3.1.3 Design strength for high strength steels

For high strength steels with a design strength greater than 460 N/mm^2 and not exceeding 690 N/mm^2 produced in accordance with the basic requirements in Annex D1.1, the design strength p_y may be taken as Y_s/1.0 but not greater than U_s/1.2, where Y_s and U_s are respectively the minimum yield strength (R_{eH}) and minimum tensile strength (R_m) specified in the relevant reference material standard or derived by the manufacturer using an acceptable Quality Assurance system. These materials typically obtain their strength through a quenching and tempering heat-treatment and there are additional restraints on fabrication and design, particularly with welding, because heat may affect the strength of the parent steel. Bolted connection should be considered for certain high strength steels when welding is not allowed. The Responsible Engineer shall justify each design on a case-by-case basis using justified parameters and formulae proposed by manufacturers and verified by himself. Correct welding procedure specifications are essential and shall be specified. When high strength steel is used in compression, it shall be limited to compact sections where local buckling of outstands will not occur.

The essentials of the basic requirements for high strength steels are as stated in Annex D1.1 except that the maximum carbon content shall not exceed 0.20% and the maximum sulphur and phosphorus contents shall not exceed 0.025%.

3.1.4 Uncertified steel

If Class 3 uncertified steel is used, it shall be free from surface imperfections and shall comply with all geometric tolerance specifications and shall be used only where the particular physical properties of the steel and its weldability will not affect the strength and serviceability of the structure. The design strength, p_y, shall be taken as 170 N/mm^2, subject to verification by testing as described in Annex D1.

The steel shall not be used in the primary structural elements of multi-storey buildings or in the primary structure of single storey buildings with long spans. Primary structural element is defined as main beams spanning directly onto columns, any beams over 6 m span, columns supporting a floor area of more than 25 m^2 or elements of lateral load resisting structural systems.

The steel shall only be used with elastic design methods for analysis and section capacity. The steel shall not be welded unless adequate tests on mechanical properties, chemical composition and hardness have demonstrated its suitability, see clause 3.1.2 and Annex D1.

3.1.5 Through thickness properties

The design strengths given in the standards refer to the longitudinal and transverse directions. Where there are through thickness tensile stresses greater than 90% of the design strength, through thickness properties as defined in acceptable references in Annex A1.1 should be specified to ensure structural adequacy. For thick T butt welds or for heavy double fillet welded joints, consideration should be given to specifying steel with guaranteed through thickness tensile properties to reduce the risk of lamellar tearing (see also clause 9.2.1).

The essential requirement is an adequate deformation capacity perpendicular to the surface to provide ductility and toughness against fracture.

3.1.6 Other properties

In carrying out the analysis, the following properties of steel may be used:

Modulus of elasticity	E = 205,000 N/mm^2
Shear modulus	$G = E/[2(1+\nu)]$
Poisson's ratio	$\nu = 0.3$
Coefficient of linear thermal expansion	$\alpha = 14 \times 10^{-6}$/°C
Density	7850 kg/m^3

9.2 WELDED CONNECTIONS

9.2.1 Through-thickness tension

Corner or T-joint welding details of rolled sections or plates involving transfer of tensile forces in the through-thickness direction should be avoided whenever possible.

If tensile stresses are transmitted through the thickness of the connected part, the connection detail, welding procedure and sequence of welding shall be designed to minimise constraints which can cause additional tensile stresses in the through-thickness direction from weld shrinkage. The through-thickness properties of the part should be such as to minimise the risk of lamellar tearing.

9.2.2 Types of welds

For the purposes of design, welds may be classified as:

(a) **Fillet welds**
- continuous welds.
- intermittent welds.
- plug welds on circular and elongated holes.
- slot welds.

(b) **Butt welds**
- full penetration butt welds.
- partial penetration butt welds.
- butt welds reinforced with fillet welds.

(c) **Flare groove welds**

9.2.3 Weldability and electrodes

Steel material shall have good weldability such that crack-free and sound structural joints can be produced without great difficulty, special or expensive requirements on the welding procedure. The welding procedure (including all parameters such as preheating or post-heating requirements, interpass temperature, AC/DC current value, arc speed etc.) shall take into account of the properties of the parent material including the carbon equivalent (CE) value, thickness and the welding consumable type. The chemical contents and mechanical properties of steel material shall conform to the requirements in section 3.1. The welding consumable shall conform to the acceptable standards given in Annex A1.4 with chemical contents matching the parent metal and mechanical properties not inferior to the parent metal.

