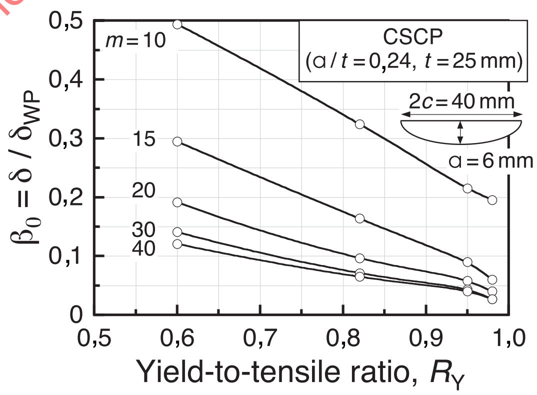
c) CSCP (a/t = 0,12; t = 25 mm): β_0 versus m



d) CSCP (a/t = 0,12; t = 25 mm): β_0 versus R_Y

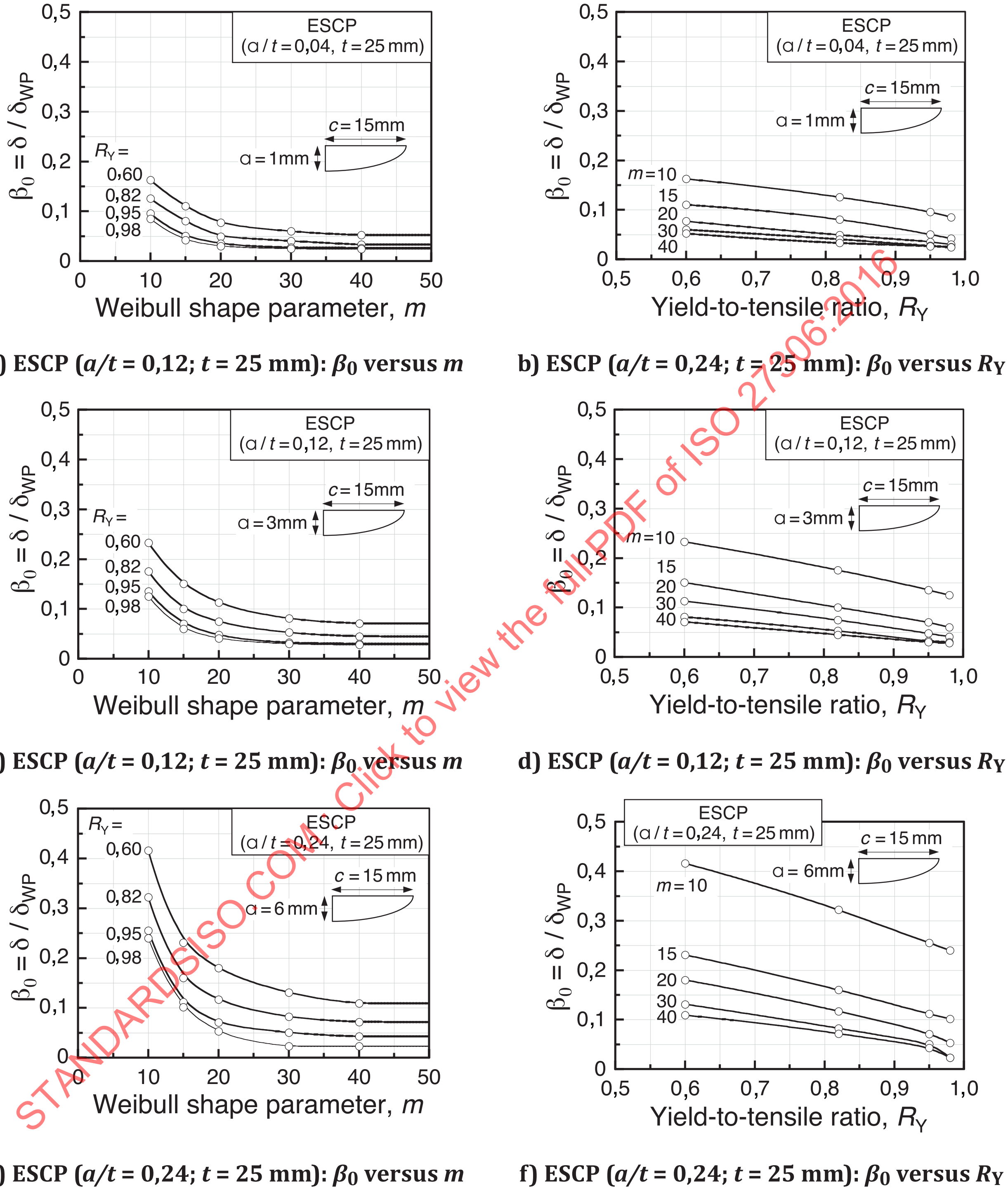


e) CSCP (a/t = 0,24; t = 25 mm): β_0 versus m



f) CSCP (a/t = 0,24; t = 25 mm): β_0 versus R_Y

Figure 7 — Nomographs of equivalent CTOD ratio, β_0, for centre surface crack panel (CSCP) with plate thickness t = 25 mm



a) ESCP (*a*/*t* = 0,12; *t* = 25 mm): β_0 versus *m*

b) ESCP (*a*/*t* = 0,24; *t* = 25 mm): β_0 versus R_Y

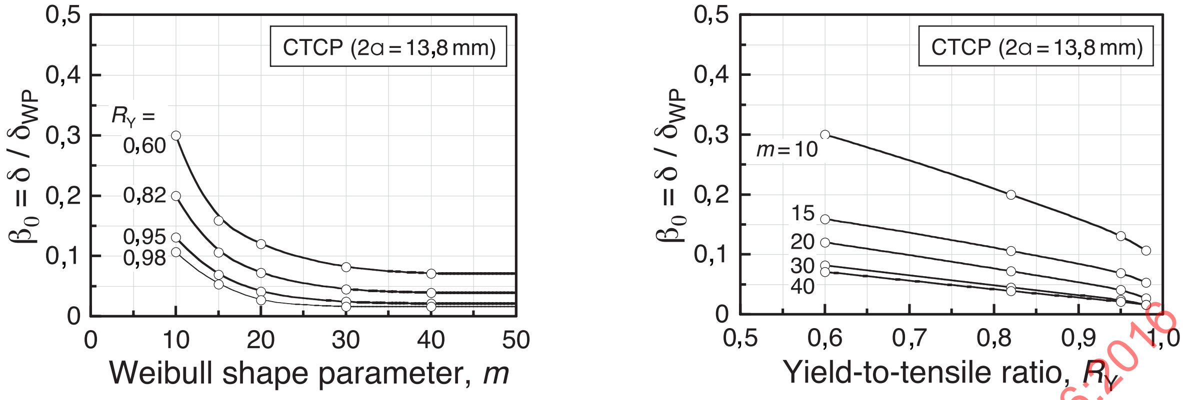
c) ESCP (*a*/*t* = 0,12; *t* = 25 mm): β_0 versus *m*

