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Selection of steel sub-grade in accordance with the Eurocodes

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Issued (in electronic format only) by:
The Steel Construction Institute
Silwood Park
Ascot
Berkshire, SL5 7QN

01344 636525
www.steel-sci.org

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FOREWORD

This guide was prepared to offer guidance on the selection of steel sub-grade, in accordance with BS EN 1993-1-10, the associated UK National Annex and other non-contradictory complementary information.

Mr A S Malik of the SCI, Mr S Cardwell of Arup, Mr W Swann of Tata Steel and members of BCSA's Process and Technical Committee offered valuable advice during the preparation of the guide.

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SUMMARY

In some circumstances, steel can behave in a non-ductile manner – failure occurs suddenly without plastic deformation – and this is commonly referred to as brittle fracture. The risk of brittle fracture in steelwork is minimised by the specification of an appropriate steel quality or sub-grade. The risk depends on a number of contributory factors, including the thickness of the element, the temperature, the state of stress and the type of detail.

These factors, and others, are considered in BS EN 1993-1-10, where limiting (maximum) thicknesses of steel are presented for different steel sub-grades. The application of BS EN 1993-1-10 is not simple. A more convenient approach, especially for buildings, is presented in PD 6695-1-10, where tables of limiting steel thicknesses are presented for different steel sub-grades, for building steelwork in internal and exposed environments.

This document discusses the use of PD 6695-1-10 to select a suitable steel quality (sub-grade) to ensure adequate resistance to brittle fracture and illustrates the process by reference to typical details and design situations for buildings.

In addition to the typical details, this guide also contains three worked examples that demonstrate the full procedure when selecting a steel sub-grade.

1 INTRODUCTION

1.1 Brittle Fracture

Structural steel is generally perceived as a ductile material; it will undergo considerable plastic strain under load before failure eventually occurs. This property is very useful, accommodating distribution of force in a structure and undergoing considerable visible deformation before any failure. However, in some specific circumstances, steel can behave in a non-ductile, brittle manner, with sudden failure; if this is likely, steel with a higher resistance to brittle fracture (a greater toughness) must be specified.

The nature of steel material is that it always contains some imperfections, albeit of very small size, and residual stresses due to the manufacturing processes. The cutting or welding of the material introduces further imperfections. When subject to tensile stress, these imperfections (generally termed flaws in fracture mechanics) tend to open. If the steel is insufficiently tough, the ‘crack’ propagates rapidly, without plastic deformation, and failure results. This is called ‘brittle fracture’, and is of particular concern because of the sudden nature of failure.

Although there have been instances of brittle fracture in bridges, brittle fracture in buildings is almost unknown in the UK, possibly because most buildings do not experience the extreme cold temperatures to which bridges may be exposed. Nevertheless, brittle fracture is not exclusively an extreme temperature phenomenon – it has occurred at ‘normal’ temperatures. Thick elements are more at risk than thin elements: when designers resort to larger and thicker members, reducing the risk of brittle fracture becomes a key consideration in material selection.

Selection of steel quality (sub-grade) for material toughness is covered by EN 1993-1-10[1], its UK NA[2] and PD 6695-1-10[3].

1.2 Risk factors in brittle fracture

Since brittle fracture of an individual component depends on factors that cannot be precisely known – actual material toughness, actual flaw size, actual residual stresses local to the flaw – design against brittle fracture must be based on achieving a certain level of reliability (a defined probability of failure), based on calibrations for the various factors that influence the likelihood of brittle fracture. The principal factors are discussed below.

Material temperature

Temperature affects the stress-strain behaviour of steel material. At normal (room) temperature, steel has the familiar tensile behaviour of elastic behaviour up to a ‘yield stress’, followed by a ‘plateau’ of increasing strain with insignificant change in stress, followed by a modest increase in stress to a maximum value and finally a slight decrease before fracture. At low temperatures, fracture occurs before the elastic behaviour reaches the normal temperature yield stress; there is no plasticity and failure is sudden or ‘brittle’. The difference in behaviour is expressed diagrammatically in Figure 1.1.

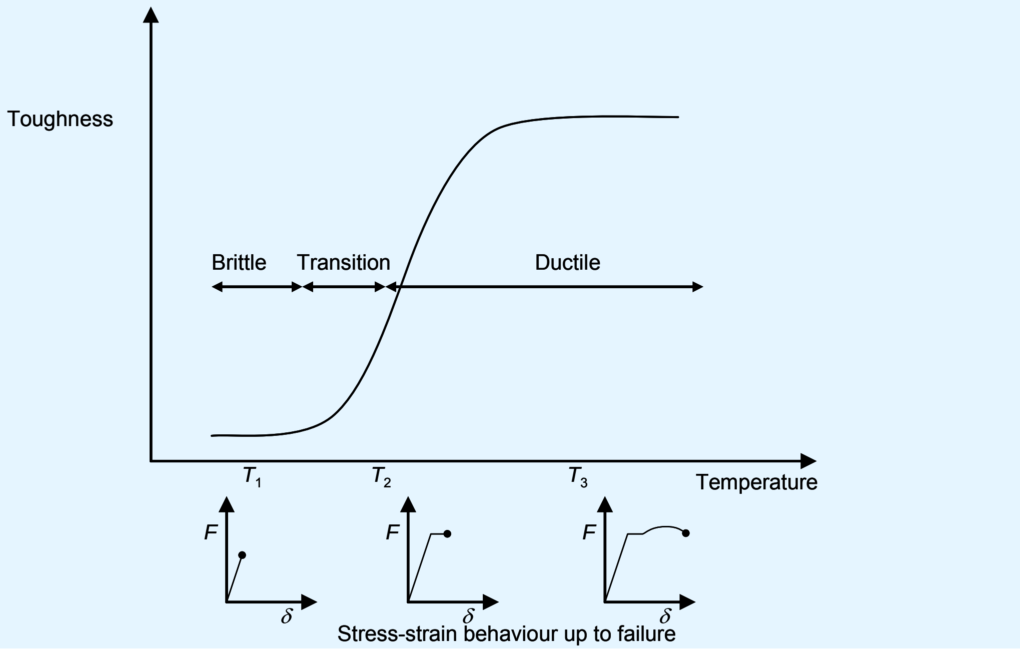


Figure 1.1 Variation of toughness with temperature

There is no sudden step between brittle behaviour and ductile behaviour; the change from one behaviour to another takes place over a temperature range known as the transition range. A lower transition range indicates a ‘tougher’ material.

State of stress

High tensile stresses increase the risk of brittle fracture; elements entirely in permanent compression are at reduced risk. Since fracture originates from the combined effect of residual and applied stress, residual stresses are important in addition to any applied stress. Local tensile stresses due to welding may be as high as yield stress. High residual stress can mean that brittle fracture is a risk even at normal temperatures.

Material thickness

In steel material, the toughness generally decreases toward the middle of thick material. Additionally, the notional flaw size that needs to be allowed for in design rules depends on thickness. The consequence is that thicker material needs to have a greater toughness for the same level of reliability against brittle fracture.

Local details

Local details influence both the initial flaw size that needs to be considered and the local stress level at the detail. Generally, details that would have a lower fatigue life are also more susceptible to brittle fracture; welded details are more susceptible that bolted details, which in turn are more susceptible than material that has only been cut. The susceptibility is also increased by the effect of stress concentration, such as at sharp corners or when there is a ‘hard point’ at the connection of one member to another.

