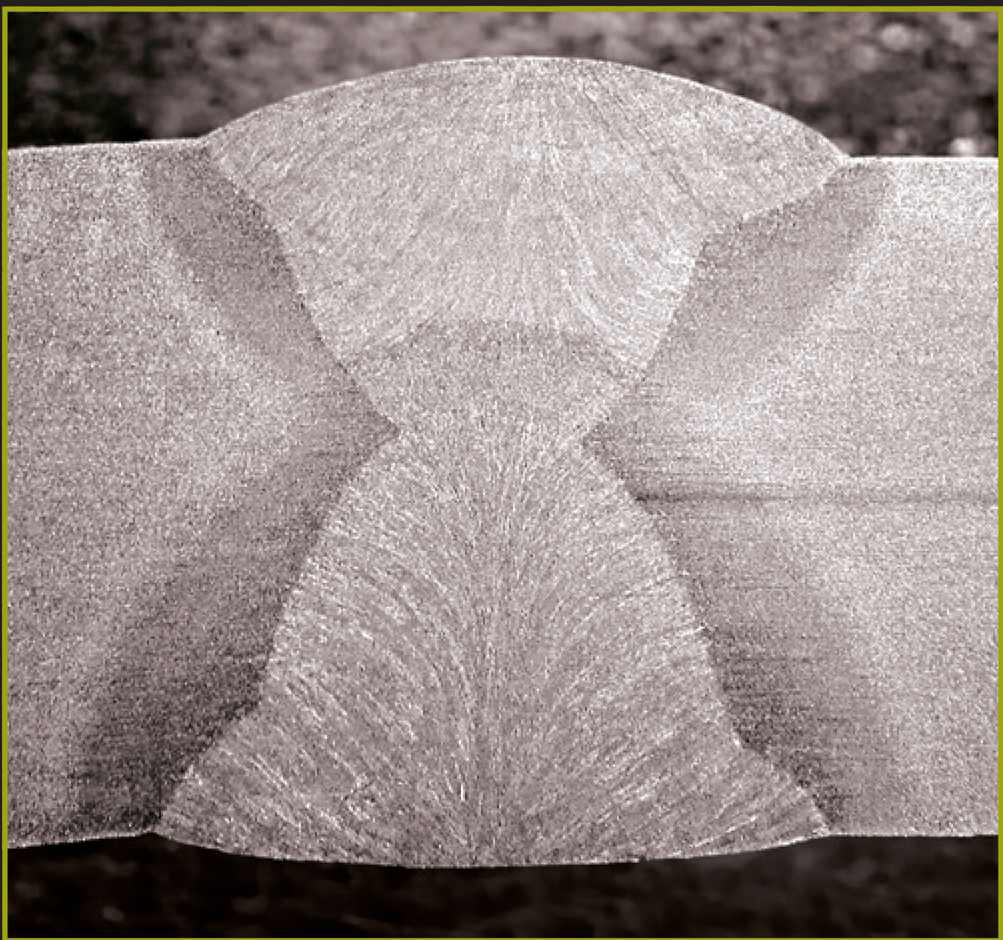
BRITTLE FRACTURE: SELECTION OF STEEL SUB-GRADE TO BS EN 1993-1-10



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Publication Number: **SCI P419**

ISBN 13: 978-1-85942-224-3

Published by:
SCI, Silwood Park, Ascot,
Berkshire. SL5 7QN UK

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British Library Cataloguing-in-Publication Data.
A catalogue record for this book is available from the British Library.

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FOREWORD

This guide explains how an approach based on fracture mechanics, which is a method permitted in BS EN 1993-1-10, may be used to determine the required steel sub-grade. Application of the procedures in this guide should be limited to quasi-static structures, where fatigue is not a design consideration.

This guide was prepared by David Brown of the Steel Construction Institute (SCI), with valuable input from Tom Cosgrove of the British Constructional Steelwork Association (BCSA). Particular thanks are due to John Gradwell of Severfield (UK) Limited, who initially demonstrated the application of a fracture mechanics approach. Subsequently, the University of Aachen was engaged by BCSA to develop the approach for quasi-static structures, which defines the scope for the procedures and guidance presented in this guide.

This guide was commissioned and funded by the BCSA and Steel for Life.

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SUMMARY

Brittle fracture and the selection of a steel sub-grade are covered by BS EN 1993 1-10[1]. The UK National Annex[2] makes various modifications, where allowed, to the Eurocode. The provisions of the UK National Annex are implemented and presented in PD 6695-1-10[3], which contains straightforward look-up tables of limiting thickness.

The scope of the Eurocodeincludes structures where fatigue is a design consideration, noting that the limiting thicknesses may be conservative for structures where fatigue is not a significant design consideration. The definitive background document to the Eurocode[4] confirms that the limiting thicknesses may be “extremely safe-sided” if used for non-fatigue structures.

In an effort to reduce the declared conservatism for structures where fatigue is not a design consideration – so called quasi-static structures – this guide follows the procedures, based on fracture mechanics, which were used to develop BS EN 1993-1-10, but modifies the contribution from fatigue. The result is increased values of limiting thickness which are appropriate for quasi-static structures.

Section 1 provides a very basic introduction to fracture mechanics. Section 2 demonstrates the process used to develop the limiting thickness data provided in BS EN 1993-1-10. Section 3 describes the simple modification to the calculation process in order to develop limiting thicknesses for quasi-static structures. Section 4 describes the important adjustments imposed by the UK National Annex and Section 5 presents the results of those adjustments with tables of limiting thicknesses for use in the UK.

Numerical examples of the calculation process are presented in the Appendix.

For structures where fatigue is not a design consideration, the limiting thicknesses presented in Section 3 may be used as a substitute for the values given in Table 2.1 of BS EN 1993-1-10. For construction in countries other than the UK, it is very important that the relevant National Annex is consulted to identify any effect on these values. For construction in the UK, the limiting thicknesses presented in Section 5 may be used.

The guidance in this guide is limited to quasi-static structures, in which fatigue is not a design consideration. For other structures, the guidance in BS EN 1993-1-10 and the relevant National Annex should be followed.

BRITTLE FRACTURE – INTRODUCTION

Limited background information is presented in the following sections. For a more exhaustive understanding, a number of helpful guides are referenced in the Bibliography.

1.1 Fracture mechanics

Fracture mechanics is concerned with the study of the propagation of cracks in materials. Principles of stress, strain, elastic behaviour and plastic behaviour are applied to develop an understanding of crack formation and growth from flaws and defects found in materials. The force propagating a crack is compared to the resistance of the material to fracture.

The mechanics of crack propagation and growth are complex, as elastic and plastic behaviour (see Section 1.2.3) must be included in the analysis. Assessment of fractures uses mathematical models, such as linear elastic fracture mechanics (LRFM), crack opening displacement (COD) and "J-integral" approaches using finite element analysis.

A useful summary of the history of fracture mechanics and basic concepts may be found on Wikipedia[5].

1.2 Basic concepts

If a sharp flaw, crack or defect is present in a structural component, non-ductile failure may occur, even if the material is capable of large plastic deformations. Failure occurs when the stress and strain concentrations adjacent to the flaw are sufficient to overcome the internal strain energy capacity.

The analysis of cracks in solids is known as fracture mechanics. The presence of a crack or flaw affects the stress in the component, which is quantified by a stress intensity factor.

The resistance of a material to fracture is known as fracture toughness, which is a property of the material determined by testing.

1.2.1 Verification

A component can resist the effect of a crack or flaw, as long as the fracture toughness of the material (Section 1.2.8) is greater than the stress intensity factor (Section 1.2.2).

The fundamental verification is that the material toughness exceeds the stress intensity. This may be expressed as:

$$K_{\text{appl,d}} \leq K_{\text{Mat,d}}$$

where:

$K_{\text{appl,d}}$ is the applied stress intensity factor (see Section 1.2.2).

$K_{\text{Mat,d}}$ is a measure of material toughness, in compatible units (see Section 1.2.8).

This fundamental relationship is transformed within the Eurocode to allow verification based on temperature, T, such that:

$$T_{\text{Ed}} \geq T_{\text{Rd}}$$

where the subscripts Ed and Rd indicate "design effect" and "design resistance" respectively.

1.2.2 Stress intensity factor

The stress intensity factor K can be presented in the following basic form:

$$K = Y\sigma\sqrt{\pi a} \quad \text{(units are Mpa}\sqrt{\text{m}}\text{)}$$

where:

Y is a function of the member geometry and crack configuration.

σ is the uniform stress on the gross area.

a is the crack length.

The expression for the stress intensity factor may be modified to allow for additional effects, such as plasticity and residual stress.

1.2.3 Stress at crack tip

Fracture mechanics generally considers an elliptical or semi-elliptical crack. Considering an elliptical crack in a plate, as shown in Figure 1.1, it can be shown that:

$$\frac{\sigma_{\text{t}}}{T} = 1 + \frac{2a}{b}$$

where:

σ_{t} is the stress at the tip of the ellipse.

T is the applied tensile stress on the gross section.

a is half the major axis dimension of the ellipse.

b is half the minor axis dimension of the ellipse.

As the ellipse becomes increasingly "flat" and more like a crack, the term $\frac{2a}{b}$ becomes large, and as dimension b tends to zero, the stress at the tip of the crack tends to infinity. The situation is complicated by redistribution of stress at the crack tip as the material behaves in a plastic manner. The theoretical infinite stress is avoided by yielding and non-linear deformation.

The basic principle illustrated in Figure 1.1 is however clear – if the applied stress is large enough, the crack may grow suddenly (at a speed approaching the speed of sound), without significant plastic behaviour and produce a brittle failure.