9.2.4 Welded connections to unstiffened flanges

In a T-joint of a plate to an unstiffened flange of I, H or box section, a reduced effective breadth b_e should be used for both the parent members and the welds.

(a) For I or H section, b_e should be obtained from Figure 9.1 as

$$b_e = t_c + 2r_c + 5T_C \qquad (9.1)$$

$$\text{but } b_e \le t_c + 2r_c + 5\left(\frac{T_c^{\,2}}{t_p}\right)\left(\frac{p_{yc}}{p_{yp}}\right)$$

where

p_{yc} is the design strength of the member
p_{yp} is the design strength of the plate
r_c is root radius of rolled section or toe of fillet on welded section
T_c is the thickness of connected flange
t_c is the stem of connected structural member
t_p is the thickness of the connected plate

E3.1.3 Design strength for high strength steel

Subject to additional requirements and restrictions given in clause 3.1.3 of the Code, it defines an additional class of high strength steel with yield strengths greater than 460 N/mm^2 and not greater than 690 N/mm^2 and produced under an acceptable Quality Assurance system as **Class 1H** steel. The clause is self-explanatory.

For Class 1H steel products, the maximum contents for sulphur and phosphorous do not exceed 0.015% and 0.025% as stipulated in BS EN 10025-6: 2004. Hence, the maximum contents for sulphur and phosphorous are set at 0.025% in clause 3.1.3 of the Code. While there is no intention to make the Code more stringent than the current reference standards, Class 1H steel products conforming to the materials reference standards from the five regions in Annex A1.1 are deemed to satisfy the chemical composition requirements. Otherwise, the chemical composition requirements as stipulated in clause 3.1.3 of the Code should be strictly observed.

E3.1.4 Uncertified steel

The purpose of this clause is to allow steel with no mill certificate documentation to be used but with a conservatively low value of design strength and not in important situations. Australian code AS4100 defines this as unidentified steel. Use of unidentified steel is not discussed in BS5950. Generally, the use of such steel is discouraged. However, from time to time, contractors will wish to use it for economy. Thus, the Code does permit its use with restrictions. The span limit of 6 m follows from Buildings Department guidance that the Responsible Engineer is not required for such restricted spans.

For mechanical steel properties, the sample coupon test should typically pass the minimum tensile yield stress of 170 N/mm^2, ultimate breaking stress of 1.2 of yield stress, Charpy V-notch test and a minimum 15% elongation.

If welding is required, then chemical tests are required and the steel material should not have a carbon equivalent value (CEV) larger than those specified in BS EN 10025 for weldability requirement. It is noted that Eurocode 3 and the Chinese standard for use of low grade steel of grade 170 MPa or below allow such steel to be used as secondary members without chemical composition tests.

Clause 3.1.4 of the Code says that if class 3 uncertified steel is used, it shall be free from surface imperfections, it shall comply with all geometric tolerance specifications and shall be used only where the particular physical properties of the steel and its weldability will not affect the strength and serviceability of the structure. The design strength, p_y, shall be taken as not exceeding 170 N/mm^2 (while the tensile strength shall be taken as not exceeding 300 N/mm^2).

E3.1.5 Through thickness properties

Clause 3.1.5 of the Code draws the attention of the Responsible Engineer to requirements for through thickness strength where steel plate is subjected to significant through thickness or "Z" stresses. For example, such situations can occur when plates are welded at right angles to thick plates. The essential requirement is an adequate strength and deformation capacity perpendicular to the surface to provide ductility and toughness against fracture. Particular weaknesses arise from laminations in the steel (lamellar tearing) or from a brittle central region of the plate (centreline segregation).

Lamellar tearing

This defect originates from inclusions in the steel which are distributed into planes of weakness as the steel is rolled. Subsequent tension across these laminations can cause failure. The welding procedures should be chosen so as to minimise tensile forces perpendicular to the plate. If necessary, material with high through thickness properties (e.g. HiZeD steel) may be specified.