d) ESCP (*a*/*t* = 0,12; *t* = 25 mm): β_0 versus R_Y

e) ESCP (*a*/*t* = 0,24; *t* = 25 mm): β_0 versus *m*

f) ESCP (*a*/*t* = 0,24; *t* = 25 mm): β_0 versus R_Y

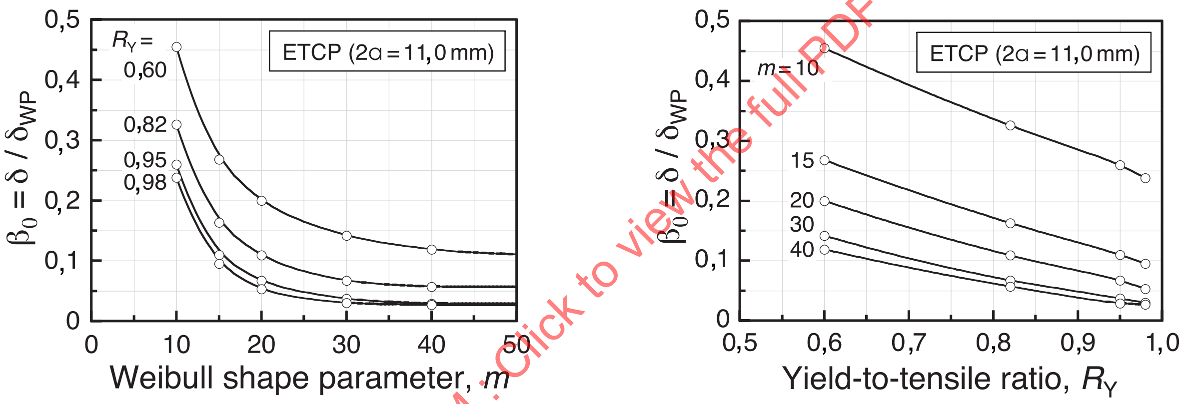
Figure 8 — Nomographs of equivalent CTOD ratio, β_0, for double-edge surface crack panel (ESCP) with plate thickness t = 25 mm



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

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

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



a) ETCP (2*a* = 11 mm): β_0 versus *m*

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

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

Annex A
(informative)

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

A.1 General

This annex describes the procedure for the selection of the Weibull shape parameter, *m*, at level II assessment. The shape parameter *m* is selected based on 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, $\delta_{\mathrm{cr,ave}}$, at the assessment temperature obtained with 25 mm thick test specimens should be used.

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

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

$$\delta_{\mathrm{min}} = \frac{500 \cdot \left(1 - \nu^{2}\right)}{\sigma_{\mathrm{Y}} \cdot E} \cdot K_{\mathrm{min}}{}^{2} \tag{A.2}$$

where

B	is the test specimen thickness, in mm;
$\delta_{\mathrm{cr,ave\text{-}}B}$	is the average CTOD fracture toughness with test specimen thickness B, in mm;
σ_{Y}	is the lower yield strength or 0,2 % proof strength, in MPa;
E	is Young's modulus of elasticity, in MPa;
ν	is Poisson's ratio;
K_{min}	is equal to 20 MPa $\sqrt{\mathrm{m}}$.

Note that Formulae (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 from the fracture toughness of the structural steel, the shape parameter *m* is selected as shown in Formula (3), depending on the average CTOD fracture toughness, $\delta_{cr,ave\ -25}$.

The *m*-value in Formula (3) is a lower-bound value in the diagram for *m* and $\delta_{cr,ave\ -25}$ (Figure A.1) exhibited with data from Reference [1] and References [9] to [26], where *m* was determined statistically with fatigue pre-cracked toughness specimens. The use of the lower-bound *m*-value leads to a conservative fracture assessment.

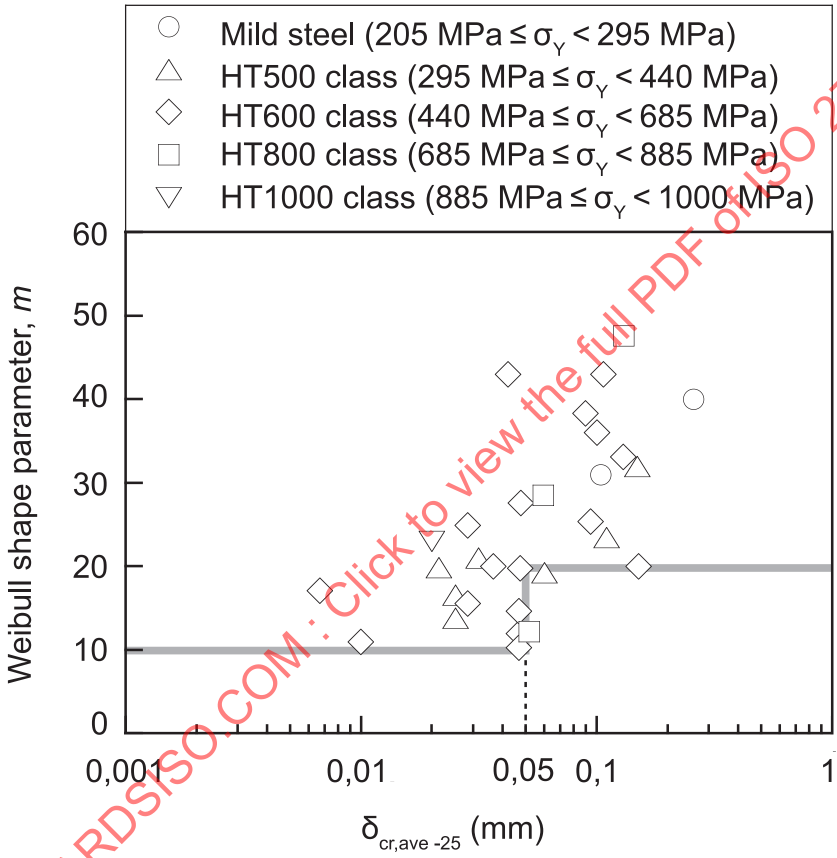


Figure A.1 — Relationship between Weibull parameter, *m*, and average CTOD fracture toughness, $\delta_{cr,ave\ -25}$

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

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

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 Formula (3).

For additional information on the relationship between the Weibull parameter and the fracture toughness of structural steels, see Reference [27].

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 Steps 1 to 3 are described in the following.

B.2 Fracture toughness test (Step 1)

Fracture toughness tests should 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 should be within the range of $0{,}45 \le a_0/W \le 0{,}55$. The toughness tests (Table B.1) should be performed with an adequate number of specimens to determine the parameter *m*, and statistical data of the critical CTOD should be obtained. After testing, the fracture surface should be observed, and the fact that brittle fracture occurred without stable crack extension larger than 0,2 mm should be confirmed.

NOTE 1 In R6 Revision 4 – Section III.9 in Chapter III, a minimum number of 30 tests is recommended.[28] [29]

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 $0{,}45 \le a_0/W \le 0{,}55$. 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 $a_0/W > 0{,}55$.[30]

NOTE 3 One set of fracture toughness data obtained by the above specimen may give a non-unique *m*-value, if the stress fields near the crack-tip show the singularity controlled by *K* or Hutchinson, Rice and Rosengren (HRR) 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 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 detail of the calibration procedure for *m* using two data sets is described in Reference [31].

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 should be analyzed 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 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 Standard for testing, such as ISO 6892-1[32] and ISO 6892-3.[33]

The test should 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 should 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 should be determined in accordance with the following procedure.

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

b) Convert the engineering stress–plastic engineering strain relationship to the true stress–true plastic strain relationship (equivalent stress–equivalent plastic strain relationship) using the following formulae.

$$\sigma = R\,(1 + e_{\mathrm{p}}) \tag{B.1}$$

$$\varepsilon = \ln\,(1 + e_{\mathrm{p}}) \tag{B.2}$$

where

σ	is the true stress, in MPa;
ε	is the true plastic strain;
R	is the engineering stress, in MPa;
e_{p}	is the plastic engineering strain.