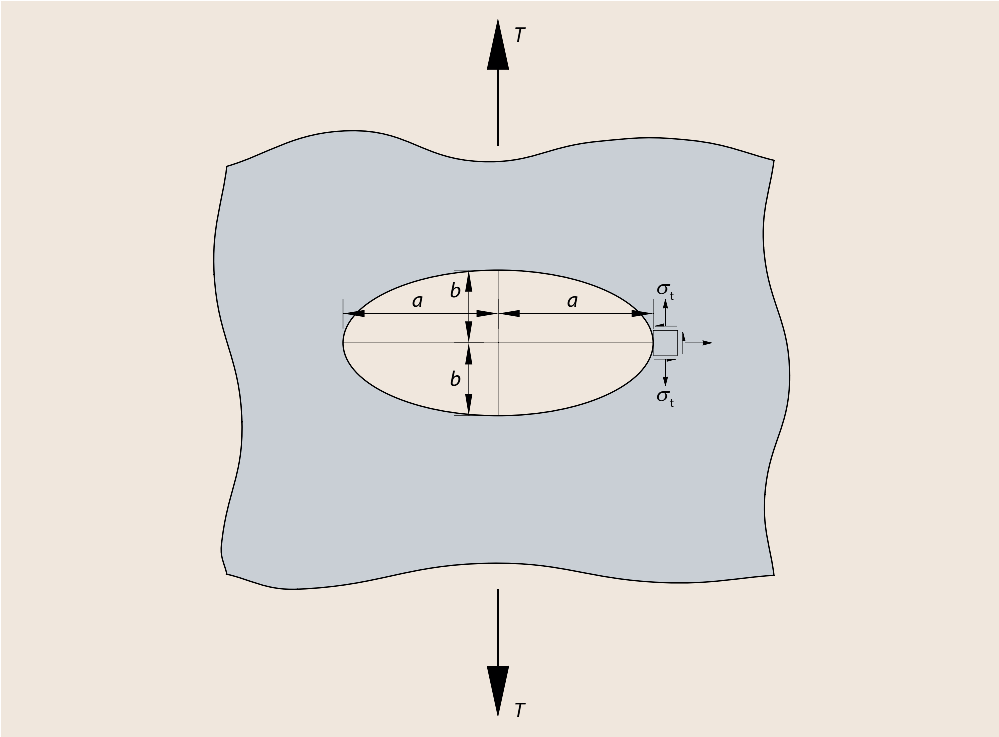

Figure 1.1
Stresses adjacent to an elliptical crack

1.2.4 Cracks and flaws

Although brittle fracture is generally associated with cracks, any type of flaw may initiate a crack. Flaws are considered inevitable as a result of welding and fabrication, with the effect of any defect amplified by misalignment, poor weld profile and applied stress.

1.2.5 Crack growth

In structures subject to fatigue, it is anticipated that an initial crack will grow in size due to the repeated cycles of applied stress. The crack growth depends on the magnitude of the stress cycle and is not linear; the rate of crack growth increases over time.

When assessing the stress intensity factor, the size of the 'design' crack is important – i.e. the crack size after it has grown due to the cyclic application of stress. If there is no cyclic application of stress, the size of the initial imperfection is important.

1.2.6 Weld shape

The shape of a weld has an impact on the stress concentration factor simply due to the abruptness of the change in cross section. As can be seen in Figure 1.2, the change in cross section is more severe with a fillet weld than a butt weld.

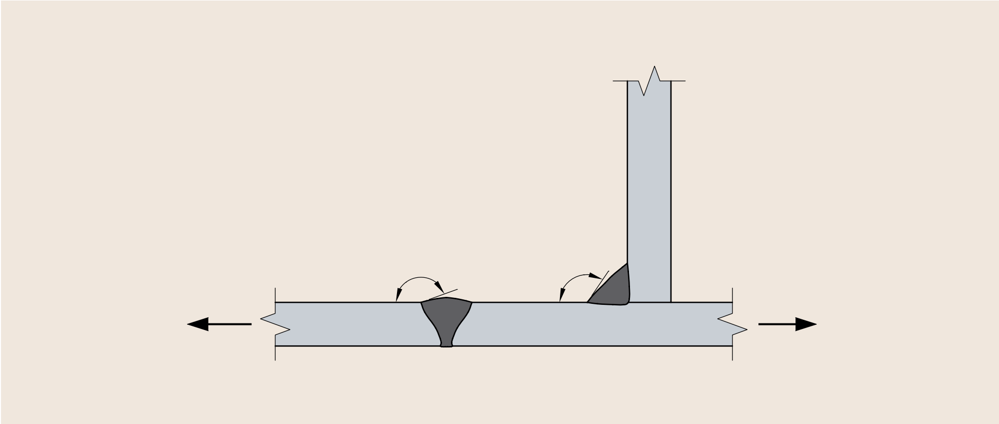

Figure 1.2 Butt and fillet weld shapes

1.2.7 Brittle fracture or fatigue failure?

A fatigue failure is generally slow, with significant plastic behaviour. In contrast, a brittle fracture is fast, at a stress level below the yield stress of the material. Although fatigue cracking is not essential to initiate a brittle fracture, initial flaws are accentuated due to any cyclic stress, which may then be followed by brittle fracture.

1.2.8 Material toughness

There is no convenient single measure of steel's resistance to brittle fracture. An indication of the tendency to brittle fracture is given by the Charpy test.

In a Charpy test, a pendulum with a profiled strike point is released to break a small steel sample, which has a pre-machined, V-shaped notch. After breaking the sample, the difference in height of the pendulum, as shown in Figure 1.3, indicates how much energy has been absorbed in fracturing the sample. The resistance of steel varies with temperature, so product specifications demand a minimum energy absorption at a stated test temperature.

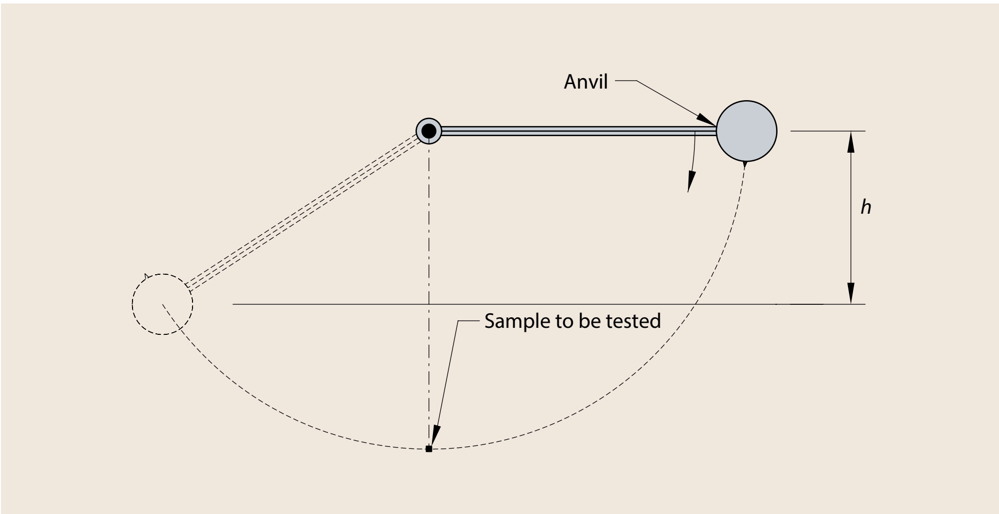

Figure 1.3 Principles of Charpy test arrangement

Steel sub-grade designations, the test temperature and the minimum energy absorption are shown in Table 1.1, which has been extracted from BS EN 10025[6]. Increased energy absorption, at lower temperatures, indicates a tougher steel sub-grade.

Steel sub-grade	Test temperature (°C)	Minimum energy absorption (J)
JR	Room temperature, taken as 20°C	27
J0	0	27
J2	–20	27
K2, M, N	–20	40
ML, NL	–50	27

Table 1.1 Steel sub-grade specification

Charpy toughness values (measured in Joules) can be converted into units of stress intensity (Section 1.2.2) so that the basic requirement that material toughness exceeds the stress intensity factor can be verified.

1.3 Eurocode procedures for sub-grade selection

Within the Eurocode system, selection of an appropriate steel sub-grade is made in accordance with BS EN 1993-1-10. The procedure is described in Clause 2.2 of the Standard and summarised in the following sections.

Table 2.1 of BS EN 1993-1-10

Table 2.1 of BS EN 1993-1-10 is key to selecting an appropriate steel sub-grade. The table reflects the design effect stress and the reference temperature, providing limiting thicknesses for each steel sub-grade. For a combination of stress and reference temperature, it is necessary to ensure that the limiting thickness is larger than the actual thickness of the member (which typically will be a plate thickness, or the thickness of a flange).

Design stress

The Eurocode considers brittle fracture to be equivalent to an accidental combination, because of the assumption of simultaneous occurrence of lowest temperature, flaw size, location of flaw and material property. The following combination of actions is used to determine the design effect stress, σ_{Ed}:

$$E_d = E\left[A\left[T_{Ed}\right] \text{“+”}\ \Sigma G_k \text{“+”}\ \psi_1 Q_1 \text{“+”}\ \Sigma \psi_{2,i} Q_{k,i} \right]$$

The ψ factors are to be taken from BS EN 1990[7] and its UK National Annex[8].

The design effect stress is compared to what is commonly known as the “design” strength, $f_y(t)$ which reduces as thickness increases. Values of the design strength may be conveniently taken from the product Standard or calculated as:

$$f_y(t) = \text{nominal strength} - 0.25(t)$$

where:

t is the element thickness.