Cold forming

If material is cold formed (curved, rolled or pressed into different cross sections or member shapes), the material is taken beyond the yield stress as part of the forming process. At high strain levels, this reduces the local plastic strain capacity between yield and fracture, thus greatly increasing the susceptibility to brittle fracture.

Impact

At high strain rates, the susceptibility to brittle fracture increases. For parts subject to strain rates higher than the value of 4×10^{-4}/sec assumed in 'static' design, an allowance must be made for this effect. Although high strain rates are uncommon in steel buildings, there are some elements which might be subject to high strain rates due to impact etc.

Reference temperature

All the above factors can be brought together in a so-called 'reference temperature', which is the lowest temperature of the material plus adjustments (temperature shifts) to account for all the other factors that affect susceptibility. It must be emphasised that the reference temperature is not the lowest temperature of the steel, although in some cases, if the net adjustment is zero, the value will be the same. The reference temperature, determined for the particular design situation, is used explicitly in Table 2.1 of BS EN 1993-1-10. Adjustments for the various factors are given in the UK NA but PD 6695-1-10 deals with the adjustments in a different manner and does not explicitly use the reference temperature (see Section 2.2 below).

1.3 Specification of toughness

A convenient measure of the toughness of steel material is given by the Charpy V-notch impact test (hence the terms 'notch toughness' and 'Charpy value' commonly used). This test measures the impact energy (in Joules) required to break a small, notched specimen by a single impact blow from a pendulum, at a specified temperature. The product standards specify the required minimum impact energy value and test temperature for different sub-grades.

The CEN product Standards for steel do not observe a universal designation system for the fracture toughness. The designations for the common standards are given below.

EN 10025-2, EN 10025-5, EN 10210-1 and EN 10219-1

In standards EN 10025-2[4] EN 10025-5[5], EN 10210-1[6] and EN 10219-1[7] there is a two character alphanumeric code which is appended to the strength grade to indicate the 'quality' (commonly referred to as sub-grade) in relation to toughness. The four codes and the specified toughness and test temperatures are:

- JR minimum 27J impact energy at 20°C (outside the scope of EN 10025-5)
- J0: minimum 27J impact energy at 0°C
- J2: minimum 27J impact energy at −20°C

- K2: minimum 40J impact energy at −20°C (equivalent to 27J at −30°C)

Thus a typical specification might be S355J2.

Note that the full specification for a steel product should include the number of the product standard and thus the full designation of the above typical specification would be:

Steel EN 10025-2 – S355J2

The inclusion of the product standard in the designation is particularly essential to distinguish between hot finished and cold formed hollow sections.

Note that weathering steel is only available as a flat product to EN 10025-5; no weathering steel sections are rolled to any of the above standards.

EN 10025-3, EN 10025-4; fine grain steels to EN 10210-1 and EN 10219-1

Steels to EN 10025-3[8] and EN 10025-4[9] and fine grain steels to EN 10210-1 and EN 10219-1 may be one of two sub-grades. One sub-grade carries no designation, the other is designated by a code. The required impact energy for each sub-grade is:

- (none) minimum 40J impact energy at −20°C (equivalent to 27J at −30°C)
- L: minimum 27J impact energy at −50°C

Note that rolled sections are not produced to EN 10025: Parts 3 or 4

EN 10025-6

Steels to EN 10025-6[10] (quenched and tempered steels) may be one of three sub-grades of toughness. One sub-grade carries no toughness designation; the lower-temperature two grades are designated by codes. The codes are:

- (none) minimum 30J impact energy at −20°C
- L: minimum 30J impact energy at −40°C
- L1: minimum 30J impact energy at −60°C

The 30J requirement is taken, for design purposes, to be the same as the 27J requirement for other product standards.

The range of possible toughness designations is summarized in Table 1.1.

Table 1.1 Steel toughness designations

Sub grade	Energy absorption (minimum)
JR	27J at 20°C
J0	27J at 0°C
J2	27J at −20°C
K2, M, N	40J at −20°C / 27J at −30°C
QL	30J at −40°C
ML, NL	27J at −50°C
QL1	30J at −60°C

↓ Increasing resistance to brittle fracture

Note that rolled sections are not produced to EN 10025-6.

1.4 Design situations

Brittle fracture is considered to be an 'accidental combination' of actions and the effects of actions appropriate to that combination are expressed in EN 1993-1-10[8], 2.2(4) as:

$$E_d = E\ \{\ A[T_{Ed}] \text{ “+” } \Sigma G_K \text{ “+” } \psi_1 Q_{K1} \text{ “+” } \Sigma\ \psi_{2,i} Q_{Ki}\ \}$$

where "+" means 'combined with'

This combination of actions should be read as the combined effect of:

- Temperature (which influences the toughness of the material and might lead to effects due to restraint of movement)
- The characteristic value of permanent actions, G_K
- ψ_1 × the characteristic value of the leading variable action, Q_{K1}
- ψ_2 × the characteristic value of any accompanying variable actions, Q_{Ki}.

The stress under this combination is calculated as an indicator of the susceptibility to brittle fracture.

1.5 Design basis in the Eurocodes

The design approach in EN 1993-1-10 is to verify that the thickness of a steel element does not exceed a maximum permissible thickness, appropriate to a steel grade and toughness, for a design reference temperature and design stress level.

The rules are set out in EN 1993-1-10, clause 2. The UK National Annex makes some changes to these rules (where it is permitted to do so) and makes reference to PD 6695-1-10, which is non-contradictory complementary information that is intended to simplify the application of the rules, as modified by the UK NA.

The rules for determining the design reference temperature are discussed in Section 2 of this document and guidance on the selection of sub-grade, for a given thickness, is given in Section 3.

2 DESIGN REFERENCE TEMPERATURE

2.1 BS EN 1993-1-10

The reference temperature is given by EN 1993-1-10, 2.2(5) as:

$$T_{\mathrm{Ed}} = T_{\mathrm{md}} + \Delta T_{\mathrm{r}} + \Delta T_{\sigma} + \Delta T_{\mathrm{R}} + \Delta T_{\dot{\varepsilon}} + \Delta T_{\varepsilon \mathrm{cf}}$$

where

T_{md} is the minimum ambient air temperature

ΔT_{r} is an adjustment for radiant loss

ΔT_{σ} is the adjustment for the stress and yield strength of the material, crack imperfection and member shape and dimensions

ΔT_{R} is a safety allowance, to reflect different reliability levels for different applications

$\Delta T_{\dot{\varepsilon}}$ is an adjustment for a strain rate other than the reference strain rate

$\Delta T_{\varepsilon \mathrm{cf}}$ is an adjustment to allow for the degree of cold forming.

Lowest steel temperature

$T_{\mathrm{md}} + \Delta T_{\mathrm{r}}$ considered together represent the minimum temperature of the steel part. For external building steelwork, $T_{\mathrm{md}} = T_{\mathrm{out}} = T_{\mathrm{min}}$, where T_{min} is given by the UK NA to BS EN 1993-1-10; no value is given for radiant loss, so $\Delta T_{\mathrm{r}} = 0$ may be assumed.

Adjustment ΔT_{σ}

Some components of this adjustment are effectively included in Table 2.1 of BS EN 1993-1-10 but other components, such as allowance for member shape and dimensions would require additional adjustment. No simple guidance is given as to how adjustment ΔT_{σ} can be evaluated, other than by reference to fracture mechanics. The UK NA makes adjustments for various components within ΔT_{R} (see Section 2.2 below) and consequently assumes $\Delta T_{\sigma} = 0$.