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

c) Constitute the equivalent stress–equivalent plastic strain relationship beyond uniform elongation e_{T} in the form:

$$\bar{\sigma} = \sigma_{\mathrm{Y}} \left(1 + \bar{\varepsilon}_{\mathrm{p}} / \alpha\right)^{n} \tag{B.3}$$

where

$\bar{\sigma}$	is the equivalent stress, in MPa;
$\bar{\varepsilon}_{\mathrm{p}}$	is the equivalent plastic strain (plastic component of equivalent strain);
σ_{Y}	is the lower yield strength or 0,2 % proof strength, in MPa;
α and n	are material constants (n being the strain hardening exponent).

It is recommended that the material constants α and n should be determined using test data between $e_{\mathrm{T}}/2$ and e_{T}, where e_{T} is the uniform elongation (= engineering strain at the maximum force).

B.3.3 FE model of fracture toughness specimen

A three-dimensional model should be used in the FE analysis. In the FE mesh, the minimum element size and the region ahead of the crack-tip covered by the minimum element should 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 x 0,03 mm (in two-dimensional plane)
Minimum mesh region	0,3 mm x 0,3 mm (in two-dimensional plane)

The force P and crack mouth opening displacement V_g relation obtained by the FE analysis should 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 subclauses, 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 Formula (B.4).

$$\sigma_W = \left\{ \frac{1}{V_0} \int_{V_f} \sigma_{eff}{}^m \mathrm{d}V_f \right\}^{1/m} \qquad \text{(B.4)}$$

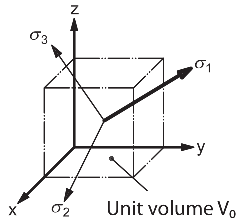
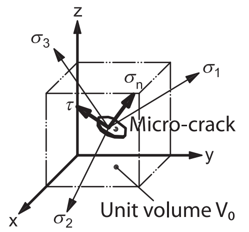
where

σ_{eff} is the effective stress for brittle fracture initiation, in MPa;

V_f is the fracture process zone that almost corresponds to the plastic zone ahead of the crack tip, in mm^3.

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.[10] [34] 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 — Definition of effective stress, σ_{eff}

Type 1[2]	Maximum principal stress criterion		$\sigma_{eff} = \sigma_1$
Type 2 [10] [34]	Fracture energy criterion		$\sigma_{eff} = \left[\frac{1}{2\pi} \int_0^{\pi} \int_0^{\pi} \left\{ \sigma_n^2 + \frac{4}{(2-\nu)^2} \tau^2 \right\}^{m/2} \sin\theta d\theta d\varphi \right]^{1/m}$ 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, $V_0 = 1\ \text{mm}^3$ 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 [10] and [34].

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) $\int_{V_f} \int_{\text{Element}} \sigma_1{}^m \text{d}V \text{d}V_f$	$\sum_{\text{In}\,V_f} \sum_{j=1}^{8} \left(\sigma_{1,j}{}^m \bullet \frac{V_i}{8} \right)$ (V_i: Volume of each element)	$\sum_{\text{In}\,V_f} \sigma_1{}^m \bullet V_i$ (V_i: Volume of each element)
Effective stress σ_{eff}	Numerical integration (Gaussian integration) $\int_{V_f} \int_{\text{Element}} \sigma_{eff}{}^m \text{d}V \text{d}V_f$	$\sum_{\text{In}\,V_f} \sum_{j=1}^{8} \left(\sigma_{eff,j}{}^m \bullet \frac{V_i}{8} \right)$ (V_i: Volume of each element)	$\sum_{\text{In}\,V_f} \sigma_{eff}{}^m \bullet V_i$ (V_i: Volume of each element)

B.4.4 Determination of critical Weibull stress

It is recommended that the critical Weibull stress should be linked with the critical CTOD at brittle fracture initiation, using CTOD as a "linking parameter." 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 should be calculated by the same procedure 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 should 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 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 should be conducted until the Weibull parameter, m, converges to a stationary value that satisfies Formula (B.5) (Figure B.1).

$$|m_i - m_{i-1}| / m_i < 1\% \tag{B.5}$$

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

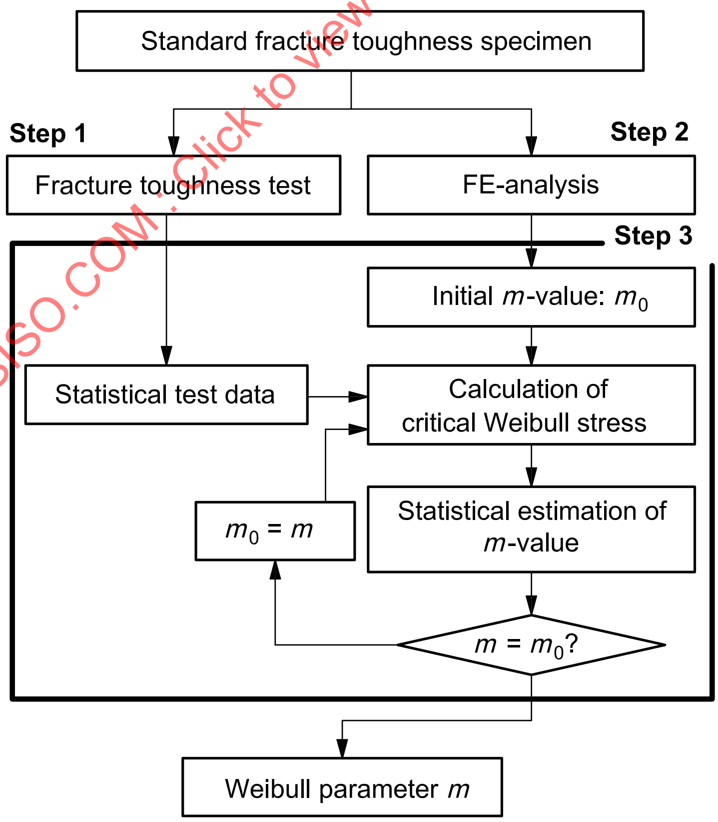


Figure B.1 — Procedure for determination of Weibull shape parameter, *m*[9] [28]

Annex C
(informative)

Guidelines for the equivalent CTOD ratio, β

C.1 General

C.1.1 Overview

Annex C describes guidelines for the determination of β at three assessments levels.

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: $0{,}45 \le a_0/W \le 0{,}55$, 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 $\delta_{\mathrm{SSY\ limit}}$, below which the standard fracture toughness specimen exhibits a small-scale yielding deformation.

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

where

a_0 is the initial crack length, in mm;

σ_{Y} is the lower yield strength or 0,2 % proof 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, $K_{\mathrm{SSY\,limit}}$, defining the small-scale yielding (SSY) limit of the fracture toughness specimen in ISO 12135.

$$K_{\mathrm{SSY\,limit}} = \left(\frac{a_0 \sigma_{\mathrm{Y}}^{2}}{2{,}5} \right)^{1/2} \tag{C.2}$$

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

$$\delta = \frac{K^2 \left(1 - \nu^2\right)}{2E\sigma_{\mathrm{Y}}} \tag{C.3}$$

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.