The stress ratio $\sigma_{Ed}/f_y(t)$ determines which zone of Table 2.1 should be used, as limiting thicknesses for stress ratios of 0.75, 0.5 and 0.25 are provided.

Reference temperature

The reference temperature is commonly known as the "service temperature" (the lowest temperature likely to be experienced by the steel), adjusted to account for a range of effects, including:

- a safety allowance,
- strain rate,
- cold forming.

The Eurocode applies a negative temperature adjustment for any effect which increases the risk of brittle fracture.

According to BS EN 1993-1-10, the reference temperature T_{Ed} is given by:

$$T_{Ed} = T_{md} + \Delta T_r + \Delta T_\sigma + \Delta T_R + \Delta T_{\dot{\varepsilon}} + \Delta T_{\varepsilon cf}$$

where:

T_{md}	is the lowest air temperature.
ΔT_r	is an adjustment for radiation loss.
ΔT_σ	is an adjustment for stress and yield strength of material, crack imperfections and member shape and dimensions.
ΔT_R	is a safety allowance, as given in the National Annex (see Section 4.1).
$\Delta T_{\dot{\varepsilon}}$	is an adjustment for strain rate.
$\Delta T_{\varepsilon cf}$	is an adjustment for the degree of cold forming.

Taken together, the two terms $T_{md} + \Delta T_r$ are the minimum service temperature, taken as –5 °C for internal steelwork in buildings and as - 15 °C for external steelwork in buildings.

$\Delta T_{\dot{\varepsilon}} = 0$ for strain rates $\dot{\varepsilon}$ no greater than 4 × 10^{-4}/second.

$\Delta T_{\varepsilon cf} = 0$ when the degree of cold forming ε_{cf} is no greater than 2%.

When using the tabulated values within the Eurocode, $\Delta T_\sigma = 0°C$.

Eurocode scope of application

Clause 2.1(2) states that the Eurocode rules are applicable to:

> *"tension elements, welded and fatigue stressed elements in which some portion of the stress cycle is tensile".*

The scope of the Eurocode may be understood to mean that there are no requirements for elements only in compression.

The NOTE to Clause 2.1(2) observes that:

> *"For elements not subject to tension, welding or fatigue, the rules can be conservative. In such cases evaluation using fracture mechanics may be appropriate, see 2.4 (of the Standard). Fracture toughness need not be specified for elements only in compression."*

1.4 Evaluation using fracture mechanics

As indicated in Clause 2.1(2) of the Eurocode, evaluation using fracture mechanics may be appropriate, notably when an element is not subject to fatigue. Clause 2.2(3) allows alternative methods to be used to determine the toughness requirements, including a fracture mechanics method.

Clause 2.4 provides more information on evaluation using fracture mechanics, with the key recommendations summarised in the following sections.

Acceptance criteria

When undertaking a fracture mechanics approach, the defining requirement is as follows:

$$T_{\mathrm{Ed}} \geq T_{\mathrm{Rd}}$$

where:

T_{Rd} is the temperature at which a safe level of fracture toughness can be relied upon under the conditions being evaluated.

Flaw characteristics

The location and shape of the flaw should be appropriate for each case considered. The fatigue classification tables in BS EN 1993-1-9[9] may be used as guidance.

For members not susceptible to fatigue, the size of the flaw should be the maximum likely to have been left uncorrected in inspections carried out to BS EN 1090-2[10].

Scope of fracture mechanics approach

If a detail falls outside the scope of BS EN 1993-1-9, or a more rigorous method is used to obtain results which are more refined than those given in Table 2.1 of BS EN 1993-1-10, then a verification supported by physical tests must be undertaken.


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DEVELOPMENT OF EUROCODE GUIDANCE

Comprehensive background information on the development of BS EN 1993 1-10 is given in Reference 4. This background document explains how the limiting thicknesses in Table 2.1 of the Standard were determined, using a fracture mechanics approach. The key steps are described in the following sections.

2.1 Detail types

The limiting thicknesses in Table 2.1 of BS EN 1993-1-10 were determined by considering one single typical detail type, as shown in Figure 2.1. The plate width, attachment thickness and attachment length are all normalised by relating the dimensions to the thickness of the plate, t.

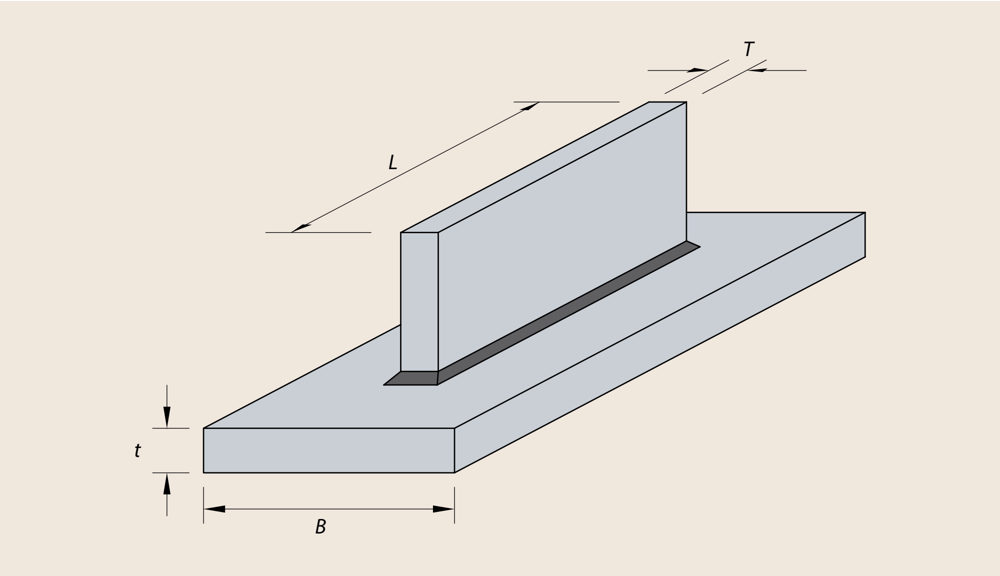

Figure 2.1 Standard detail

Other details illustrated in BS EN 1993-1-9 were investigated, but it was concluded that the standard detail shown in Figure 2.1 represents the most onerous situation in practical use. Reference 4 states that all other detail types, thicknesses and crack shapes are safe-sided with respect to the standard detail used.

Reference 4 confirms that Table 2.1 of BS EN 1993-1-10 may be used for all details specified with fatigue categories in BS EN 1993-1-9.

If a detail falls outside the categories in BS EN 1993-1-9, special consideration is necessary, beyond the scope of this present guide.

2.2 Crack size

When developing the guidance in BS EN 1993-1-10, an initial crack was assumed, of a size that may be missed in inspection after fabrication. Reference 4 demonstrates that the minimum crack width detectable by inspection methods after fabrication is smaller than the assumed crack width, implying that even the assumed crack size should be detected. BS EN 1993-1-10 assumes that all steelwork is fabricated, welded and inspected in accordance with the requirements of BS EN 1090-2.

The initial crack is assumed to grow in size as a result of fatigue loading.

A semi-elliptical crack is assumed, with the dimensions indicated in Figure 2.2.

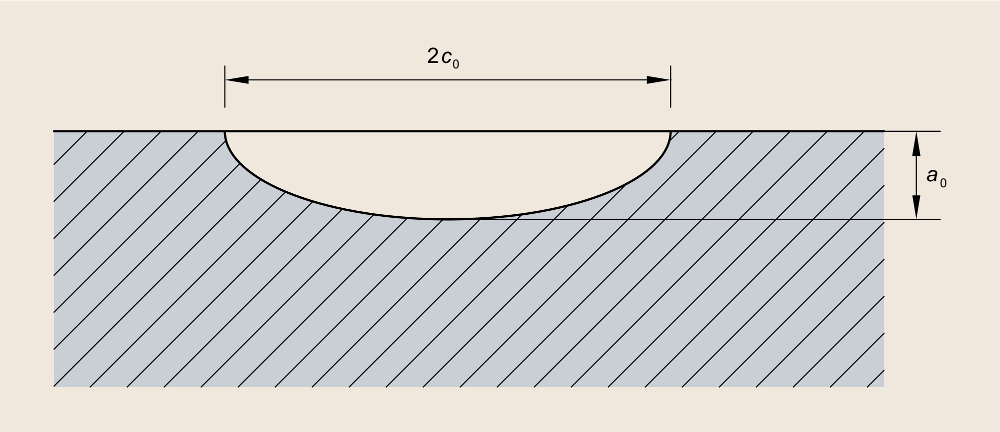

Figure 2.2 Initial crack form and dimensions

2.2.1 Initial crack size

The initial crack depth, a_0, relates to the plate thickness and is given by:

for $t < 15$ mm:

$$a_0 = 0.5\ln\left(1 + \frac{t}{t_0}\right)$$

for $t \geq 15$ mm:

$$a_0 = 0.5\ln\left(\frac{t}{t_0}\right)$$

where:

t Is the plate thickness.

t_0 is 1 mm.

The relationship between plate thickness t and initial crack depth a_0 is shown in Figure 2.3.

The geometry of the assumed crack is such that the initial crack width is $5a_0$, which is considered to be readily detectable by post-weld inspection methods.