Centreline segregation

Centreline segregation is a material deficiency that may exist within the centre of continuously cast (concast) plate products and some sections. It arises from impurities on the surface of the molten steel being drawn down into the centre of the steel as it comes out of the vat (or furnace) into the roller chain. It can lead to local reductions in toughness and weldability that can cause cracking in tee butt and cruciform weld configurations.

The use of good welding practice and design details may be sufficient to avoid these problems, i.e. :

- Avoid tee, butt or cruciform welds in which the attachment plate is thicker than the through plate.
- Minimising through thickness tension especially at the edges of plates.
- Dressing any cut edges to remove any areas of increased hardness.
- Using smaller weld volumes.
- Developing weld details and processes that minimise the restraint to welds.

E3.1.6 Other properties

Clause 3.1.6 of the Code gives values for Young's modulus, Poisson's ratio and the coefficient of thermal expansion for steel and is self-explanatory. The clause gives a value of 14×10^{6} /°C for the coefficient of thermal expansion in order to be consistent with section 12 but for normal working temperatures of steel, i.e. less than 100°C, a value of 12×10^{6} /°C is appropriate.

In composite construction, normal weight concrete and reinforcement shall comply with the recommendations given in HKCC. However, the elastic modulus of reinforcement shall be taken as 205 kN/mm^2, i.e. same as that of structural steel sections.

E3.2 PREVENTION OF BRITTLE FRACTURE

Brittle fracture can occur in welded steel structures subjected to tension at low temperatures. In certain situations, where fracture-sensitive connection details, inappropriate fabrication conditions or low toughness weld materials are used, brittle fracture can also occur at normal temperatures. The problem is tackled by specifying steel and welded joints with appropriate grades of notch toughness, usually implemented in practice by specifying grades of notch ductility in the Charpy test. Higher grades are required for thicker steel and joints.

Guidance on selection of appropriate Charpy grades of steel to provide sufficient notch toughness at the design temperature of the steel is given in clause 3.2 of the Code. In some contracts, the Responsible Engineer will provide requirements in the form of a performance specification and the steelwork fabricator will provide the correct Charpy grade to meet this specification.

Clause 3.2 of the Code gives descriptive guidance that brittle fracture should be avoided by ensuring parent steel plates and fabrication are free from significant defects and by using a steel quality with adequate notch toughness as quantified by the Charpy impact properties. The criteria to be considered are:- minimum service temperature, thickness, steel grade, type of detail, fabrication procedure, stress level.

The welding consumables and welding procedures should be chosen to give Charpy impact properties in the weld metal and heat affected zone of the joint that are equivalent to, or better than, that the minimum specified for the parent material.

In Hong Kong, the minimum service temperature T_{min} in steel is normally taken as 0.1°C for external steelwork. For cold storage, locations subject to exceptionally low temperatures or structures to be constructed in other countries, T_{min} should be taken as the minimum temperature expected to occur in the steel within the design working life.

The calculation procedure given in clause 3.2 of the Code is generally self-explanatory. The Code also contains in Table 3.7 tabulated values of maximum basic thickness for the normally available strengths of steel (in the range from 215 to 460 N/mm^2) and Charpy 27 Joule impact energies. These are given for a minimum design temperature of 0.1°C

In general, connections are required to transmit forces and moments and to accommodate rotations. In the Code, the rigid connection is designed to resist moment and force while the pinned connection is designed to resist force and accommodate rotations in simple construction.

Rotation of connections can be provided by using elements in connections which can deform appreciably. Detailing of connections should, as practical as possible, allow deformation to take place or moment to be transmitted. Rigid connections normally have connecting elements away from the centre of rotation in order to provide moment more effectively. On the other hand, connecting element such as cleats should be close to the centre of rotation for pinned connections in order to minimize resisting moment androtation more easily.

Three connection types are available in the Code – they are the flexible connections, rigid connections and the semi-rigid connections. The stiffness should be detailed as close as possible to the assumption made in the analysis and design as it affects the moment and stress distributions in a framed structure. The strength of a connection should be capable of resisting the external load and the rotational capacity affects the maximum rotation that a connection can accommodate. The following figure shows the typical assumption for pinned, rigid and semi-rigid connections in terms of strength, stiffness and rotational capacities.