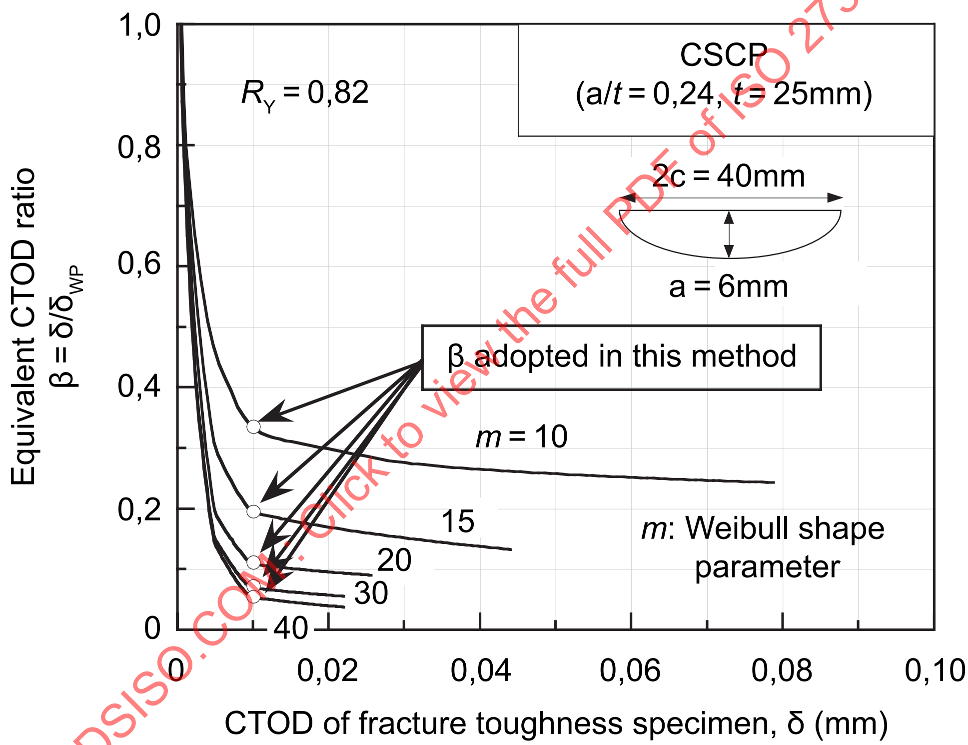


Figure C.1 — CSCP (a/t = 0,24; t = 25 mm): Equivalent CTOD ratio, β, adopted in this International Standard

Thus, from an engineering viewpoint, the β-value 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 that almost corresponds to $\delta_{\mathrm{SSY\,limit}}$ for 25 mm thick toughness specimen. This International Standard adopts such β in the whole CTOD range beyond $\delta_{\mathrm{SSY\,limit}}$, 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 assessment levels I, II and III of β 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 likely for long cracks. In order to avoid this risk, level II assessment is recommended instead of level I, particularly for cases where 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 length (Figures 7 to 10) and the conversion formulae for the crack length [Formulae (5), (6), (8), and (9)]. 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 in 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	-

Formulae (5), (6), (8), and (9), used to convert the equivalent CTOD ratio, β_0, for the reference crack length to β for the target crack length, are derived from numerical analyses, examples of which are shown in Figure C.3. Formulae (5) and (6) for CSCP and ESCP include the plate thickness effect on β, which is based on the following properties:

— Weibull stresses for CSCP and ESCP do not depend on the plate thickness, t, under a given crack depth ratio, a/t;

— thickness effect on the CTOD fracture toughness is approximated as $\delta_{cr,\,t} = \delta_{cr,\,25} \bullet \sqrt{25\,/\,t}$ for brittle fracture.

Examples of the thickness effect on β are shown in Figure C.4. It should be noted that these conversion formulae are applicable within the range of crack size and plate thickness shown in Table C.2 because the numerical analysis was performed in this range.

Table C.2 — Range of crack size and plate thickness for Formulae (5) to (9)

	Range of FE analysis		
	Crack length	Crack depth ratio	Plate thickness
CSCP	$2c \geq 16$ mm	$0{,}04 \leq a/t \leq 0{,}24$	$12{,}5 \leq t \leq 50$ mm
ESCP	$2c \geq 24$ mm	$0{,}04 \leq a/t \leq 0{,}24$	$12{,}5 \leq t \leq 50$ mm
CTCP	$5 \leq 2a \leq 50$ mm	-	-
ETCP	$5 \leq 2a \leq 30$ mm	-	-

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

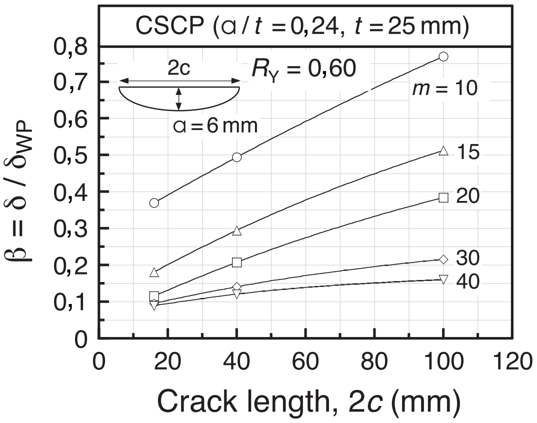
It is also noted that, as shown in Figure C.2, the use of a lower bound m-value may give an excessive over-estimation of β in the following cases:

a) $R_Y < 0{,}8$ and

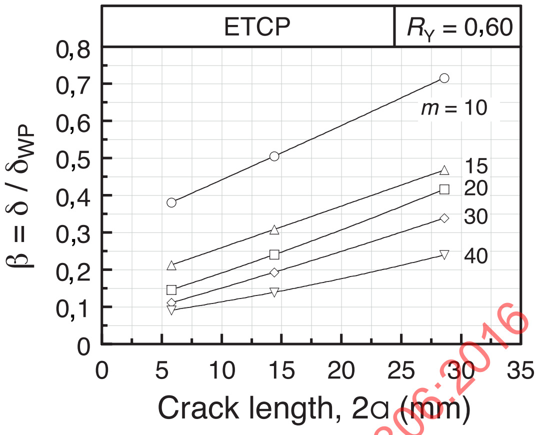
b) Surface crack length: $2c > 50$ mm (CSCP, ESCP) or

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

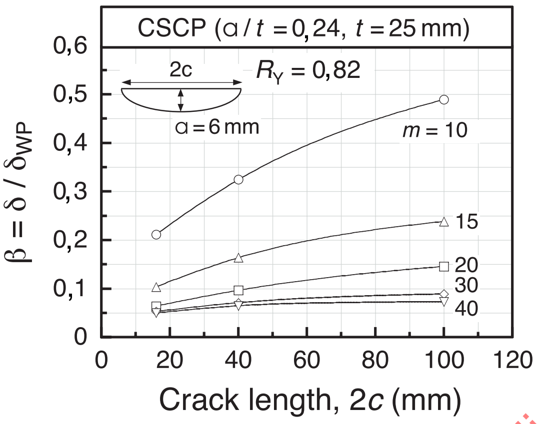
In such cases, level III assessment is recommended.



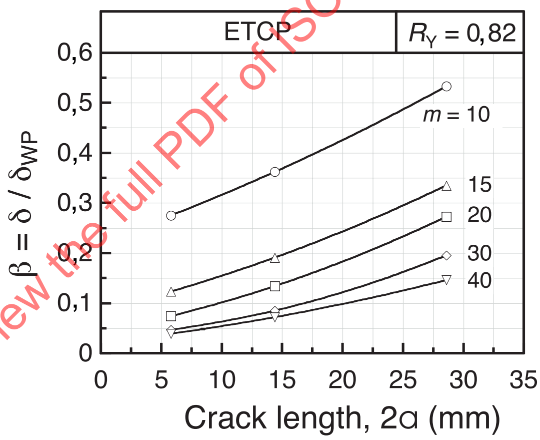
a) CSCP (R_Y = 0,60)