Adjustment ΔT_{R}

The adjustment is to be taken as 0°C, unless given otherwise in the National Annex. No guidance is offered on how an adjustment might be made.

Adjustment $\Delta T_{\dot{\varepsilon}}$

An expression is given for evaluating this adjustment but no guidance is given on appropriate values for strain rates. In the absence of impact loading, a value of 0°C should be used.

Adjustment $\Delta T_{\varepsilon \mathrm{cf}}$

An expression is given for evaluating this adjustment. For cold formed hollow sections, which have inside bend radii typically twice the wall thickness, the resulting strain is 20% and the temperature adjustment $\Delta T_{\varepsilon \mathrm{cf}}$ is then −60°C.

2.2 The UK National Annex to BS EN 1993-1-10

The UK National Annex to BS EN 1993-1-10 includes helpful clarification on the evaluation of reference temperature, in particular on dealing with a range of practical details. It also abandons the use of the Table 2.1 values for tensile stress levels of $0.5f_y$ and $0.25f_y$, using instead the values for $0.75f_y$ and including in the adjustment ΔT_R a component related to stress level.

The UK NA uses the same expression for reference temperature but expands the definition of ΔT_R as follows:

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

where

ΔT_{RD} is an adjustment for the detail type	(UK NA.2.1.1.2).
ΔT_{Rg} is an adjustment for gross stress concentrations	(UK NA.2.1.1.3).
ΔT_{RT} is an adjustment for the Charpy test temperature	(UK NA.2.1.1.4).
$\Delta T_{R\sigma}$ is an adjustment for the applied stress level	(UK NA.2.1.1.5).
ΔT_{Rs} is an adjustment for the strength grade	(UK NA.2.1.1.6).

When using this procedure, the adjustment ΔT_σ (in the expression for T_{Ed}) is taken as zero.

Adjustment ΔT_{RD}

This adjustment, given in NA.2.1.1.2, caters for a range of details from unwelded, as-rolled or machined surfaces to highly constrained welded details and the range of values is from +30°C to −30°C.

Adjustment ΔT_{Rg}

This adjustment, given in NA.2.1.1.3, caters for stress concentrations at corners or hard points of connections. The value ranges from 0°C (with no stress concentration) to −30°C for a stress concentration factor of 3 (peak stress 3 × nominal stress).

Adjustment ΔT_{RT}

This adjustment, given in NA.2.1.1.4, caters for the view in the UK that the Eurocode rules are not appropriate when the steel temperature is more than 20° below the Charpy test temperature. For bridges, it is not permitted to use steel more than 20° below the test temperature (thus J0 cannot be used for steel temperatures below −20°C. for example) whereas for buildings a ‘tapered’ adjustment value is provided between 20°C and 35°C below the test temperature.

Adjustment $\Delta T_{R\sigma}$

This adjustment, given in NA.2.1.1.5, caters for the actual stress level, from nominal compression to a value of $0.50f_y$ and facilitates the use of a single set of values tabulated for $0.75f_y$. It is considered in the UK that parts in compression should be verified for toughness (though the requirement is less onerous), since local residual tensile stresses might exceed the applied compressive stress and thus the part would still be at risk of brittle fracture.

Adjustment ΔT_{Rs}

This adjustment, given in NA.2.1.1.5, provides an additional adjustment depending on the grade of steel, effectively indicating that Table 2.1 of BS EN 1993-1-10 is appropriate for S355 but should be adjusted for other steel grades.

Use of the NA

For construction in the UK, EN 1993-1-10 should be used in conjunction with its UK NA. However, it was recognized that the use of the many clauses in the NA, in conjunction with only part of Table 2.1 in the EN, might prove confusing. Consequently, the NA refers to PD 6695-1-10 for more readily usable tables.

2.3 PD 6695-1-10

PD 6695-1-10 takes the information in the Eurocode and the UK National Annex, and provides a much simpler route to select the steel sub-grade. Tables of limiting thicknesses are presented for internal steelwork used in buildings (a minimum service temperature of −5°C), for external steelwork in buildings (a minimum service temperature of −15°C) and for bridges (a minimum service temperature of −20°C). The reference temperature T_{Ed} is not calculated and instead the various adjustments are made by choosing an appropriate column in the relevant Table, dependent on the value of adjustment required by the UK NA.

The Tables for buildings in PD 6695-1-10 are based on the values in EN 1993-1-10, Table 2.1, for $\sigma_{Ed} = 0.75 f_y$. The columns in the Tables make the adjustments according to the UK NA for ΔT_{RD}, ΔT_{RT}, $\Delta T_{R\sigma}$ and ΔT_{Rs} (see Section 2.2). The Tables are reproduced here in Appendix A and Appendix B.

Use of the PD tables

Having selected the appropriate Table for the lowest steel temperature, the principal parameters required to use these tables are the tensile stress level and the detail type. In some cases, other parameters also need to be considered (see below).

The tensile stress level is calculated as the ratio σ_{Ed}/f_y where σ_{Ed} is calculated for the combination of actions given in Section 1.4 above and f_y is the value of the yield strength for the relevant thickness. Although f_y may be calculated precisely, the Standard permits the use of the design strength taken from the product standard, which has steps at 16, 40, 63 mm etc. This simple approach is recommended.

The detail type is intended to correspond to the adjustment ΔT_{RD} as follows:

Detail type	Adjustment
Plain material	ΔT_{RD} = +30°C
Bolted	ΔT_{RD} = +20°C
Welded – moderate	ΔT_{RD} = + 0°C
Welded – severe	ΔT_{RD} = −20°C
Welded – very severe	ΔT_{RD} = −30°C

The PD contains no examples of details falling into the different types. Examples are given in Section 4 of this guide.

For the particular combination of detail type and tensile stress level σ_{Ed}/f_y, one of the columns in Table 2 (internal steelwork) or Table 3 (external steelwork) is applicable. In this column, a maximum thickness is obtained by looking up the limiting value for the particular steel grade and sub-grade.

This value may need to be adjusted if the simplifying assumptions noted at the foot of the Table are not valid. The adjustment is made by moving one or more columns to the left or right from the initial value, depending on the values of the parameters that do not meet the assumptions, as described below.

Column adjustments

If there is any radiation loss ΔT_r, move one column to the right for each −10°C of adjustment.

If the stress concentration factor is not unity, move one column to the right for each −10°C of adjustment ΔT_{Rg}

If the strain rate is high, calculate the adjustment according to EN 1993-1-10, 2.3.1(2) and move one column to the right for each −10°C of adjustment.

If the element has been cold formed, calculate the adjustment according to EN 1993-1-10, 2.3.1(2) and move one column to the right for each −10°C of adjustment.

Interpolation between columns is permitted.

3 SELECTION OF SUB-GRADE

3.1 Verification procedure

Having calculated the reference temperature, the maximum permitted thickness for various steel grades and sub-grades is given by EN 1993-1-10, Table 2.1, for the level of tensile stress (expressed as σ_{Ed}/f_y). Values are given for tensile stress levels between $0.25f_y$ and $0.75f_y$. Note that the Table only applies for a tensile stress of at least $0.25f_y$; no requirement is given for parts in compression (or at a tensile stress lower than $0.25f_y$).