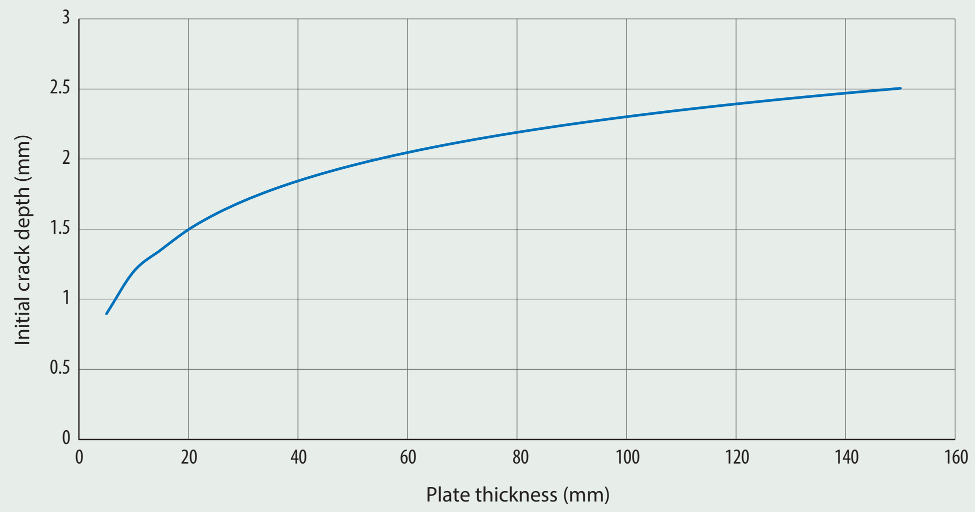

Figure 2.3 Assumed initial crack depth

2.3 Crack growth

In the development of BS EN 1993-1-10, it was assumed that initial cracks of depth a_0 grow under repeated cycles of stress to a design crack depth a_d. Two million stress cycles are assumed over a service life of 100 years, but the calculation process in BS EN 1993-1-10 considers only 0.5 million cycles, or 25 years. This approach therefore anticipates inspection of the structure at 25 year intervals, and repair if necessary to reinstate the original conditions.

The design crack depth a_d is expressed as:

$$a_d = 2 \times 10^{-6}\, t^3 + 6 \times 10^{-4}\, t^2 + 0.1341t + 0.6349$$

where:

t is the plate thickness.

The relationship between plate thickness t and design crack depth a_d is shown in Figure 2.4.

The design crack width is $5a_d$. This is a considerable size, (for example a 22 mm wide crack in a plate 25 mm thick). Reference 4 comments that:

> *"the verification has been performed for rather large design values of crack sizes. It is applicable to unwelded and welded structures subjected to fatigue loading, such as bridges or crane runways".*

For quasi-static structures covered by this guide, the crack growth will be modified, as described in Section 3.1.

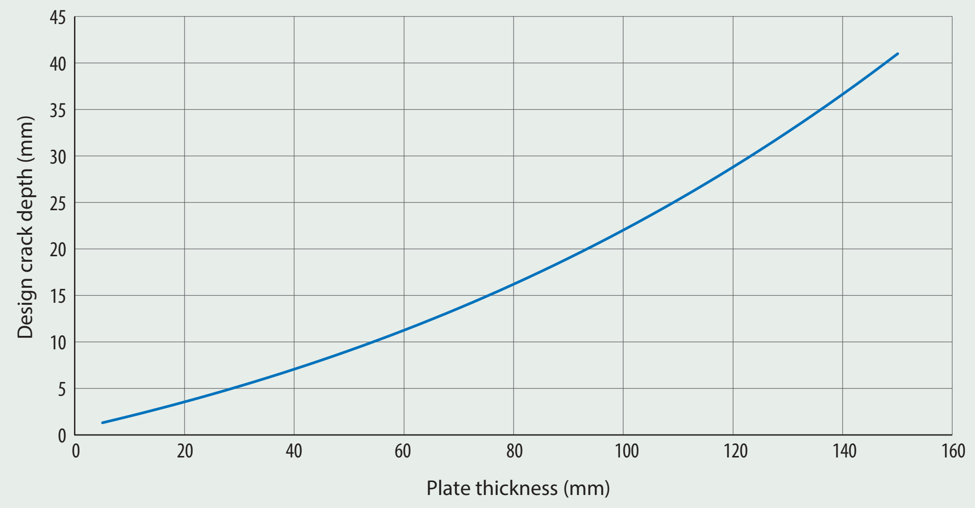

Figure 2.4
Design crack depth

2.4 Stress intensity factor

BS EN 1993-1-10 uses a modified version of the basic expression presented in Section 1.2.2 of this guide. The basic expression is modified to account for the detail type, plasticity at the tip of the crack (see Section 1.2.3) and local residual stress. In the derivation of the values presented in BS EN 1993-1-10, the following expression is used for the stress intensity factor, $K_{\mathrm{appl,d}}$.

$$K_{\mathrm{appl,d}} = \frac{\sigma_{\mathrm{Ed}} Y \sqrt{\pi a_{\mathrm{d}}} M_{\mathrm{k}}}{k_{\mathrm{R6}} - \rho}$$

where:

Y	is described in Reference 4 as a correction function for crack position and shape, sometimes called a stress concentration factor or stress intensity correction factor.
M_{k}	is a factor reflecting the type of detail, described as a stress intensity correction factor.
k_{R6}	is a factor reflecting the plastic behaviour at the crack tip.
ρ	is a correction for local residual stress.

Other variables are as described in Section 1.2.2.

2.4.1 Stress concentration factor, Y

The stress concentration factor, Y, is determined from published literature as indicated in Reference 4. The factor depends on the crack shape and location.

2.4.2 Stress intensity factor, M_{k}

Local changes in geometry are reflected in the stress intensity factor, M_{k}.

The stress intensity factor, M_k, is determined from published literature as indicated in Reference 4. The factor depends on the crack depth and the geometry of the plate and attachment.

2.4.3 Plasticity correction factor, k_{R6}

The plasticity correction factor, k_{R6}, is taken from published literature as indicated in Reference 4 and depends on the crack depth, material design strength (which varies with thickness) and residual stress.

2.4.4 Residual stress

BS EN 1993-1-10 includes a stress of 100 N/mm^2 as a residual stress. This is a 'global' residual stress, not the 'local' residual stress due to welding (which is often near the yield stress). This 'global' residual stress may arise from, for example, restraint from other members in a welded assembly.

2.4.5 Residual stress correction factor, ρ

The residual stress correction factor, ρ, depends on the design stress, the global residual stress and the load ratio (the ratio of applied stress to a limiting plastic stress).

2.5 Limiting temperature, T_{Ed}

Having calculated the stress intensity factor $K_{appl,d}$ (see Section 2.4), the limiting temperature T_{Ed} may be determined from:

$$T_{Ed} \geq \left[T_{27J} - 18^{\circ}C\right] + 52\ln\left[\frac{\left(K_{appl,d} - 20\right)\times\left(5a_d/25\right)^{1/4} - 10}{70}\right] + \Delta T_R$$

where:

T_{27J} is the temperature at which the steel should achieve at least 27J in a Charpy test.

ΔT_R is a safety adjustment of −7 °C, as given in the background document.

Other symbols are as previously defined.

Where the impact test is carried out to demonstrate a minimum of 40J (K2, M, N grades – see Table 1.1), the required adjustment is given by:

$$T_{40J} = T_{27J} + 10^{\circ}C$$

2.6 Numerical example

An example demonstrating the application of the preceding guidance to calculate a limiting thickness as given in Table 2.1 of BS EN 1993-1-10 is shown in Appendix A.1.

GUIDANCE FOR QUASI-STATIC STRUCTURES

This section describes how the Eurocode guidance may be modified to apply to quasi-static structures, where fatigue is not a design consideration. Therefore, this guidance may not be applied to bridges, or any building structure where fatigue is anticipated, such as structures containing cranes. Within this guide, a structure that will not experience more than 20k cycles of stress is defined as quasi-static.

3.1 Modified calculation process

The calculation process described in Section 2 may be modified by varying the crack growth calculated due to fatigue. Without fatigue, a crack is not expected to grow. Within this guide, it is assumed that the initial crack may grow due to 20k stress cycles. In every other respect, the process described in Reference 4 and Section 2 of this guide is followed.

3.1.1 Calculation of crack growth

To modify the calculation process correctly, an appropriate expression for crack growth must be determined. The University of Aachen prepared the following expression for crack growth due to 20k stress cycles[11], which may be compared with the expression given in Section 2.3.

The design crack depth a_d is expressed as:

$$
\begin{aligned}
a_d = \; & 3.6258 \times 10^{-11} t^5 \\
& -2.2316 \times 10^{-8} t^4 \\
& + 5.3365 \times 10^{-6} t^3 \\
& + 6.3837 \times 10^{-4} t^2 \\
& + 0.045124\, t \\
& + 0.82483
\end{aligned}
$$

where:

t is the plate thickness.

The resulting design crack depth is only a little larger than the initial crack depth, as can be seen in Figure 3.1. The ratio $\frac{\text{design crack depth}}{\text{initial crack depth}}$ is plotted against the right hand axis.

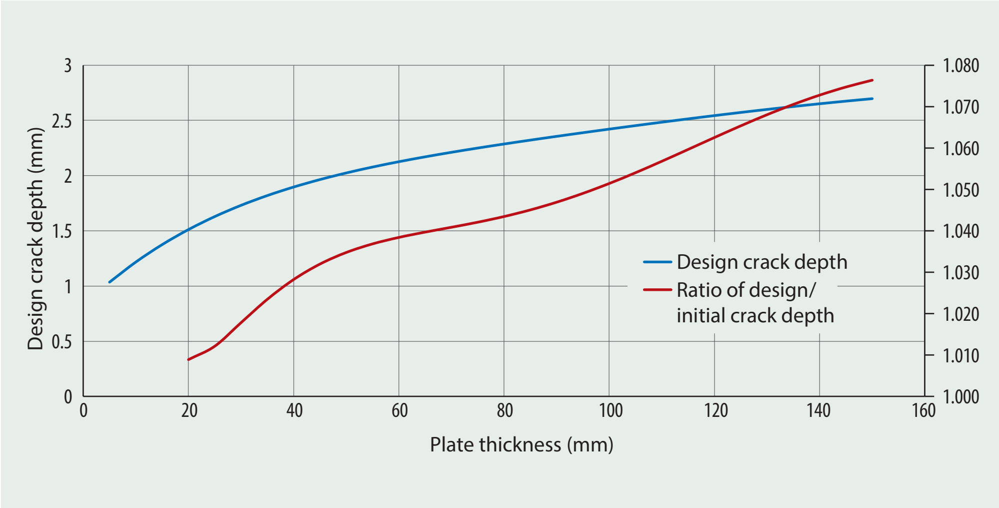

Figure 3.1 Design crack depth (20k cycles) and comparison to initial crack depth

3.2 Numerical example – quasi-static structures

An example demonstrating the calculation of a limiting thickness for a quasi-static structure is shown in Appendix A.2.