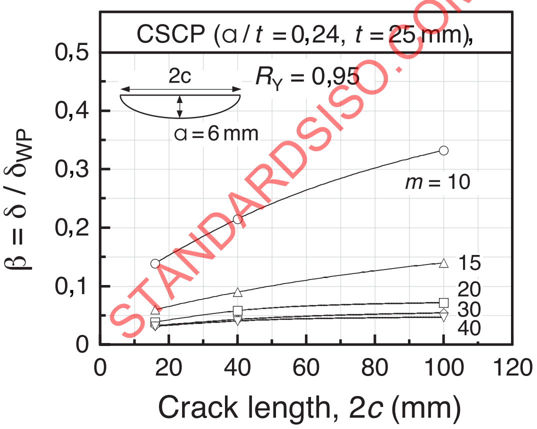
b) ETCP (R_Y = 0,60)



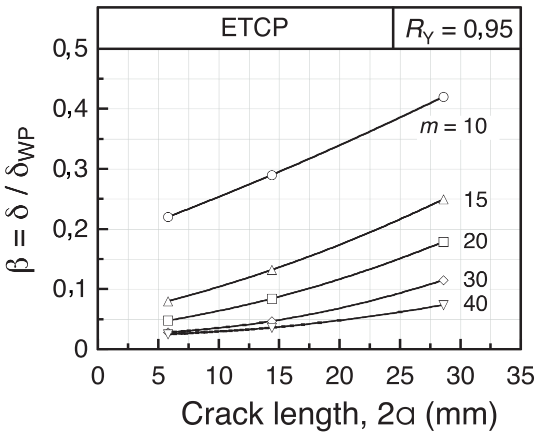
c) CSCP (R_Y = 0,82)



d) ETCP (R_Y = 0,82)



e) CSCP (R_Y = 0,95)



f) ETCP (R_Y = 0,95)

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

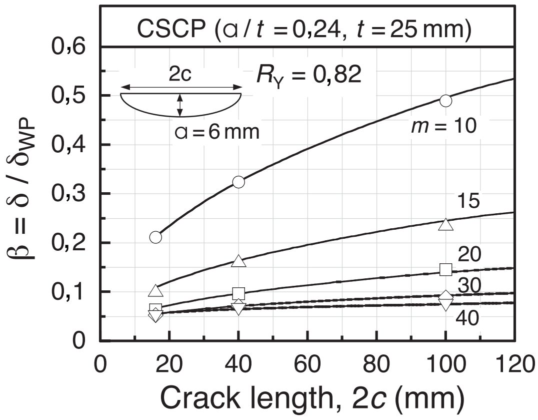
Figure C.2 — Effect of Weibull parameter, *m*, on β

C.2.4 Level III: Material specific assessment

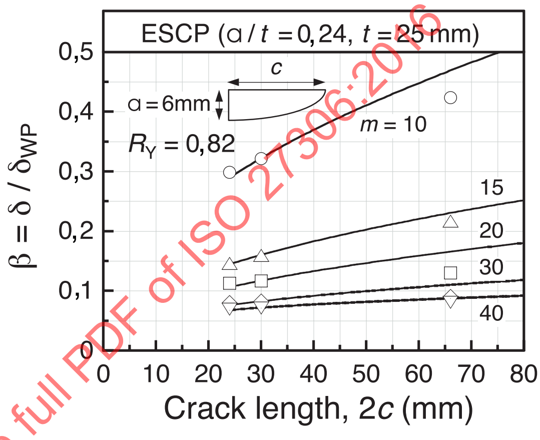
Assessment level III is applicable to cases where the information for the assessment of β is fully known. At level III, the equivalent CTOD ratio, β, is determined using the Weibull shape parameter, m, specific to the material used.

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.

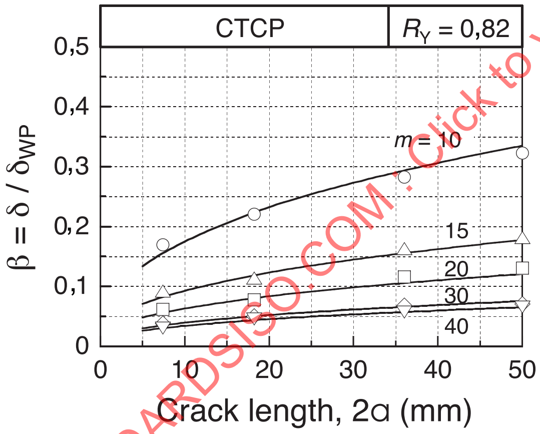
A complimentary explanation of Annex C is given in References [30] and [35].



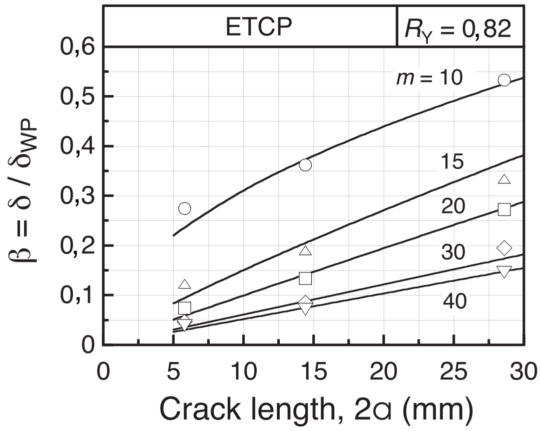
a) CSCP [See Formula (5)]



b) ESCP [See Formula (6)]

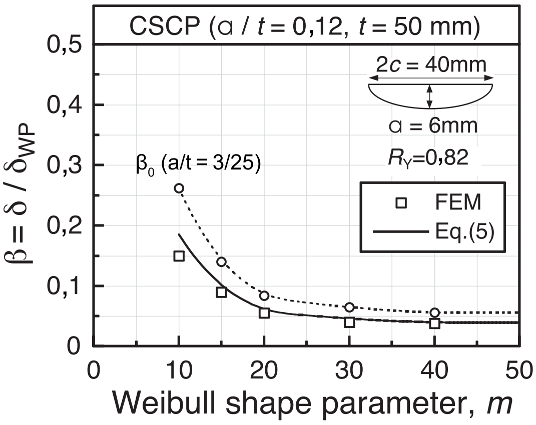


c) CTCP [See Formula (8)]

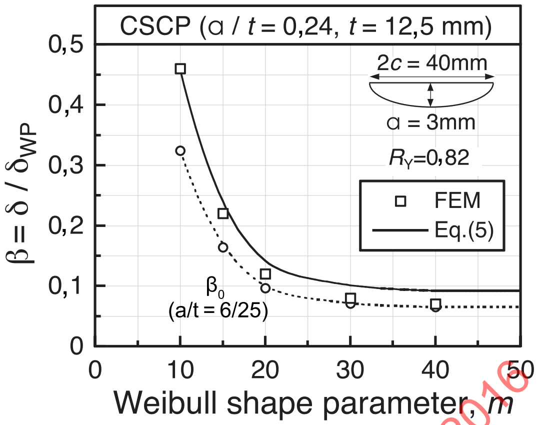


d) ETCP [See Formula (9)]

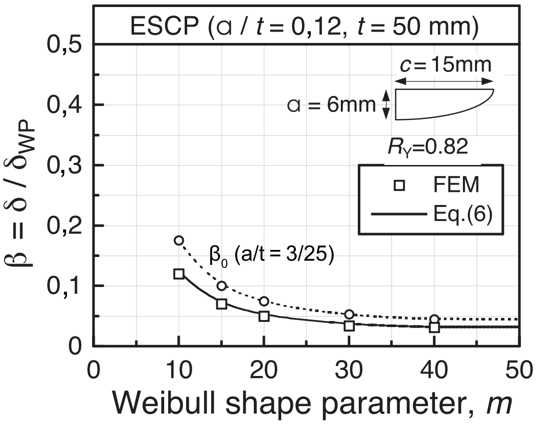
Figure C.3 — Crack length effect on equivalent CTOD ratio, β