The following steps should be followed to select an adequate steel sub-grade, dependent on element thickness, for steel in buildings:

(a) Classify the detail type (see Section 4)
(b) Calculate the tensile stress level (see below)
(c) Determine the appropriate column in Table 3 (internal steelwork) or Table 4 (external steelwork) of PD 6695-1-10 (Appendix A or Appendix B of this document), for the combination of detail type and stress level.
(d) Adjust the chosen column to allow for any stress concentration factor
(e) Adjust the chosen column for any cold forming
(f) Adjust the chosen column for any impact loading
(g) Select a steel sub-grade such that the limiting thickness is at least equal to that of the element of the member under consideration (see Section 3.6).

3.2 Tensile stress level

The tensile stress level σ_{Ed} is to be determined as a proportion of the nominal yield strength, which should be taken as the design strength.

The design strength varies with thickness – EN 1993-1-10 states that the strength may be determined from the product standard, or determined from the expression:

$$f_y(t) = f_{y,nom} - 0.25\frac{t}{t_0}$$

where

t is the thickness of the element

t_0 is a reference thickness, taken as 1 mm

It is recommended that the design strength be taken from the product standards, summarised in Table 3.1.

Table 3.1 Steel design strengths f_y

Section type	Steel grade	f_y (N/mm^2) for nominal thickness of element t (mm)			
		$t \leq 16$	$16 < t \leq 40$	$40 < t \leq 63$	$63 < t \leq 80$
Open sections	S275	275	265	255	245
	S355	355	345	335	325
Hollow sections	S355	355	345	335	325

As noted in Section 1.4 above, the design combination of effects is expressed as:

$$E_d = E\left\{A\left[T_{Ed}\right] + \sum G_k + \psi_1 Q_k + \sum \psi_2 Q_k\right\}$$

For determining stresses in the members, this means the combined effect of:

- Temperature change, plus
- The characteristic value of permanent actions, plus
- ψ_1 × the characteristic value of the leading variable action, plus
- ψ_2 × the characteristic value of any accompanying variable actions.

The stress due to temperature change (= $T_{Ed} - T_0$, where T_0 is the initial temperature) may be zero, as often, particularly in orthodox building structures, it is considered that any locked in stresses due to temperature change will be accommodated by slip in the bolts or similar mechanisms, or that the stress is small enough to be neglected.

Note that careful attention must be paid to the ψ factors, since both ψ_1 and ψ_2 factors are referenced; both depend on the type of action considered and should be obtained from the UK National Annex to BS EN 1990[11]. Values of ψ_1 and ψ_2 (taken from the UK NA) for common actions are presented in Table 3.2.

Table 3.2 Values of ψ_1 and ψ_2 for buildings

Action	ψ_1	ψ_2
Imposed loads in buildings, category (see BS EN 1991-1-1)		
Category A: domestic, residential areas	0.5	0.3
Category B: office areas	0.5	0.3
Category C: congregation areas	0.7	0.6
Category D: shopping areas	0.7	0.6
Category E: storage areas	0.9	0.8
Category H: roofs	0	0
Snow loads on buildings (see BS EN 1991-1-3)		
– for sites located at altitude H > 1 000 m a.s.l.	0.50	0.20
– for sites located at altitude H ≤ 1 000 m a.s.l.	0.20	0
Wind loads on buildings (see BS EN 1991-1-4)	0.2	0
Temperature (non-fire) in buildings (see BS EN 1991-1-5)	0.5	0

3.3 Stress concentration

Stress concentrations arise from connections to ‘hard spots’, where there is not an even stress distribution across the joint. In buildings, stress concentrations typically occur with welded connections to unstiffened flanges, or in welded connections to hollow sections. These are shown in Figure 3.1.

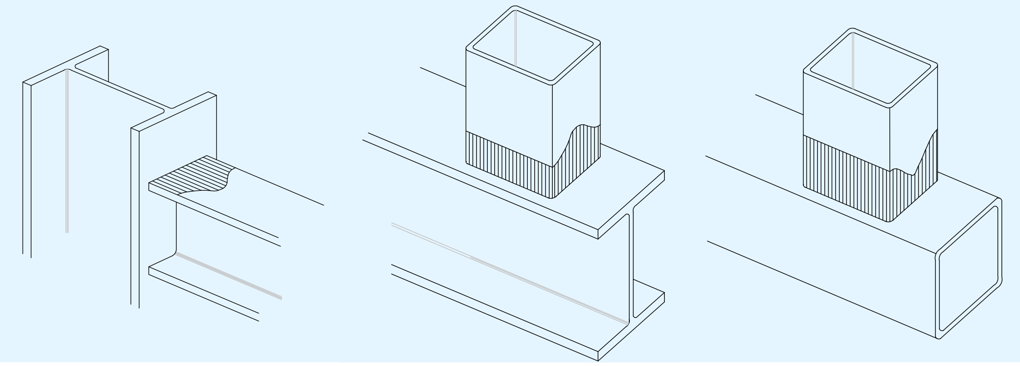


Figure 3.1 Stress concentrations in connections to unstiffened flanges and to hollow sections

In these situations, the stress concentration factor k_f can be calculated by dividing the actual width by the effective width of the connection, such that

$$k_{\mathrm{f}} = \frac{b_{\mathrm{p}}}{b_{\mathrm{eff}}}$$

Values of effective width b_{eff} for connections are given in EN 1993-1-8[12].

Stress concentrations also arise around large holes and at re-entrant corners. A simple conservative approach is to assume that in these situations, the stress factor is 3. More detailed guidance can be found in PD 6695-1-9 [13].

The stress concentration factor affects the adjustment factor ΔT_{Rg} as shown in Table 3.3.

Table 3.3 Values of ΔT_{Rg} for stress concentration factors

Stress concentration factor k_f	ΔT_{Rg} (°C)
1	0
1.5	−10
2	−20
3	−30

For every −10°C, move one column to the right in the appropriate Table.

3.4 Cold forming

The cold forming adjustment $\Delta T_{\varepsilon ef}$ depends on the strain ε_{ef} and is calculated as

$$\Delta T_{\varepsilon_{ef}} = -3 \times \varepsilon_{ef}$$

For every −10°C, move one column to the right in the appropriate Table.

Strain is calculated as the difference in length of the extreme fibres, compared to the length at the neutral axis of the element. If an element of *t* thickness is curved by cold forming to a radius of 3*t* at the neutral axis, the strain at the external fibres is given by:

$$\varepsilon_{ef} = \frac{0.5t}{3t} = \frac{0.5}{3} = 17\%$$

The corresponding cold forming adjustment $\Delta T_{\varepsilon ef}$ is therefore

$$\Delta T_{\varepsilon_{ef}} = -3 \times \varepsilon_{ef} \quad = -3 \times 17 = 51°C$$

This requires a movement of five columns to the right in the appropriate Table.

3.5 Impact

If the strain rate can be calculated, BS EN 1993-1-10 has an expression to relate the strain rate to the adjustment factor $\Delta T_{\dot{\varepsilon}}$. In most circumstances, the calculation of a strain rate will be difficult or impossible. A conservative solution is to assume $\Delta T_{\dot{\varepsilon}}$ = −30°C for parts subject to direct impact, such as due to vehicle collision. This adjustment requires moving three columns to the right in the Table.

3.6 Element thickness

The limiting thickness given by the assessment procedure is the thickness of the element and detail type that has been considered. For sections fabricated from plate, each flange and web plate are separate elements that may be assessed separately for their own thickness. It is common to conclude that different sub-grades are needed for the flanges and web.