3.3 Modified thickness limits

If the calculation process demonstrated in Appendix A.2 is completed for a range of steel grades, stress levels and reference temperatures, Table 3.1 may be developed, which is an equivalent table to Table 2.1 in BS EN 1993-1-10, but for quasi-static structures.

The limiting thicknesses in Table 3.1 have been determined assuming that $\Delta T_{\dot{\varepsilon}} = 0°\text{C}$ and $\Delta T_{\varepsilon_{cf}} = 0°\text{C}$ (see Section 1.3).

A maximum thickness of 200 mm has been applied as part of the calculation process and should not be taken to imply that a particular steel sub-grade is available, or not, at or above a thickness of 200 mm.

Table 3.1 BS EN 1993-1-10 Limiting thicknesses for quasi-static structures

Steel Grade	Sub-Grade	Charpy energy CVN		Reference temperature T_{Ed} (°C)																				
		at T (°C)	J_{min}	$\sigma_{Ed} = 0.75 f_y(t)$							$\sigma_{Ed} = 0.5 f_y(t)$							$\sigma_{Ed} = 0.25 f_y(t)$						
				10	0	–10	–20	–30	–40	–50	10	0	–10	–20	–3	–40	–50	10	0	–10	–20	–30	–40	–50
S275	JR	20	27	200	200	200	133	91	64	47	200	200	200	200	200	170	121	200	200	200	200	200	200	200
	J0	0	27	200	200	200	200	200	133	91	200	200	200	200	200	200	200	200	200	200	200	200	200	200
	J2	–20	27	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
	M, N	–20	40	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
	ML, NL	–50	27	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
S355	JR	20	27	200	177	114	77	54	40	30	200	200	200	200	147	104	76	200	200	200	200	200	200	200
	J0	0	27	200	200	200	177	114	77	54	200	200	200	200	200	200	147	200	200	200	200	200	200	200
	J2	–20	27	200	200	200	200	200	177	114	200	200	200	200	200	200	200	200	200	200	200	200	200	200
	K2, M, N	–20	40	200	200	200	200	200	200	177	200	200	200	200	200	200	200	200	200	200	200	200	200	200
	ML, NL	–50	27	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
S460	Q	–20	30	200	200	200	200	147	96	65	200	200	200	200	200	200	187	200	200	200	200	200	200	200
	M, N	–20	40	200	200	200	200	200	147	96	200	200	200	200	200	200	200	200	200	200	200	200	200	200
	QL	–40	30	200	200	200	200	200	200	147	200	200	200	200	200	200	200	200	200	200	200	200	200	200
	ML, NL	–50	27	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
	QL 1	–60	30	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200

UK NATIONAL ANNEX PROVISIONS

4.1 UK NA adjustments

The UK National Annex to BS EN 1993-1-10 makes a series of adjustments to the application of BS EN 1993-1-10, as described in the following sections. The adjustments are applied as temperature shifts when determining the reference temperature T_{Ed}.

The combined adjustment ΔT_R to the reference temperature is given by:

$$\Delta T_R = \Delta T_{RD} + \Delta T_{Rg} + \Delta T_{RT} + \Delta T_{R\sigma} + \Delta T_{Rs}$$

where:

ΔT_{RD}	is an adjustment for the detail type.
ΔT_{Rg}	is an adjustment for the gross stress concentration.
ΔT_{RT}	is an adjustment for the Charpy test temperature.
$\Delta T_{R\sigma}$	is an adjustment for the applied stress level.
ΔT_{Rs}	is an adjustment for the steel strength grade.

The UK National Annex should be consulted for the detail of the necessary adjustments, which are described in the following Sections.

4.1.1 Adjustment for detail type (NA.2.1.1.2 and Table NA.1)

Clause NA.2.1.1.2 identifies adjustments to be made depending on the type of detail. Details without welding are credited with a positive shift in the reference temperature; welded details may have a negative shift depending on the precise detail type. *Selection of steel sub-grade in accordance with the Eurocodes* (SCI guide ED007)[12] offers guidance on the classification of common details.

4.1.2 Adjustment for gross stress concentration (NA.2.1.1.3 and Table NA.2)

Where the detail in question is located in a site of gross stress concentration, the UK NA imposes a negative shift in the reference temperature.

4.1.3 Adjustment for Charpy test temperature (NA.2.1.1.4 and Table NA.3)

As the difference between the service temperature (taken as –5 °C for internal steelwork and –15 °C externally) and Charpy test temperature (see Table 1.1) increases, the UK NA imposes an increasing negative shift in the reference temperature.

4.1.4 Adjustment for applied stress (NA.2.1.1.5 and Table NA.4)

The UK NA requires that only the limiting thickness values for $\sigma_{\mathrm{Ed}} = 0.75 f_{\mathrm{y}}(t)$ be used. As the tensile stress ratio $\sigma_{\mathrm{Ed}} / f_{\mathrm{y}}(t)$ reduces, an increasing positive shift is applied to the reference temperature.

4.1.5 Adjustment for steel strength grade (NA.2.1.1.6 and Table NA.5)

If the steel grade is less than S355, a positive temperature shift is applied to the reference temperature. For steel grades greater than S355, a negative shift is applied.

4.2 Modified thickness limits for use with quasi-static structures and the UK NA

As explained in Section 4.1.4, the part of Table 2.1 of BS EN 1993-1-10 that is of interest are the limiting thickness values for $\sigma_{\mathrm{Ed}} = 0.75 f_{\mathrm{y}}(t)$. The other adjustments described in Section 4.1 mean that the range of reference temperatures needs to be increased and additional data for a wider range of reference temperatures is provided in Table 1 of PD 6695-1-10.

For quasi-static structures, a similar table can be developed, presented here as Table 4.1. The core of Table 4.1 is part of Table 3.1 presented in Section 3.

Table 4.1 is for a single stress ratio of $0.75 f_{\mathrm{y}}(t)$ with an extended range of reference temperatures (70 °C to –80 °C) and is to be used for quasi-static structures in the UK.

The limiting thicknesses in Table 4.1 have been determined assuming that $\Delta T_{\dot{\varepsilon}} = 0°\mathrm{C}$ and $\Delta T_{\varepsilon_{\mathrm{cf}}} = 0°\mathrm{C}$ (see Section 1.3).

Table 4.1 Extended range of reference temperatures and limiting thicknesses for quasi-static structures, for $\sigma_{Ed} = 0.75 f_y(t)$

Steel Grade	Sub-Grade	Charpy energy CVN		Reference temperature T_{Ed} (°C)															
				$\sigma_{Ed} = 0.75 f_y(t)$															
		at T (°C)	J_{min}	70	60	50	40	30	20	10	0	–10	–20	–30	–40	–50	–60	–70	–80
S275	JR	20	27	200	200	200	200	200	200	200	200	200	133	91	64	47	36	29	23
	J0	0	27	200	200	200	200	200	200	200	200	200	200	200	133	91	64	47	36
	J2	–20	27	200	200	200	200	200	200	200	200	200	200	200	200	200	133	91	64
	M, N	–20	40	200	200	200	200	200	200	200	200	200	200	200	200	200	200	133	91
	ML, NL	–50	27	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
S355	JR	20	27	200	200	200	200	200	200	200	177	114	77	54	40	30	23	18	15
	J0	0	27	200	200	200	200	200	200	200	200	200	177	114	77	54	40	30	23
	J2	–20	27	200	200	200	200	200	200	200	200	200	200	200	177	114	77	54	40
	K2, M, N	–20	40	200	200	200	200	200	200	200	200	200	200	200	200	177	114	77	54
	ML, NL	–50	27	200	200	200	200	200	200	200	200	200	200	200	200	200	200	177	114
S460	Q	–20	30	200	200	200	200	200	200	200	200	200	200	147	96	65	45	33	24
	M, N	–20	40	200	200	200	200	200	200	200	200	200	200	200	147	96	65	45	33
	QL	–40	30	200	200	200	200	200	200	200	200	200	200	200	200	147	96	65	45
	ML, NL	–50	27	200	200	200	200	200	200	200	200	200	200	200	200	200	147	96	65
	QL 1	–60	30	200	200	200	200	200	200	200	200	200	200	200	200	200	200	147	96

IMPLEMENTATION OF THE UK NA PROVISIONS FOR QUASI-STATIC STRUCTURES

For structures subject to fatigue, the provisions of the UK National Annex are implemented and presented in PD 6695-1-10. Within the PD, Table 2 covers internal steelwork in buildings, Table 3 covers external steelwork in buildings and Table 4 covers external steelwork in bridges.

Directly equivalent tables, presented in the format given in PD 6695-1-10, can be developed for quasi-static structures. Table 5.1 (internal steelwork) and Table 5.2 (external steelwork) provide limiting thicknesses for quasi-static building structures.