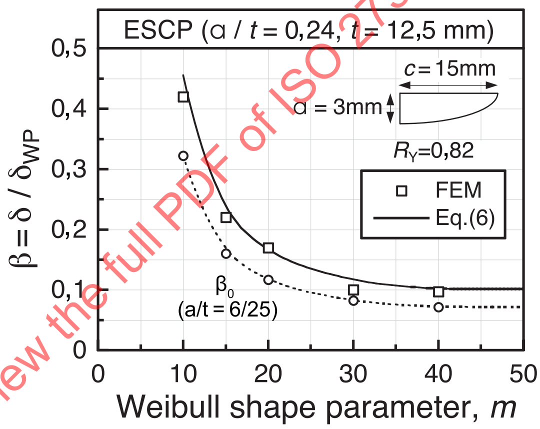
a) CSCP (a/t = 0,12) [See Formula (5)]



b) CSCP (a/t = 0,24) [See Formula (5)]



c) ESCP (a/t = 0,12) [See Formula (6)]



d) ESCP (a/t = 0,24) [See Formula (6)]

Figure C.4 — Crack depth 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 Failure Assessment Diagram (FAD) as specified in BS 7910[6] is presented, and practical examples are exhibited.

NOTE The FAD specified in BS 7910:2013 is somewhat different from one in BS 7910:2005. This annex employs BS 7910:2013.

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

D.2.1 General

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

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

The critical CTOD of the standard fracture toughness test specimens should 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] [36] If more than three toughness test results are available, the use of a minimum of three equivalent results (MOTE)[37] is recommended.[6] [36]

D.2.3 Calculation of the equivalent CTOD ratio, β

The equivalent CTOD ratio, β, is calculated according to the procedure at assessment levels I, II and III as described in this International Standard. The assessment level to be applied should 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[6]

In BS 7910, FAD curves at Option 1 and Option 2 are given as a function of the load ratio, L_r:

$$L_r = P / P_L = \sigma_{ref} / \sigma_Y \tag{D.1}$$

where

P is the applied load;

P_L is the limit load;

σ_{ref} is the reference stress corresponding to the average stress at net section, in MPa;

σ_Y is the lower yield strength or 0,2 % proof strength, in MPa

The maximum value for L_r is defined as

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

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

The FAD curve at Option 1 for materials with continuous yielding is as follows:

$$f\left(L_r\right) = \left(1 + \frac{1}{2} L_r^{\ 2}\right)^{-1/2} \left[0{,}3 + 0{,}7\exp\left(-\mu L_r^{\ 6}\right)\right] \text{ for } L_r \leq 1 \tag{D.3}$$

$$f\left(L_r\right) = f\left(1\right) \cdot L_r^{\ (N-1)/(2N)} \text{ for } 1 < L_r < L_{r,max} \tag{D.4}$$

$$f\left(L_r\right) = 0 \text{ for } L_{r,max} \leq L_r \tag{D.5}$$

where

$$\propto = \min(0{,}001E / R_{p0,2}, 0{,}6) \tag{D.6}$$

$$N = 0{,}3(1 - R_{p0,2} / R_m) \tag{D.7}$$

For materials exhibiting a yield discontinuity, the FAD curve at Option 1 is replaced by Formula (D.8) to Formula (D.11):

$$f\left(L_r\right) = \left(1 + \frac{1}{2} L_r^{\ 2}\right)^{-1/2} \text{ for } L_r < 1 \tag{D.8}$$

$$f\left(L_r\right) = \left(\lambda + \frac{1}{2\lambda}\right)^{-1/2} \text{ for } L_r = 1 \tag{D.9}$$

$$f\left(L_r\right) = f\left(1\right) \cdot L_r^{\ (N-1)/(2N)} \text{ for } 1 < L_r < L_{r,max} \tag{D.10}$$

$$f\left(L_r\right) = 0 \text{ for } L_{r,max} \leq L_r \tag{D.11}$$

The quantity $\lambda > 1$ in Formula (D.9) is defined as

$$\lambda = 1 + E\Delta\varepsilon / R_{eL} \tag{D.12}$$

where

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

$\Delta\varepsilon$ is the increase in strain at R_{eL} without any increase in stress, namely, Lüders strain;

R_{eL} is the lower yield strength, in MPa.

The strain hardening exponent N is given by Formula (D.7) where R_{eL} is employed instead of $R_{p0,2}$.

The FAD curve at Option 2 is defined by Formulae (D.13) and (D.14):

$$f\left(L_r\right) = \left(\frac{E\varepsilon_{ref}}{L_r\sigma_Y} + \frac{L_r{}^3\sigma_Y}{2E\varepsilon_{ref}}\right)^{-1/2} \quad \text{for } L_r < L_{r,max} \tag{D.13}$$

$$f\left(L_r\right) = 0 \text{ for } L_{r,max} \le L_r \tag{D.14}$$

where ε_{ref} is the true strain corresponding to σ_{ref}.

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

D.2.4.2 Convert the CTOD toughness, δ_{cr}, to the critical stress intensity factor, K_{mat}

In BS 7910, the CTOD fracture toughness, $\delta_{mat} = \delta_{cr}$, shall be converted to the critical stress intensity factor, K_{mat}:

$$K_{mat} = \sqrt{\frac{M\sigma_Y\delta_{cr}E}{1-\nu^2}} \tag{D.15}$$

where

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

σ_Y is the lower yield strength or 0,2 % proof strength, in MPa;

ν is Poisson's ratio.

E and σ_Y are determined at the same temperature as the fracture toughness.

The coefficient, M, is given in Formula (D.16) for steels:

$$M = 1{,}517R_Y^{-0{,}3188} \quad \text{for } 0{,}3 < R_Y < 0{,}98 \tag{D.16}$$

where R_Y is the yield-to-tensile ratio (= σ_Y/R_m). The yield strength, σ_Y, and ultimate tensile strength, R_m, should be determined at the fracture toughness test temperature.

D.2.4.3 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:

— referring to K-value handbook[38];

— analysing by the finite element method (FEM).

D.2.4.4 Calculate the loading path of the structural component

The loading path of the structural component with the correction of constraint loss is given as

$$K_r^c\left(L_r\right)=\frac{K\left(L_r\right)}{K_{mat}/\sqrt{\beta}}=\sqrt{\frac{\beta\left(1-\nu^2\right)}{M\sigma_Y\delta_{cr}E}}\cdot K\left(L_r\right) \quad \text{(D.17)}$$

where K_{mat} is the material fracture toughness defined by Formula (D.15).

D.2.4.5 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 [Formula (D.17)] crosses the FAD curve at Option 1 or Option 2.

Figure D.2 shows the procedure for determining the material facture toughness, δ_{cr}, needed to meet design requirements of performance of structural components, using 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 CTCP subjected to uniaxial tension (Figure D.3). The structural steel used was SM490YB (JIS G 3106[39]) 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 mechanical properties of the steel at –100 °C were R_{eL} = 530 MPa and R_m = 646 MPa.

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

D.3.1.2 Determination of CTOD fracture 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 (standard specimens of B x $2B$ type with 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
0,2MOTE	0,068
Average, $\delta_{cr,ave\text{-}25}$	0,11
NOTE 0,2MOTE 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.