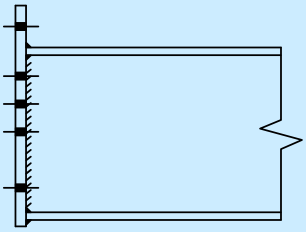
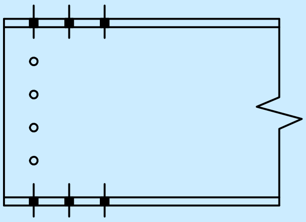
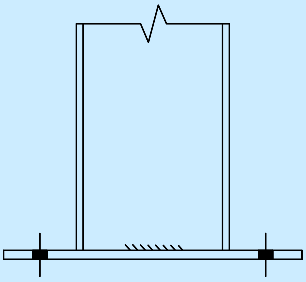
For a rolled section, the detail being considered (and which might require application of a stress concentration factor) may be on either the flange or the web, and the limiting thickness applies to whichever is being considered. Clearly, the section only conforms to a single sub-grade and this will be determined by the more onerous of the requirements for the web and the flange – in most cases this will be the flange (which is thicker than the web) although if the details on the web are particularly susceptible, then the web thickness might govern.

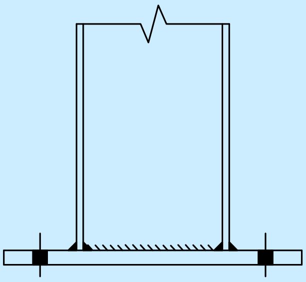
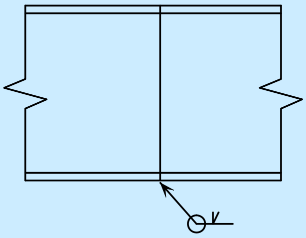
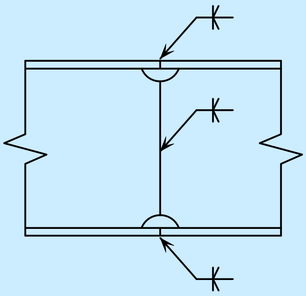
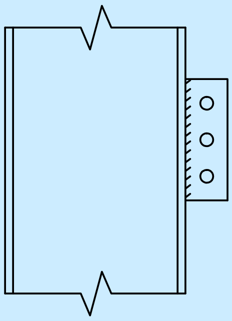
4 EXAMPLES OF DETAIL TYPES

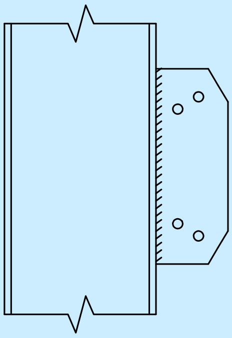
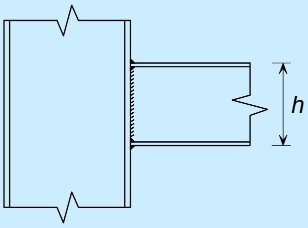
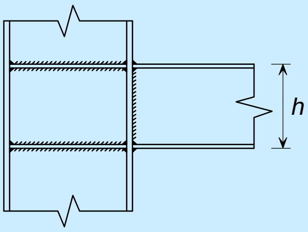
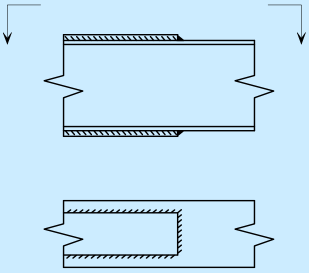
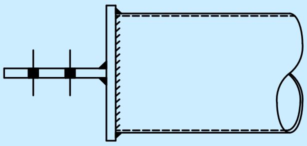
Table 4.1 indicates detail types for typical steelwork details found in buildings. The detail types have been derived from consideration of Table NA.1 (presented in Appendix C) and fatigue detail categories in EN 1993-1-9. Only three component/detail types are given in Table NA.1 and it can be difficult to use the table for some connection details commonly found in building steelwork. Consequently, the recommendations for some details in Table 4.1 have been determined by considering the fatigue category given in EN 1993-1-9. After establishing the relationship between the details given in Table NA.1 and their fatigue category, details not given in Table NA.1 can be categorised for brittle fracture based on their fatigue category.

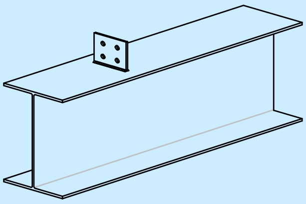
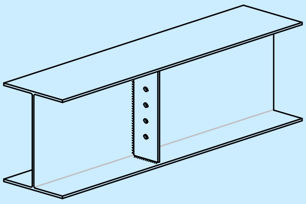
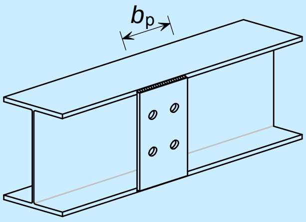
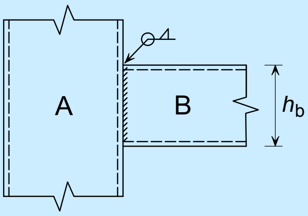
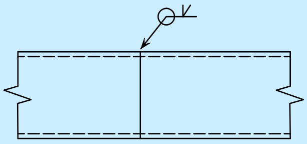
In Table 4.1, designers are warned when stress concentration is likely to be a concern.

Table 4.1 Typical steelwork details in buildings, and detail type

Typical detail	Description	Detail type
	Nominally pinned joint Partial depth end plate	**Beam** Welded – moderate **Plate** Welded - moderate
	Nominally pinned joint Full depth end plate	**Beam** Welded – moderate **Plate** Welded - moderate
	Moment-resisting joint	**Beam** Welded – severe **Plate** Welded – very severe
	Beam splice, bolted	**Beam** Bolted
	Nominally pinned base	**Column** Welded - moderate **Baseplate** Welded - moderate

Typical detail	Description	Detail type
	Fixed base	**Column** Welded – moderate **Baseplate** bolts in tension: Welded – very severe no bolt tension: Welded – severe
	Beam splice, butt welded	**Rolled section** Welded – very severe **Plate girder** Welded – severe
	Plate girder splice, butt welded with cope holes	**Flanges** Welded – moderate **Web** Welded – moderate Stress concentration factor in web due to cope holes
	Fin plate to column flange	**Column flange** Welded – severe **Plate** Welded – moderate

Typical detail	Description	Detail type
	Gusset plate to column flange	**Column flange** Welded – severe **Plate** Welded – severe
	Welded beam to column, unstiffened flanges	**Column** If *h* > 150: Welded – very severe If *h* < 150; Welded - moderate **Beam** Welded – severe Stress concentration factor applied for beam flange
	Welded beam to column, stiffened flanges	**Column** If *h* > 150: Welded – very severe If *h* < 150; Welded - moderate **Beam** Welded – severe
	Cover plate, welded across ends	**Beam flange** Welded – very severe **Plate** Welded – moderate
	Fitting welded to end of hollow section	**Hollow section** Welded – severe **Plate** Welded – very severe **Stem** Welded – severe

Typical detail	Description	Detail type
	Purlin cleat	**Beam** Welded - moderate **Cleat** Welded - moderate
	Web cleat or transverse stiffener	**Beam** Welded - moderate **Stiffener** Welded - moderate
	End plate welded across toes of beam	**Beam flange** $b_p < 150$; welded - moderate $b_p > 150$; welded - severe **Plate** Welded - moderate
	Hollow section joint, fully welded (Same if member A is a rolled section)	**Member A** If $h_b > 150$ mm: Welded – very severe If $h_b < 150$ mm: Welded – severe **Member B** Welded – moderate Stress concentration factor in member B due to unstiffened column flange
	Butt weld in hollow section (hot finished and cold formed)	**Hollow section** Welded - very severe

5 WORKED EXAMPLES

5.1 Example 1

This example covers the selection of an appropriate steel sub-grade for an exposed steel member in a canopy. The member is a 305 × 165 × 40 UKB, S275, shown in Figure 5.1.