In both Table 5.1 and Table 5.2, the adjustment according to stress concentration factor, $\Delta T_{\mathrm{Rg}} = 0°\mathrm{C}$ (see section 4.1.2). In both tables, $\Delta T_{\dot{\varepsilon}} = 0°\mathrm{C}$ and $\Delta T_{\varepsilon_{\mathrm{cf}}} = 0°\mathrm{C}$ (see Section 1.3).

Examples of how these thicknesses are derived are given in Appendix A.3.

Table 5.1 Maximum thicknesses for internal steelwork in quasi-static structures for T_{md} = -5°C

Detail type Description		Tensile stress level $\sigma_{Ed}/f_y(t)$									
Plain material		≤ 0	0.15	0.3	≥ 0.5						
Bolted			≤ 0	0.15	0.3	≥ 0.5					
Welded – moderate					≤ 0	0.15	0.3	≥ 0.5			
Welded – severe							≤ 0	0.15	0.3	≥ 0.5	
Welded – very severe								≤ 0	0.15	0.3	≥ 0.5
Steel Grade	**Sub-Grade**	**Maximum thickness (mm)**									
		Comb. 1	**Comb. 2**	**Comb. 3**	**Comb. 4**	**Comb. 5**	**Comb. 6**	**Comb. 7**	**Comb. 8**	**Comb. 9**	**Comb. 10**
S275	JR	200	200	200	200	200	200	200	166.5	112	77.5
	J0	200	200	200	200	200	200	200	200	200	200
	J2	200	200	200	200	200	200	200	200	200	200
	M, N	200	200	200	200	200	200	200	200	200	200
	ML, NL	200	200	200	200	200	200	200	200	200	200
S355	JR	200	200	200	200	188.5	145.5	95.5	65.5	47	35
	J0	200	200	200	200	200	200	200	188.5	145.5	95.5
	J2	200	200	200	200	200	200	200	200	200	188.5
	K2, M, N	200	200	200	200	200	200	200	200	200	200
	ML, NL	200	200	200	200	200	200	200	200	200	200
S460	Q	200	200	200	200	200	200	200	173.5	121.5	80.5
	M, N	200	200	200	200	200	200	200	200	173.5	121.5
	QL	200	200	200	200	200	200	200	200	200	173.5
	ML, NL	200	200	200	200	200	200	200	200	200	200
	QL 1	200	200	200	200	200	200	200	200	200	200

Table 5.2 Maximum thicknesses for external steelwork in quasi-static structures for T_{md} = -15°C

Detail type Description		Tensile stress level $\sigma_{Ed}/f_y(t)$									
Plain material		≤ 0	0.15	0.3	≥ 0.5						
Bolted			≤ 0	0.15	0.3	≥ 0.5					
Welded – moderate					≤ 0	0.15	0.3	≥ 0.5			
Welded – severe							≤ 0	0.15	0.3	≥ 0.5	
Welded – very severe								≤ 0	0.15	0.3	≥ 0.5
Steel Grade	**Sub-Grade**	**Maximum thickness (mm)**									
		Comb. 1	**Comb. 2**	**Comb. 3**	**Comb. 4**	**Comb. 5**	**Comb. 6**	**Comb. 7**	**Comb. 8**	**Comb. 9**	**Comb. 10**
S275	JR	200	200	200	200	166.5	112	77.5	55.5	41.5	32.5
	J0	200	200	200	200	200	200	200	200	200	166.5
	J2	200	200	200	200	200	200	200	200	200	200
	M, N	200	200	200	200	200	200	200	200	200	200
	ML, NL	200	200	200	200	200	200	200	200	200	200
S355	JR	200	188.5	145.5	95.5	65.5	47	35	26.5	20.5	16.5
	J0	200	200	200	200	200	200	188.5	145.5	95.5	65.5
	J2	200	200	200	200	200	200	200	200	188.5	145.5
	K2, M, N	200	200	200	200	200	200	200	200	200	188.5
	ML, NL	200	200	200	200	200	200	200	200	200	200
S460	Q	200	200	200	200	200	200	173.5	121.5	80.5	55
	M, N	200	200	200	200	200	200	200	173.5	121.5	80.5
	QL	200	200	200	200	200	200	200	200	173.5	121.5
	ML, NL	200	200	200	200	200	200	200	200	200	173.5
	QL 1	200	200	200	200	200	200	200	200	200	200

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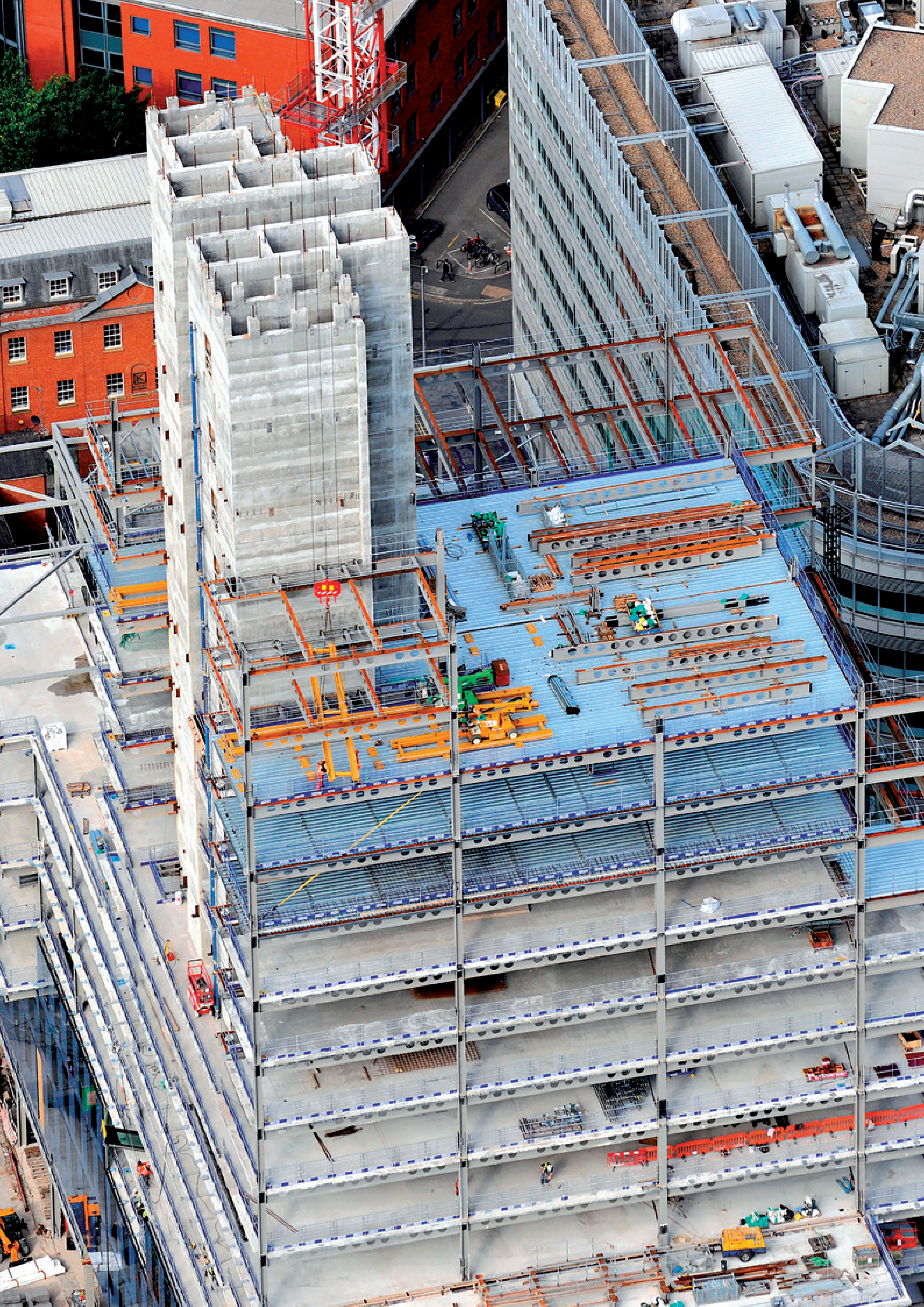

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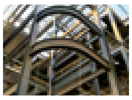
Cover Macro of a vee butt weld.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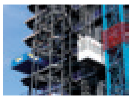
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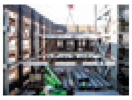
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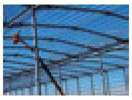
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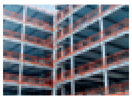
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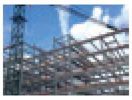
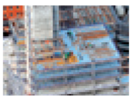

22 The Porter Building, Slough.


26 The Range distribution centre, Avonmouth.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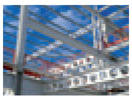
30 Warwick Quadrant, Redhill, Surrey.


32 Moberley Leisure Centre and Prime Place, Kensal Rise, London.

APPENDIX A NUMERICAL EXAMPLES

A.1 Example from BS EN 1993-1-10, for an element subject to fatigue

The form of the detail to be assessed is shown in Figure A.1. As explained in Section 2.1, the key dimension is the plate thickness, as all other dimensions are related to this basic variable.

The material to be assessed is S355 J0, and the plate is 24 mm thick.