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, $R_Y = R_{eL} / R_m$ = 0.82 (R_{eL} = 530 MPa, R_m = 646 MPa at –100 °C)

Step 2: Set the Weibull shape parameter, m:

— At level II assessment, a lower-bound value is employed for the Weibull shape parameter, m. Since the CTOD fracture toughness $\delta_{cr,ave\text{-}25}$ = 0,11 mm is larger than 0,05 mm, the lower-bound 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 length:

— From the nomograph (Figure 9), the β_0-values for the reference crack length 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 Formula (8) as follows:

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

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

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

D.3.1.4 Fracture assessment of structural component based on FAD

D.3.1.4.1 Construct the FAD curve in BS 7910[6]

The SM490YB steel exhibited a yield discontinuity at –100 °C. The extent of the Lüders strain, $\Delta\varepsilon$, was 0,020. Thereby, the FAD curve at Option 1 employs Formula (D.8) to Formula (D.11). The FAD curve at Option 2 [Formulae (D.13) and (D.14)] in Figure D.4 is constructed with the true stress–true strain curve of SM490YB steel at the test temperature.

D.3.1.4.2 Convert the CTOD toughness, δ_{cr}, to the critical stress intensity factor, K_{mat}

Convert the CTOD fracture toughness, δ_{cr}, to the critical stress intensity factor, K_{mat}, using Formula (D.15). The coefficient, M, at –100 °C is $1{,}517 \times 0{,}82^{-0{,}311\,8} = 1{,}614$.

D.3.1.4.3 Calculate the stress intensity factor, K, of the structural component

The stress intensity factor, K, for CTCP is given as follows:[38]

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

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

D.3.1.4.4 Calculate the loading path of the structural component

$$K_r^c(L_r) = \frac{K(L_r)}{K_{mat}/\sqrt{\beta}} = \sigma_\infty \sqrt{\pi a} \cdot F \sqrt{\frac{\beta(1-\nu^2)}{M\sigma_Y \delta_{cr} E}} = \sqrt{\frac{\pi\beta(1-\nu^2) a \sigma_Y}{M\delta_{cr} E}} \cdot F \cdot \frac{W-2a}{W} \cdot L_r$$

Since a number of toughness data were available, 0,2MOTE toughness was adopted here as the material fracture toughness: δ_{cr} = 0,068 mm. The coefficient, M, at −100 °C is 1,614. Thereby,

$K_r^c(L_r)$ = 0,75L_r ····· at level I

= 0,37L_r ····· at level II

= 0,27L_r ····· at level III

D.3.1.4.5 Determine the failure load

The critical load ratio, $L_{r,\,cr}$, and critical fracture ratio, $K_{r,cr}^c$, calculated are summarized in Table D.2.

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

TP-No.	Critical load ratio $L_{r,\,cr}$ (=$\sigma_{ref,\,cr}/R_{eL}$)	Critical fracture ratio $K_{r,\,cr}^c$		
		Level I	Level II	Level III
UT-1	1,06 (560/530)	0,79	0,39	0,29
UT-2	1,01 (534/530)	0,75	0,37	0,28
TP-No.: Test piece number				

The results of fracture assessments, $L_{r,cr}$ - $K_{r,cr}^c$ relationships, using the equivalent CTOD ratio, β, give better agreement with the FAD curve as shown in Figure D.4. The fracture assessments of the CTCP are summarized in Table D.3.

D.3.2 Fracture assessment of CTCP (2)

BS 4360 Grade 50D[40] steel plate with thickness t = 52 mm was used. Two CTCP components with a crack of length 2a = 30,6 mm and 37,2mm were tested at −65 °C[41] [42]. Twenty-one three-point bend specimens of standard type with the specimen thickness B = 50 mm were tested at −65 °C. The yield-to-tensile ratio, R_Y (= R_{eL}/R_m), at −65 °C was 0,65, that was estimated from tensile tests results at −100 °C, −70 °C, and −40 °C, as described in Reference [41].

The critical CTOD values, $\delta_{cr\text{-}50}$, were in the range 0,02 mm to 1,041 mm, which included brittle fracture with a stable crack growth. Since a number of toughness data were available, 0,2MOTE toughness of $\delta_{cr\text{-}50}$ = 0,118 mm was adopted as the material fracture toughness. The average CTOD toughness, $\delta_{cr,ave\text{-}50}$, was 0,338 mm.

The average CTOD fracture toughness, $\delta_{cr,ave\text{-}50}$, for 50 mm thick specimen was converted to $\delta_{cr,ave\text{-}25}$ for 25 mm thick specimen using Formulae (A.1) and (A.2) as follows:

$$\delta_{cr,ave\text{-}25} = \left\{\sqrt{\delta_{min}} + \left(\sqrt{\delta_{cr,ave\text{-}50}} - \sqrt{\delta_{min}}\right) \cdot \left(\frac{50}{25}\right)^{1/4}\right\}^2$$

$$= 0{,}478 \text{ mm at } -65\ °\text{C}$$

Since $\delta_{cr\,-25}$ was larger than 0,05 mm, the lower-bound m -value was set as m = 20.

The results of fracture assessments using β for CTCP with $2a$ = 30,6 mm and 37,2 mm are summarized in Table D.4 and Table D.5, respectively.

D.3.3 Fracture assessment of CSCP

The steel used was SM490YB (JIS G 3106[39]), 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. The yield-to-tensile ratio, $R_Y = R_{eL}/R_m$ = 0.82 (see D.3.1).

The CSCP components 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 Formula (5), 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.[38]

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

D.3.4 Fracture assessment of ESCP with crack in stress concentration area

The steel used in the tests was SM490B (JIS G 3106[39]) class steel with a plate thickness of 25 mm. Twenty-four three-point bend specimens of standard type were tested at –100 °C. The yield-to-tensile ratio, R_Y (= R_{eL}/R_m), of the steel at –100 °C was 0,71. The critical CTOD values, δ_{cr}, were in the range 0,01 mm to 0,16 mm. Since the average CTOD toughness, $\delta_{cr,ave\text{-}25}$ = 0,062 mm, was larger than 0,05 mm, the lower-bound m-value at level II assessment was set as m = 20. The m-value at level III assessment determined statistically from fracture toughness results was also 20.

The configuration and dimensions of the ESCP are shown in Table D.7. The ESCP had two corner cracks of 20 mm (surface length) x 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-stress, $\sigma_{ref,cr}$, of the ESCP was in the range 410 MPa to 455 MPa.

At level II and level III assessments, β_0 was 0.15 from Figure 8 with m = 20 and R_Y = 0,71. β for the target crack length of $2c$ = 40 mm was calculated using Formula (6), giving β = 0,17.

The stress intensity factor, K, at the bottom of the surface crack was calculated by FE analysis.

Since a number of toughness data were available, 0,2MOTE 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 References [22] and [43].

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 [44] and [45]. The fracture performance of beam-to-column connections that are subjected to cyclic loading is evaluated with β in Reference [44]. 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 [45].

A comparison is shown in Reference [46] between constraint corrections by this International Standards and FITNET procedure, currently implemented into BS 7910 as Annex N.