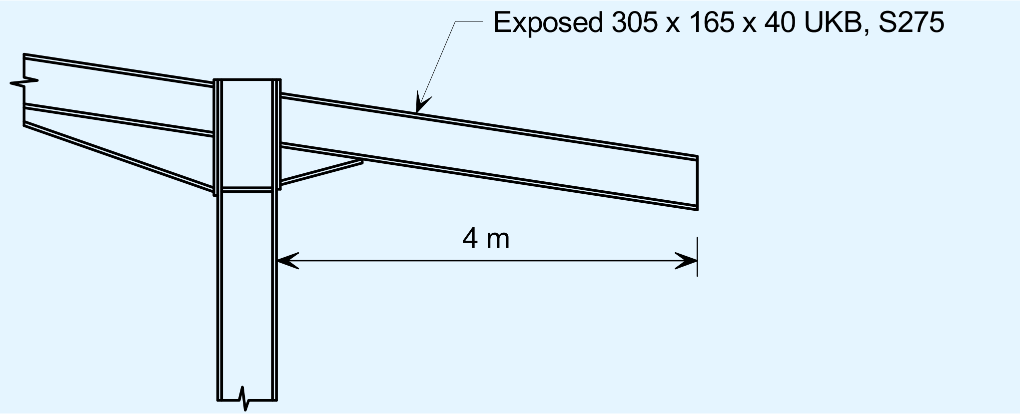


Figure 5.1 **Canopy cantilever beam**

The characteristic actions are shown in Table 5.1.

Table 5.1 **Characteristic actions**

Action	Characteristic value of action
Permanent	2.0 kN/m
Imposed roof load	4.8 kN/m
Snow load	3.6 kN/m (assumed more than 1000 m a.s.l)
Wind action (down)	3.2 kN/m
Wind action (uplift)	4.0 kN/m

The stresses are calculated from the value for the accidental design situation of the moment at the support of the cantilever, divided by the elastic modulus of the section. Thus, for the permanent actions, the stress is given by

$$\sigma_G \quad = \quad 2.0 \times 4 \times 2 \times 10^6/560 \times 10^3 = 28.6 \text{ N/mm}^2$$

Repeating this process for the other actions, the stresses are shown in Table 5.2.

Table 5.2 Design stresses for accidental design situation

Action	Stress
Permanent	28.6 N/mm^2
Imposed roof load	68.6 N/mm^2
Snow load	51.4 N/mm^2
Wind action (down)	45.7 N/mm^2
Wind action (uplift)	57.1 N/mm^2

A series of combinations of actions is to be considered, determining the design stress under each combination using the following expression:

$$E_{\mathrm{d}} = E\left\{A\left[T_{\mathrm{Ed}}\right] + \sum G_{\mathrm{k}} + \psi_1 Q_{\mathrm{k}} + \sum \psi_2 Q_{\mathrm{k}}\right\}$$

The stress due to temperature effects is zero.

From Table 3.2, values of ψ_1 and ψ_2 are:

For imposed roof loads; $\psi_1 = 0$; $\psi_2 = 0$

For snow loads; $\psi_1 = 0.5$; $\psi_2 = 0.2$

For wind actions; $\psi_1 = 0.2$; $\psi_2 = 0$

The combinations of actions to be considered are:

Permanent + imposed roof load

$\sigma_{\mathrm{Ed}} = 28.6 + 0 \times 68.6 = 28.6$ N/mm^2

Permanent + snow load

$\sigma_{\mathrm{Ed}} = 28.6 + 0.5 \times 51.4 = 54.3$ N/mm^2

Permanent + snow + wind (snow is the leading variable action)

$\sigma_{\mathrm{Ed}} = 28.6 + 0.5 \times 51.4 + 0 \times 45.7 = 54.3$ N/mm^2

Permanent + wind + snow (wind is the leading variable action)

$\sigma_{\mathrm{Ed}} = 28.6 + 0.2 \times 45.7 + 0.2 \times 51.4 = 48.0$ N/mm^2

Permanent + wind uplift

$\sigma_{\mathrm{Ed}} = 28.6 - 0.2 \times 57.1 = 17.1$ N/mm^2

From these combinations of actions, the most onerous design stress is 54.3 N/mm^2

Because the beam flange is 10.2 mm, which is less than 16 mm, according to Table 3.1, $f_{\mathrm{y}} = 275$ N/mm^2

Therefore, as a proportion of the nominal yield stress, the tensile stress is given by 54.3 / 275 = 0.2

From Table 4.1, the detail type is ‘welded – moderate’.

From Appendix B, for external steelwork in buildings, limiting thicknesses are provided for tensile stress levels of 0.15 and 0.3. Although interpolation is allowed, in this case, the conservative stress level of 0.3 will be selected.

The limiting thickness for S275 JR is 27.5 mm. As this is larger than the actual thickness of the thickest element of the member (the flange, at 10.2 mm) sub-grade JR is satisfactory.

The full specification for this steelwork is therefore BS EN 10025-2 - S275JR.

5.2 Example 2

This example covers the selection of an appropriate steel-subgrade for a typical nominally pinned baseplate for an internal column, as shown in Figure 5.2.

The baseplate is in S275 steel. The design load is predominantly due to the permanent actions and imposed floor loads.

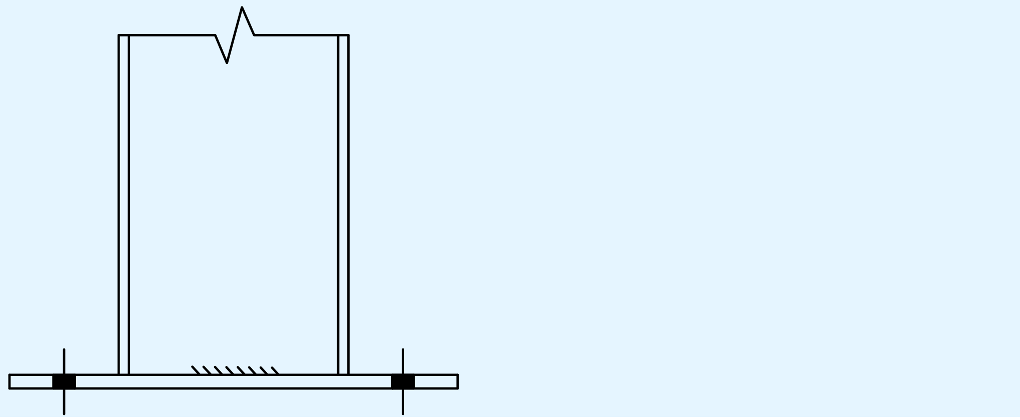


Figure 5.2 Nominally pinned baseplate

The baseplate thickness has been calculated according to BS EN 1993-1-8 clause 6.2.5. Although a thickness of only 10 mm is required by calculation, a thickness of 15 mm has been specified.

For the ULS fundamental combination, the stress in the baseplate is therefore

$$275 \times \frac{10}{15} = 183 \text{ N/mm}^2$$

In this example, it is assumed that the characteristic values of the permanent and variable actions are in the ratio 3.5:5.0.