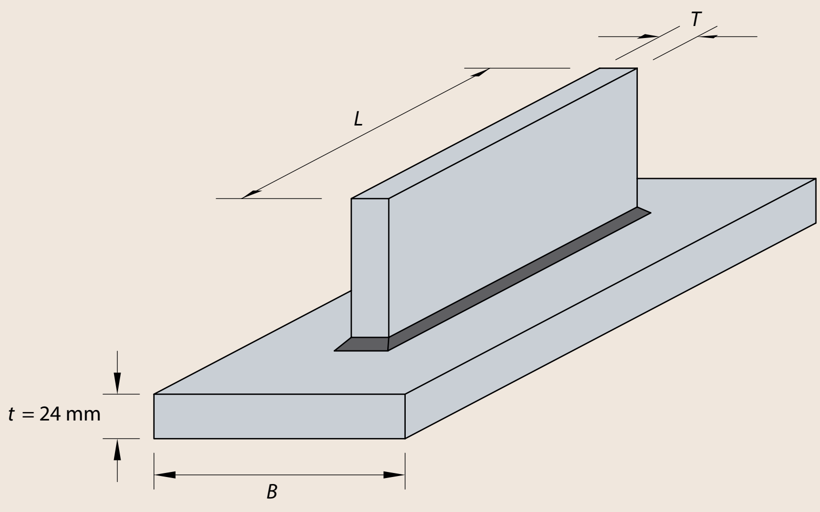

Figure A.1
Assessed detail

Each element of the calculation is illustrated below. For each part of the process, a cross reference to the background document is provided, so that the background document may be consulted for further details.

Basic dimensions (Section 2.2.4.3)

Thickness,	t	$= 24$ mm	
Attachment length,	L	$= 8.2t$	$= 196.8$ mm
Breadth,	B	$= 7.5t$	$= 180$ mm
Attachment thickness,	T	$= 0.15t$	$= 3.6$ mm
Angle of fillet weld,	Θ	$= 45°$	

Initial crack dimensions (Section 2.2.7.2)

Initial crack depth, $a_0 = 0.5\ln\left(\frac{t}{1}\right) = 1.59$ mm

Half crack width, $c_0 = a_0/0.4 = 3.97$ mm

Design crack dimensions (Figure 2-53)

Design crack depth, $a_d = 0.000002t^3 + 0.0006t^2 + 0.1341t + 0.6349$
$= 4.23$ mm

Half design crack width $c_d = a_d/0.4 = 10.58$ mm

Stress intensity correction factor, Y (Table 2-3)

Intermediate values:

$$M_1 = 1.13 - 0.09\left(\frac{a_d}{c_d}\right) = 1.094$$

$$M_2 = -0.54 + \frac{0.89}{0.2 + \frac{a_d}{c_d}} = 0.944$$

$$M_3 = 0.5 - \frac{1}{0.65 + \frac{a_d}{c_d}} + 14\left(1 - \frac{a_d}{c_d}\right)^{24} = -0.452$$

$$\varphi = 0.5\pi = 1.571$$

$$g = 1 + \left[0.1 + 0.35\left(\frac{a_d}{t}\right)^2\right](1 - \sin\varphi)^2 = 1.000$$

$$f_\varphi = \left[\left(\frac{a_d}{c_d}\right)^2 \cos^2\varphi + \sin^2\varphi\right]^{1/4} = 1.000$$

$$f_w = \left[\frac{1}{\cos\left(\frac{\pi c_d}{B}\sqrt{\frac{a_d}{t}}\right)}\right]^{1/2} = 1.001$$

$$F_s = \left[M_1 + M_2\left(\frac{a_d}{t}\right)^2 + M_3\left(\frac{a_d}{t}\right)^4\right] g f_\varphi f_w = 1.125$$

$$Q = 1 + 1.464\left(\frac{a_d}{c_d}\right)^{1.65} = 1.323$$

Stress intensity correction factor, $Y = \frac{F_s}{\sqrt{Q}} = 0.978$

Stress intensity correction factor, M_k (Table 2-4)

Intermediate values:

$$C = 0.9089 - 0.2357\left(\frac{T}{t}\right) + 0.0249\left(\frac{L}{t}\right) - 0.00038\left(\frac{L}{t}\right)^2 + 0.0186\left(\frac{B}{t}\right) - 0.1414\frac{\Theta}{45°}$$
$$= 1.050$$

$$k = -0.02285 + 0.0167\left(\frac{T}{t}\right) - 0.3863\left(\frac{\Theta}{45°}\right) + 0.1230\left(\frac{\Theta}{45°}\right)^2 = -0.284$$

Stress intensity correction factor, $M_k = C\left(\frac{a_d}{t}\right)^k$ but ≥ 1 $= 1.719$

Plasticity correction factor, k_{R6} (Table 2-5)

Applied stress = stress ratio $\times f_y(t) + 100$

In this example, stress ratio = 0.75

$f_y(t) = 355 - 0.25 \times 24 = 349$ N/mm^2

Applied stress = $0.75 \times 349 + 100 = 361.8$ N/mm^2

Intermediate values:

$$\sigma_{gy} = f_y(t)\left(1 - \frac{\pi 2.5 a_d^2}{2t(5a_d + t)}\right) = 326 \text{ N/mm}^2$$

$$L_r = \frac{\sigma_{Ed}}{\sigma_{gy}} = 0.802$$

Plasticity correction factor, $k_{R6} = \dfrac{1}{\sqrt{1 + 0.5L_r^2}} = 0.870$

Residual stress factor, ρ (Table 2-6)

Intermediate value $\psi = \dfrac{\sigma_s L_r}{\sigma_P}$

In this example, the applied stress, $\sigma_P = 0.75 f_y(t) = 261.8$ N/mm^2

The residual stress, $\sigma_s = 100$ N/mm^2

$$\psi = \frac{\sigma_s L_r}{\sigma_P} = 0.306$$

Because $\psi < 5.2$

then $\rho_1 = 0.1\psi^{0.714} - 0.007\psi^2 + 0.00003\psi^5 = 0.042$

Because $0.8 \leq L_r \leq 1.05$

then $\rho = 4\rho_1 (1.05 - L_r) = 0.042$

Stress intensity, $K_{appl,d}$ (Table 2-12)

Stress intensity $K_{appl,d} = \dfrac{\sigma_{Ed}\sqrt{\pi a_d}\, Y M_k}{k_{R6} - \rho} = 84.6$ (N/mm$^2\sqrt{\text{m}}$)

Design temperature, T_{Ed} (Figure 2-57)

$$T_{Ed} = \left[T_{27J} - 18°\text{C}\right] + 52\ln\left[\frac{\left(k_{appl,d} - 20\right)\left(5a_d / 25\right)^{0.25} - 10}{70}\right] + \Delta T_R = -40.5°\text{C}$$

where $T_{27J} = 0°$C for J0 material and $\Delta T_R = -7°$C

Although this example starts with a thickness and calculates the critical temperature, the tables present the reversed relationship. Thus for:

- An applied stress level of $0.75f_y\,(t)$, and
- A reference temperature of −40 °C;

The limiting thickness for S355 J0 material is 24 mm. (Table 2.1 of BS EN 1993-1-10 presents the value as 20 mm).

A.2 Modified example for quasi-static structures

The form of the example is the same as the example shown in Figure A.1, but with a thickness of 77 mm.

The material to be assessed is S355 J0.

Each element of the calculation is illustrated below. For each part of the process, a cross reference to the background document (unless noted otherwise) is provided, so that the background document may be consulted for further details.

Basic dimensions (Section 2.2.4.3)

Thickness,	t	$= 77$ mm	
Attachment length,	L	$= 8.2t$	$= 631.4$ mm
Breadth,	B	$= 7.5t$	$= 577.5$ mm
Attachment thickness,	T	$= 0.15t$	$= 11.55$ mm
Angle of fillet weld,	Θ	$= 45°$	

Initial crack dimensions (Section 2.2.7.2)

Initial crack depth, $a_0 = 0.5\ln\left(\frac{t}{1}\right) = 2.17$ mm

Half crack width, $c_0 = {a_0}/{0.4} = 5.43$ mm

Design crack dimensions (Section 3.1.1 of this guide)

Design crack depth,
$$a_d = 3.6258 \times 10^{-11}\,t^5 - 2.2316 \times 10^{-8}\,t^4 + 5.3365 \times 10^{-6}\,t^3 + 6.3837 \times 10^{-4}\,t^2 + 0.045124\,t + 0.82483 = 2.26 \text{ mm}$$

Half design crack width, $c_d = {a_d}/{0.4} = 5.66$ mm

Stress intensity correction factor, *Y* (Table 2-3)

Intermediate values:

$$M_1 = 1.13 - 0.09\left(\frac{a_d}{c_d}\right) = 1.094$$

$$M_2 = -0.54 + \frac{0.89}{0.2 + \frac{a_d}{c_d}} = 0.943$$

$$M_3 = 0.5 - \frac{1}{0.65 + \frac{a_d}{c_d}} + 14\left(1 - \frac{a_d}{c_d}\right)^{24} = -0.452$$

$$\varphi = 0.5\pi = 1.571$$

$$g = 1 + \left[0.1 + 0.35\left(\frac{a_d}{t}\right)^2\right](1 - \sin\varphi)^2 = 1.000$$

$$f_\varphi = \left[\left(\frac{a_d}{c_d}\right)^2 \cos^2\varphi + \sin^2\varphi\right]^{1/4} = 1.000$$

$$f_w = \left[\frac{1}{\cos\left(\frac{\pi c_d}{B}\sqrt{\frac{a_d}{t}}\right)}\right]^{1/2} = 1.000$$

$$F_s = \left[M_1 + M_2\left(\frac{a_d}{t}\right)^2 + M_3\left(\frac{a_d}{t}\right)^4\right] g f_\varphi f_w = 1.095$$

$$Q = 1 + 1.464\left(\frac{a_d}{c_d}\right)^{1.65} = 1.323$$

Stress intensity correction factor, $Y = \frac{F_s}{\sqrt{Q}}$ $= 0.952$

Stress intensity correction factor, M_k (Table 2-4)