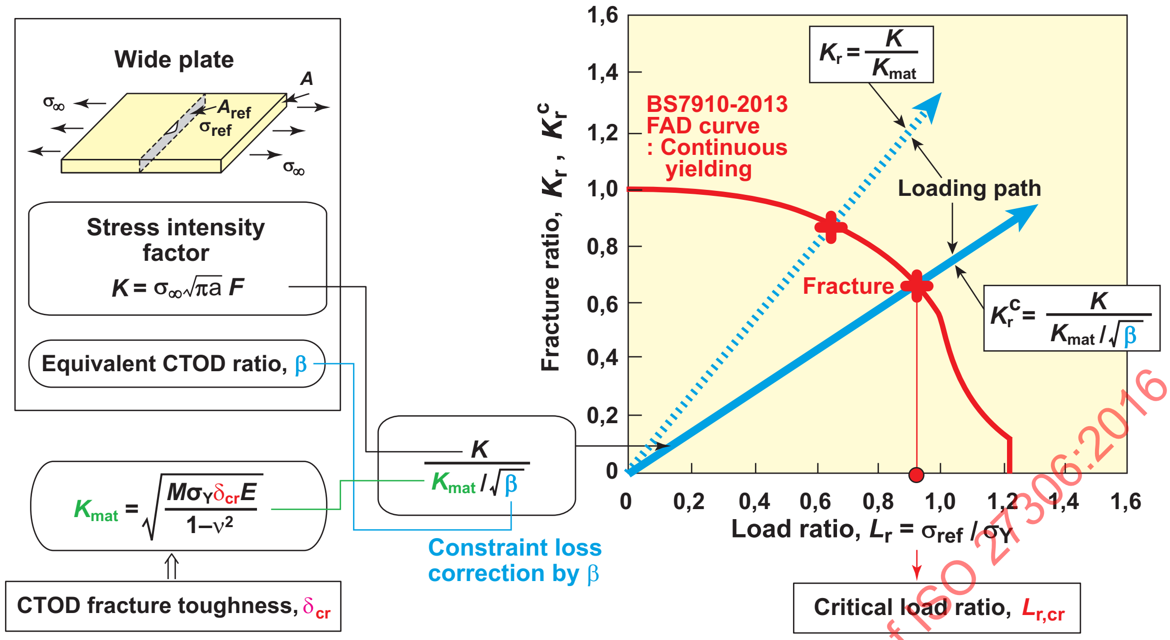


Figure D.1 — Procedure for failure assessment by FAD approach with equivalent CTOD ratio, β

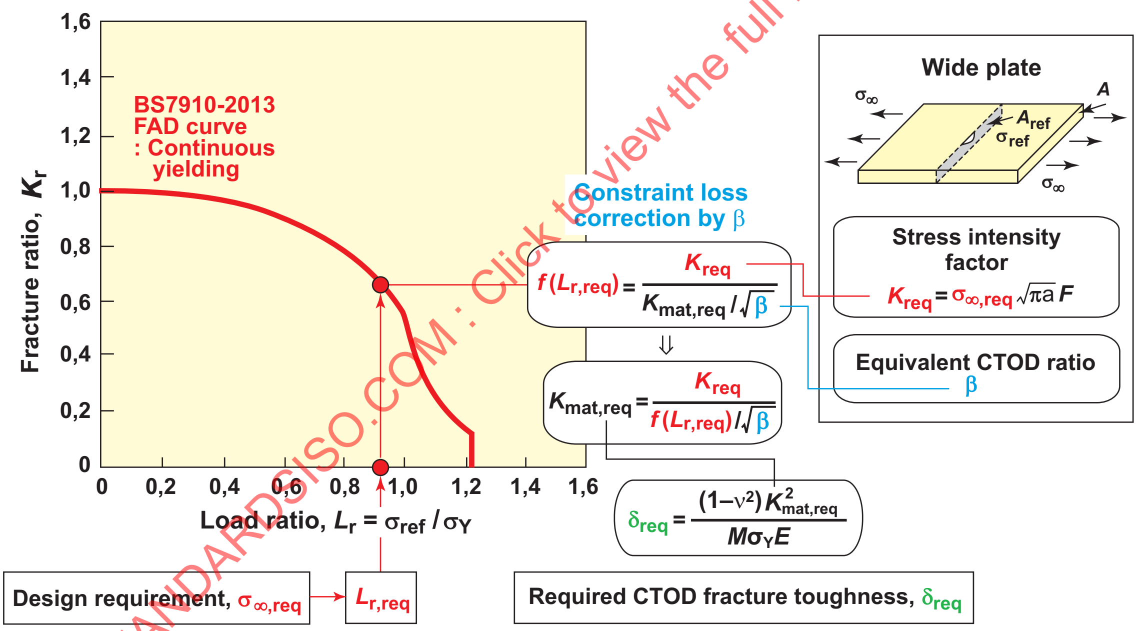


Figure D.2 — Procedure for determining CTOD fracture toughness required to meet design requirements of performance of structural components

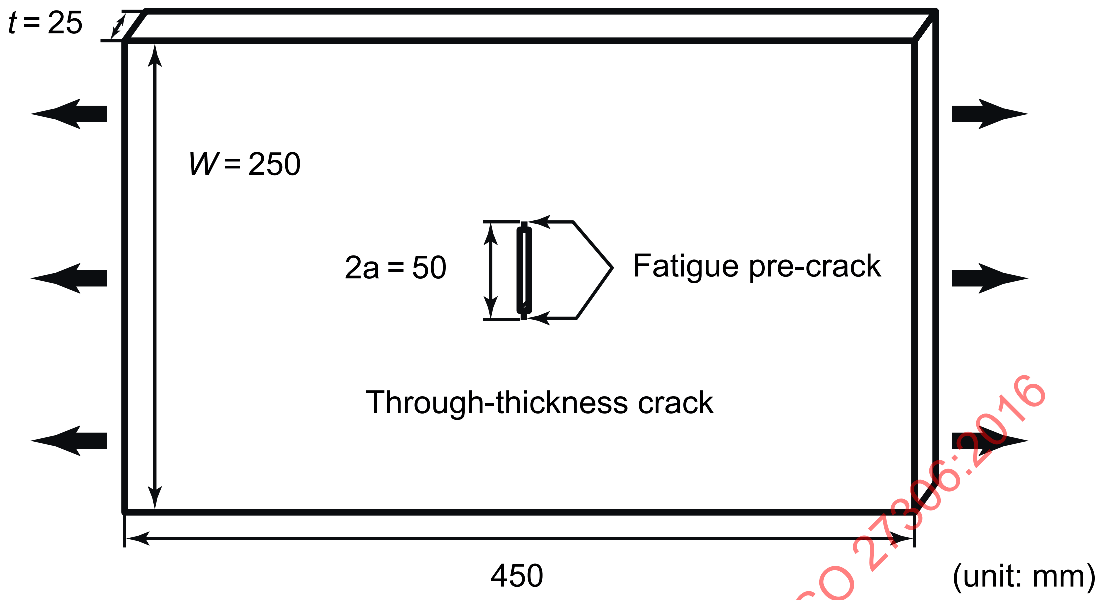


Figure D.3 — Configuration of CTCP used in the case study D.3.1

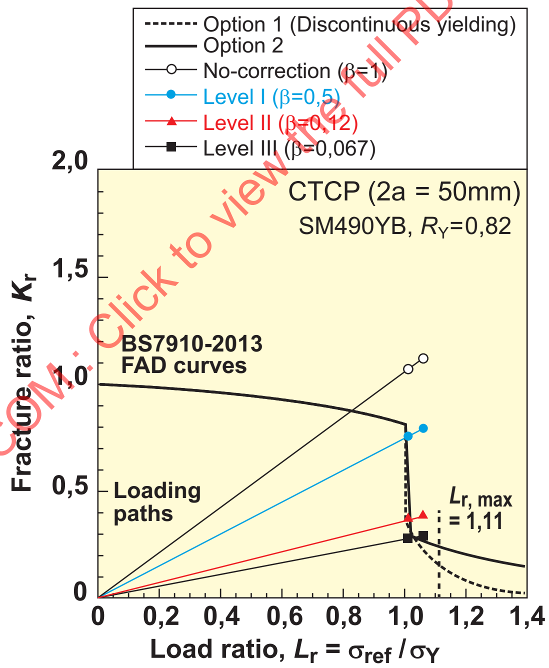


Figure D.4 — Fracture assessment results at Option 1 and Option 2 in BS 7910 with different *β*-values