Therefore, if the stress due to the characteristic value of the permanent actions is σ_g, and that due to the variable action is σ_q then:

$$1.35 \times \sigma_g + 1.5 \times \frac{5}{3.5} \times \sigma_g = 183$$

Therefore $\sigma_g = 52$ N/mm^2 and $\sigma_q = 75$ N/mm^2

From Table 4.1, the detail is 'welded – severe'

From Table 3.2, ψ_1 for category B office areas is 0.5

For the accidental design situation, $\sigma_{Ed} = 52 + 0.5 \times 75 = 90$ N/mm^2

Therefore, as a proportion of the nominal yield stress, the tensile stress is given by 90 / 275 = 0.33

From Appendix A, for internal steelwork in buildings, limiting thicknesses are provided for tensile stress levels of 0.3 and 0.5 and greater.

At a tensile stress level of 0.3, the limiting thickness of subgrade JR is 32.5 mm.

At a tensile stress level of 0.5, the limiting thickness of subgrade JR is 27.5 mm.

Therefore, even without interpolation, sub-grade JR is satisfactory.

The full specification for this steelwork is therefore BS EN 10025-2 - S275JR.

5.3 Example 3

This example covers the selection of an appropriate steel-subgrade when a hot-finished hollow section is welded to a UKC section, as shown in Figure 5.3.

The hollow section is acting as a cantilever, supporting predominantly permanent actions and snow loads on a roof. The steelwork is S355, and exposed.

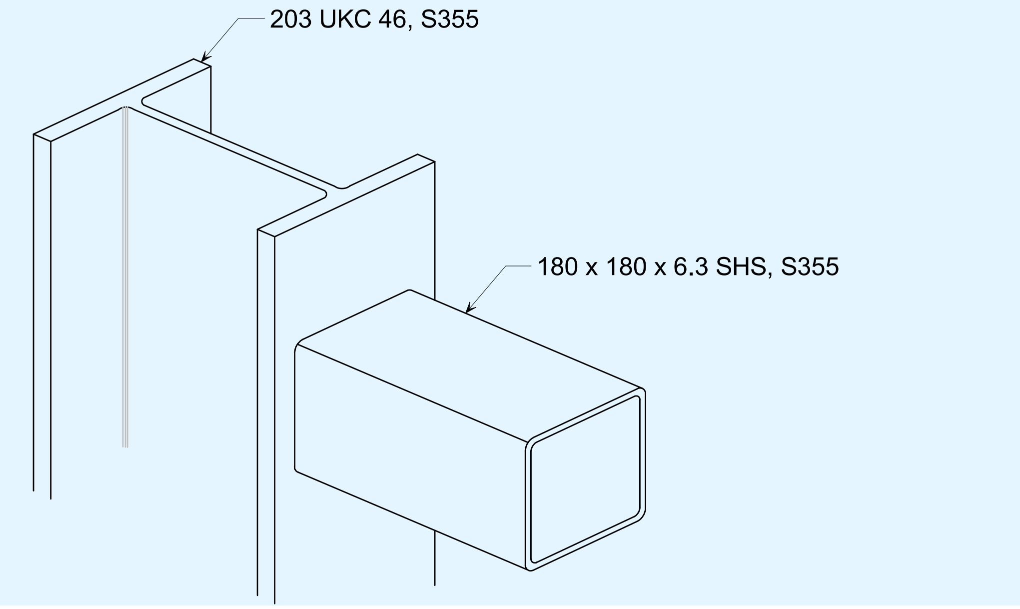


Figure 5.3 Hollow section welded to UKC

Hollow section

Based on BS EN 1993-1-8, clause 7.6.(8), the effective width b_e is given by:

$b_e = t_w + 2r + 7t_f$

From the Blue Book[14],

$t_w = 7.2$ mm; $r = 10.2$ mm; $t_f = 10$ mm

Then $b_e = 7.2 + 2 \times 10.2 + 7 \times 10 = 98$ mm

For the ULS fundamental combination, it is assumed that the stress across the effective breadth b_e is 355 N/mm^2

In this example, it is assumed that the characteristic values of the permanent and variable actions are in the ratio 0.2:0.8.

Therefore, if the stress due to the characteristic value of the permanent actions is σ_g, and that due to the variable action is σ_q then:

$$1.35 \times \sigma_g + 1.5 \times \frac{0.8}{0.2} \times \sigma_g = 355$$

Therefore $\sigma_g = 48$ N/mm^2 and $\sigma_q = 192$ N/mm^2

From Table 3.2, ψ_1 for the snow load on a roof is 0.5

For the accidental design situation, $\sigma_{Ed} = 48 + 0.5 \times 192 = 144$ N/mm^2

Because the stress concentration factor is being used to allow for the non-uniform stress pattern, the average stress is used to calculate the stress level.

The average stress = $144 \times \frac{98}{180}$ = 78 N/mm^2

Therefore, as a proportion of the nominal yield stress, the tensile stress is given by 78 / 355 = 0.22

From Table 4.1, for the hollow section, the detail is ‘welded – moderate’.

The stress concentration factor is given by Section 3.3 as:

$$k_f = \frac{b_p}{b_{eff}} = \frac{180}{98} = 1.8$$

From Table 3.3, taking $k_f = 2$, $\Delta T_{Rg} = -20°C$, which is equivalent to moving two columns to the right in the table of limiting thickness. Conservatively taking the column in Appendix B for a stress level of 0.3, and then moving two columns to the right to allow for the stress concentration factor, the limiting thickness for S355 JR is 10 mm.

Therefore, sub-grade JR is satisfactory. However, the standard strength and sub-grade produced by Tata Steel is S355 J2H. Other grades may be available, but it is advisable to check their availability

The full specification for this steelwork is therefore BS EN 10210-1 - S355J2H.

UKC section

In this example, it is assumed that the ULS stress in the column is 300 N/mm^2, and that the characteristic values of the permanent and variable actions are 0.25 kN/m^2 and 0.8 kN/m^2 respectively.

Therefore, if the stress due to the characteristic value of the permanent actions is σ_g, and that due to the variable action is σ_q then:

$$1.35 \times \sigma_g + 1.5 \times \frac{0.8}{0.25} \times \sigma_g = 300$$

Therefore $\sigma_g = 49$ N/mm^2 and $\sigma_q = 157$ N/mm^2

From Table 3.2, ψ_1 for the snow load on a roof is 0.5

Then $\sigma_{Ed} = 49 + 0.5 \times 157 = 128$ N/mm^2

Therefore, as a proportion of the nominal yield stress, the tensile stress is given by 128 / 355 = 0.36

From Table 4.1, for the UKC, the detail is ‘welded – very severe’, because the hollow section is greater than 150 mm.

The UKC flange thickness is 10 mm. Conservatively taking the column in Appendix B for a stress level of 0.5, the limiting thickness for S355 J0 is 17.5 mm.

Therefore, sub-grade J0 is satisfactory.

The full specification for this steelwork is therefore BS EN 10025-2 - S355JR.

Note that, even with interpolation, sub-grade JR would not have been adequate.

6 REFERENCES

1 BS EN 1993-1-10:2005. *Eurocode 3: Design of steel structures. Material thickness and through-thickness properties*. BSI.

2 NA to BS EN 1993-1-10:2005. *National Annex to Eurocode 3: Design of steel structures. Material thickness and through-thickness properties*. BSI.

3 PD 6695-1-10:2009. *Recommendations for the design of structures to BS EN 1993-1-10.* BSI.

4 BS EN 10025-2:2004 *Hot rolled products of structural steels. Technical delivery conditions for non-alloy structural steels*. BSI.