Intermediate values:

$$C = 0.9089 - 0.2357\left(\frac{T}{t}\right) + 0.0249\left(\frac{L}{t}\right) - 0.00038\left(\frac{L}{t}\right)^2 + 0.0186\left(\frac{B}{t}\right) - 0.1414\frac{\Theta}{45°}$$

$$= 1.050$$

$$k = -0.02285 + 0.0167\left(\frac{T}{t}\right) - 0.3863\left(\frac{\Theta}{45°}\right) + 0.1230\left(\frac{\Theta}{45°}\right)^2 = -0.284$$

Stress intensity correction factor, $M_k = C\left(\frac{a_d}{t}\right)^k$ but ≥ 1 $= 2.855$

Plasticity correction factor, k_{R6} (Table 2-5)

Applied stress = stress ratio × $f_y(t)$ + 100

In this example, stress ratio = 0.75

$f_y(t) = 355 - 0.25 \times 77$ $= 335.8$ N/mm^2

Applied stress = 0.75 × 335.8 + 100 $= 351.8$ N/mm^2

Intermediate values:

$$\sigma_{gy} = f_y(t)\left(1 - \frac{\pi 2.5 a_d^2}{2t(5a_d + t)}\right) = 334.8 \text{ N/mm}^2$$

$$L_r = \frac{\sigma_{Ed}}{\sigma_{gy}} = 0.752$$

Plasticity correction factor, $k_{R6} = \frac{1}{\sqrt{1+0.5L_r^2}} = 0.883$

Residual stress factor, ρ (Table 2-6)

Intermediate value $\psi = \frac{\sigma_s L_r}{\sigma_P}$

In this example, the applied stress, $\sigma_P = 0.75 f_y(t) = 251.8 \text{ N/mm}^2$

The residual stress, $\sigma_s = 100 \text{ N/mm}^2$

$$\psi = \frac{\sigma_s L_r}{\sigma_P} = 0.299$$

Because $\psi < 5.2$

then $\rho_1 = 0.1\psi^{0.714} - 0.007\psi^2 + 0.00003\psi^5 = 0.042$

Because $L_r \leq 0.8$

then $\rho = \rho_1 = 0.042$

Stress intensity, $K_{appl,d}$ (Table 2-12)

Stress intensity, $K_{appl,d} = \frac{\sigma_{Ed}\sqrt{\pi a_d}\, Y M_k}{k_{R6} - \rho} = 95.85 \left(\text{N/mm}^2\sqrt{\text{m}}\right)$

Design temperature, T_{Ed} (Figure 2-57)

$$T_{Ed} = \left[T_{27J} - 18°C\right] + 52\ln\left[\frac{\left(k_{appl,d} - 20\right)\left(5a_d / 25\right)^{0.25} - 10}{70}\right] + \Delta T_R = -40.2°C$$

where $T_{27J} = 0°C$ for J0 material and $\Delta T_R = -7°C$

Although this example starts with a thickness and calculates the critical temperature, the tables present the reversed relationship. Thus for:

- An applied stress level of $0.75 f_y(t)$, and
- A reference temperature of −40 °C;

The limiting thickness for S355 J0 material, for quasi-static structures is 77 mm. This value appears in Table 3.1 of this guide.

A.3 Application of the UK National Annex provisions applied to quasi-static structures

Example A.3.1

S355 J2 material, so $T_{27J} = -20°C$

Internal steelwork, so $T_{md} = -5°C$

Design stress level, $\sigma_{Ed} / f_y(t) = 0.5$

Detail is "welded – severe".

From Table NA.1, (and comparing with the Tables in PD 6695-1-10) the adjustment ΔT_{Rd} for a "welded-severe" detail is $\Delta T_{Rd} = -20°C$

From Table NA.3, the difference between the service temperature (–5 °C) and the test temperature (–20 °C) is 15 °C

Thus the adjustment $\Delta T_{RT} = 0°C$

From Table NA.4, because $\sigma_{Ed} = 0.5 f_y\ (t)$, the adjustment for applied stress, $\Delta T_{R\sigma} = 0°C$.

From Table NA.5, because the steel is S355, the adjustment according to steel grade, $\Delta T_{Rs} = 0°C$.

The reference temperature T_{Ed} is given by:

$$T_{Ed} = T_{md} + \Delta T_{Rd} + \Delta T_{RT} + \Delta T_{R\sigma} + \Delta T_{Rs}$$

$$T_{Ed} = -5 - 20 + 0 + 0 + 0 = -25°C$$

From Table 4.1 of this guide, the limiting thickness for this situation may be interpolated between 200 mm at –20 °C and 200 mm at –30 °C.

Thus the limiting thickness is 200 mm, as shown in Table 5.1 of this guide, under Combination 9.

Example A.3.2

S355 JR material, so $T_{27J} = 20°C$

Internal steelwork, so $T_{md} = -5°C$

Design stress level, $\sigma_{Ed} / f_y(t) = 0.3$

Detail is "welded – severe".

From Table NA.1, (and comparing with the Tables in PD 6695-1-10) the adjustment ΔT_{Rd} for a "welded-severe" detail is $\Delta T_{Rd} = -20°C$

From Table NA.3, the difference between the service temperature (–5 °C) and the test temperature (20 °C) is 25 °C

Thus the adjustment $\Delta T_{RT} = -10°C$

From Table NA.4, because $\sigma_{Ed} = 0.3 f_y\ (t)$, the adjustment for applied stress, $\Delta T_{R\sigma} = +10°C$.

From Table NA.5, because the steel is S355, the adjustment according to steel grade, $\Delta T_{Rs} = 0°C$.

The reference temperature T_{Ed} is given by:

$$T_{Ed} = T_{md} + \Delta T_{Rd} + \Delta T_{RT} + \Delta T_{R\sigma} + \Delta T_{Rs}$$

$$T_{Ed} = -5 - 20 - 10 + 10 + 0 = -25°C$$

From Table 4.1 of this guide, the limiting thickness for this situation may be interpolated between 77 mm at –20 °C and 54 mm at –30 °C.

Thus the limiting thickness is 65.5 mm, as shown in Table 5.1 of this guide, under Combination 8.

Example A.3.3

S460 M material, so $T_{40J} = -20°C$

External steelwork, so $T_{md} = -15°C$

Design stress level, $\sigma_{Ed} / f_y(t) = 0.3$

Detail is “welded – severe”.

From Table NA.1, (and comparing with the Tables in PD 6695-1-10) the adjustment ΔT_{Rd} for a “welded-severe” detail is $\Delta T_{Rd} = -20°C$

From Table NA.3, the difference between the service temperature (–15 °C) and the test temperature (–20 °C) is 5 °C

Thus the adjustment $\Delta T_{RT} = 0°C$

From Table NA.4, because $\sigma_{Ed} = 0.3 f_y\ (t)$, the adjustment for applied stress, $\Delta T_{R\sigma} = +10°C$.

From Table NA.5, because the steel is S460, the adjustment according to steel grade, $\Delta T_{Rs} = -10°C$.

The reference temperature T_{Ed} is given by:

$$T_{Ed} = T_{md} + \Delta T_{Rd} + \Delta T_{RT} + \Delta T_{R\sigma} + \Delta T_{Rs}$$

$$T_{Ed} = -15 - 20 + 0 + 10 - 10 = -35°C$$

From Table 4.1 of this guide, the limiting thickness for this situation may be interpolated between 200 mm at –30 °C and 147 mm at –40 °C.

Thus the limiting thickness is 173.5 mm, as shown in Table 5.2 of this guide, under Combination 8.

Example A.3.4

S355 JR material, so $T_{40J} = 20°C$

External steelwork, so $T_{md} = -15°C$

Design stress level, $\sigma_{Ed} / f_y(t) = 0.3$

Detail is “welded – moderate”.

From Table NA.1, (and comparing with the Tables in PD 6695-1-10) the adjustment ΔT_{Rd} for a “welded-moderate” detail is $\Delta T_{Rd} = 0°C$

From Table NA.3, the difference between the service temperature (–15 °C) and the test temperature (20 °C) is 35 °C

Thus the adjustment $\Delta T_{RT} = -30°C$

From Table NA.4, because $\sigma_{Ed} = 0.3f_y(t)$, the adjustment for applied stress, $\Delta T_{R\sigma} = +10°C$.

From Table NA.5, because the steel is S355, the adjustment according to steel grade, $\Delta T_{Rs} = 0°C$.

The reference temperature T_{Ed} is given by:

$$T_{Ed} = T_{md} + \Delta T_{Rd} + \Delta T_{RT} + \Delta T_{R\sigma} + \Delta T_{Rs}$$

$$T_{Ed} = -15 + 0 - 30 + 10 + 0 = -35°C$$

From Table 4.1 of this guide, the limiting thickness for this situation may be interpolated between 54 mm at -30°C and 40 mm at -40°C.

Thus the limiting thickness is 47 mm, as shown in Table 5.2 of this guide, under Combination 6.

BRITTLE FRACTURE: SELECTION OF STEEL SUB-GRADE TO BS EN 1993-1-10

In structures where fatigue is not a design consideration, BS EN 1993-1-10 notes that the tabulated limiting thicknesses can be conservative. This guide presents limiting thicknesses for internal and external steelwork in the UK when fatigue is not a design consideration. Apart from a revised assessment of crack growth, the Eurocode procedures to calculate the limiting thickness are followed precisely, including the full provisions of the UK National Annex.

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Produced by:

Steel Knowledge

The Steel Construction Institute
www.steel-sci.com

SCI Ref: P419

ISBN 978-1-85942-224-3

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