5 BS EN 10025-5:2004 *Hot rolled products of structural steels. Technical delivery conditions for structural steels with improved atmospheric corrosion resistance*. BSI.

6 BS EN 10210-1:2006 *Hot finished structural hollow sections of non-alloy and fine grain steels. Technical delivery requirements*. BSI.

7 BS EN 10219-1:2006 *Cold formed welded structural hollow sections of non-alloy and fine grain steels. Technical delivery requirements*. BSI.

8 BS EN 10025-3:2004 *Hot rolled products of structural steels. Technical delivery conditions for normalized/normalized rolled weldable fine grain structural steels*. BSI.

9 BS EN 10025-4:2004 *Hot rolled products of structural steels. Technical delivery conditions for thermomechanical rolled weldable fine grain structural steels*. BSI.

10 BS EN 10025-6:2004 *Hot rolled products of structural steels. Technical delivery conditions for flat products of high yield strength structural steels in the quenched and tempered condition*.

11 NA to BS EN 1990:2002+A1:2005 *UK National Annex for Eurocode. Basis of structural design.* BSI.

12 BS EN 1993-1-8:2005. *Eurocode 3: Design of steel structures. Design of joints*. BSI.

13 PD 6695-1-9:2008 *Recommendations for the design of structures to BS EN 1993-1-9*. BSI.

14 Steel Building Design: Design Data, In accordance with Eurocodes and the UK National Annexes (P363)
The Steel Construction Institute, 2009

15 National Structural Steelwork Specification for Building Construction, 5th Edition
The British Constructional Steelwork Association and The Steel Construction Institute, 2007

APPENDIX A. LIMITING THICKNESSES FOR STEEL IN INTERNAL ENVIRONMENTS (−5°C)

Table A.1 Internal environment (taken from UK NA to BS EN 1993-1-10, Table 3)

Detail type		**Tensile stress level, $\sigma_{Ed}/f_y(t)$**									
Description	**ΔT_{RD}**							*			
Plain material	$+30^{\circ}$	≤0	0.15	0.3	≥0.5						
Bolted	$+20^{\circ}$		≤0	0.15	0.3	≥0.5					
Welded - moderate	0°				≤0	0.15	0.3	≥0.5			
Welded - severe	-20°						≤0	0.15	0.3	≥0.5	
Welded - very severe	-30°							≤0	0.15	0.3	≥0.5
Steel grade	**Subgrade**	**Maximum thickness (mm) according to combination of stress level and detail type**									
S275	JR	122.5	102.5	85	70	60	50	40	32.5	27.5	22.5
	JO	192.5	172.5	147.5	122.5	102.5	85	70	60	50	40
	J2	200	200	192.5	172.5	147.5	122.5	102.5	85	70	60
	M, N	200	200	200	192.5	172.5	147.5	122.5	102.5	85	70
	ML, NL	200	200	200	200	200	192.5	172.5	147.5	122.5	102.5
S355	JR	82.5	67.5	55	45	37.5	30	22.5	17.5	15	12.5
	JO	142.5	120	100	82.5	67.5	55	45	37.5	30	22.5
	J2	190	167.5	142.5	120	100	82.5	67.5	55	45	37.5
	K2, M, N	200	190	167.5	142.5	120	100	82.5	67.5	55	45
	ML, NL	200	200	200	190	167.5	142.5	120	100	82.5	67.5

Notes:

This Table is based on the following conditions:

i) $\Delta T_{Rg} = 0$

ii) $\Delta T_{\dot{\varepsilon}} = 0$

If either of conditions i) or ii) are not complied with, an appropriate adjustment towards the right side of the table should be made

Use of NSSS Table 2.2

The values in the row labelled ‘Internal steelwork’ in the National Structural Steelwork Specification[15] (NSSS) Table 2.2 correspond to limiting values in the column noted * above.

The factors in the NSSS Table to adjust the limiting thickness for other situations are approximate values, corresponding to a shift of one or more columns to the left or right.

APPENDIX B. LIMITING THICKNESSES FOR STEEL IN EXTERNAL ENVIRONMENTS (−15°C)

Table B.1 External environment (taken from UK NA to BS EN 1993-1-10, Table 3)

Detail type		**Tensile stress level, $\sigma_{Ed}/f_y(t)$**									
Description	**ΔT_{RD}**							*			
Plain material	+30o	≤0	0.15	0.3	≥0.5						
Bolted	+20o		≤0	0.15	0.3	≥0.5					
Welded - moderate	0o				≤0	0.15	0.3	≥0.5			
Welded - severe	−20o						≤0	0.15	0.3	≥0.5	
Welded - very severe	−30o							≤0	0.15	0.3	≥0.5
Steel grade	**Subgrade**	**Maximum thickness (mm) according to combination of stress level and detail type**									
S275	JR	70	60	50	40	32.5	27.5	22.5	17.5	12.5	10
	JO	172.5	147.5	122.5	102.5	85	70	60	50	40	32.5
	J2	200	192.5	172.5	147.5	122.5	102.5	85	70	60	50
	M, N	200	200	192.5	172.5	147.5	122.5	102.5	85	70	60
	ML, NL	200	200	200	200	192.5	172.5	147.5	122.5	102.5	85
S355	JR	45	37.5	30	22.5	17.5	15	12.5	10	7.5	5
	JO	120	100	82.5	67.5	55	45	37.5	30	22.5	17.5
	J2	167.5	142.5	120	100	82.5	67.5	55	45	37.5	30
	K2, M, N	190	167.5	142.5	120	100	82.5	67.5	55	45	37.5
	ML, NL	200	200	190	167.5	142.5	120	100	82.5	67.5	55

Notes:

This Table is based on the following conditions:

i) $\Delta T_{Rg} = 0$

ii) $\Delta T_{\dot{\varepsilon}} = 0$

If either of conditions i) or ii) are not complied with, an appropriate adjustment towards the right side of the table should be made

Use of NSSS Table 2.2

The values in the row labelled ‘External steelwork’ in the National Structural Steelwork Specification[15] (NSSS) Table 2.2 correspond to limiting values in the column noted * above.

The factors in the NSSS Table to adjust the limiting thickness for other situations are approximate values, corresponding to a shift of one or more columns to the left or right.

APPENDIX C. RULES FOR DETERMINING DETAIL TYPE

Details which are not welded with as-rolled, ground or machined surfaces should be classed as ‘plain material’

Details which are not welded, with bolted joints or with flame cut edges should be classed as ‘bolted’

Generally, other details should be classed as ‘welded – moderate’ except for the details given in Table NA.1, reproduced below. However, as noted in Section 4, it can be difficult to reconcile some typical building connection details with the descriptions, in which case, guidance may be taken from the recommendations in Table 4.1.

Table C.1 Detail type for specific welded details (taken from Table NA.1)

Component or detail	Initiation site	Attachment dimensions A)		ΔT_{Rd}	Detail classification
		Length B) (mm)	Width C) (mm)	(°C)	
Welded attachment	Transverse weld toe	>150	<50	−20	Welded-severe
			>50	−30	Welded – very severe
Member fabricated from plates	Transverse butt weld D)	None	None	−20	Welded-severe
Rolled sections	Transverse butt weld D)	None	None	−30	Welded – very severe

A) Measured overall between weld toes on member concerned.

B) Measured in direction of tensile stress.

C) Measured transverse to direction of tensile stress.

D) Applies only to welds joining the full cross section, not those joining individual plates prior to sub-assembly.