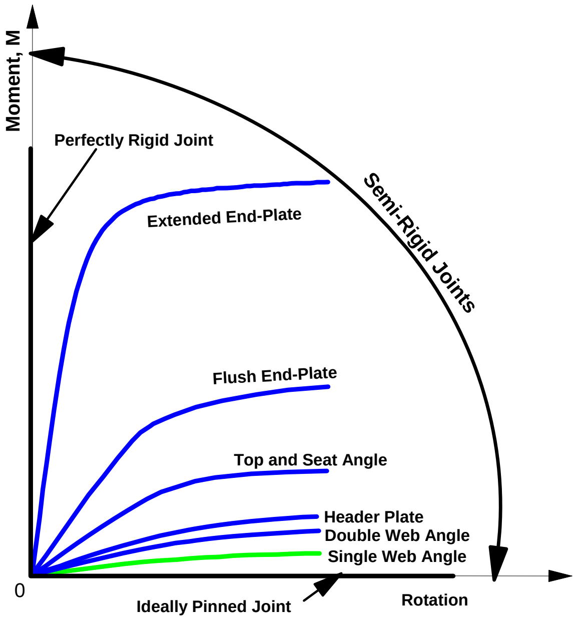


Figure E9.2 - Stiffness, Strength and Rotational Capacity of Pinned, Rigid and Semi-rigid connections

E9.2 WELDED CONNECTIONS

Butt weld and fillet welds are included in the section of welded connections. Butt welds are normally used for in-line jointing in plates or sections and fillet welds are used for tee or lap jointing.

Some precautions for avoiding problem in welding are given in this section of the Code. Explanation of the reason of action is given since following blindly an instruction without understanding the joint behaviour is dangerous.

E9.2.1 Through thickness tension

Lamellar tearing is a type of cracking perpendicular to the thickness dimension of a plate. Tension force on the surface of a thick plate can create lamellar tearing easily. Two methods are available to prevent this type of failure, the first method is the connection detailing to avoid direct lamellar tearing of steel plate, and the second method is to use steel of sufficient strength in the transverse direction of the steel plate confirmed by the through-thickness tearing test when this transverse stress is greater than 90% of the design strength of the steel material.

Relevant standards of Australia, China, Japan and United States of America in mitigating the risk of lamellar tearing which will be updated in Annex A2.3.

Please also make reference to the latest articles on lamellar tearing of steel plates.

E9.2.2 Types of welds

The design strength of fillet welds should follow Table 9.2 of the Code for the lowest grade of material joined. In principle, the vector sum of applied stress should not be greater than the design strength of weld.

The strength of a butt weld should be taken as that of the parent metal. The throat thickness of partial penetration should be taken as depth of penetration -3mm for V (bevel) weld, and for J or U weld the same depth of penetration applies but it should not be less than $2\sqrt{t}$, where t is the connected plate thickness.

For weld illustration and symbolic representation, refer to BS EN 22553.

E9.2.3 Weldability and electrodes

Single sided fillet or partial penetration butt welds shall not be used to transmit a bending moment about the longitudinal axis of weld.

E9.2.4 Welded connections to unstiffened flanges

In a tee-joint of a plate to an unstiffened flange of an I, H or a box section, a reduced effective breadth shall be taken into account both for the parent material and for the welds. This consideration is to account for flexibility of connecting plates.

This criterion of effective breadth is valid for connections subjected to compression or tension. However, for connection under compression, web crippling should always be checked.

E9.2.5 Strength of weld

Fillet welds

Fillet weld is more commonly used because its cost is lower than full penetration weld. Fillet weld does not require end preparation of the element to be welded and the size or leg length is smaller. The amount of testing required for fillet weld is also smaller.

The Code provides information on maximum and minimum size of fillet welds.

BS 5950 (2000) and BS5400 allow deep penetration in fillet welds. They permitted a depth of 0.2a up to 2 mm in addition to the effective throat thickness ‘a’ only for submerged arc weld. AWS allows up to 3 mm as credit for penetration beyond the root. Here, this extra penetration is ignored in local practice and in consideration of the fact that the actual depth of penetration cannot be easily detected and verified by non-destructive tests. In practice, a minimum 3 mm weld electrode is used.

Effective length

Effective length is used to determine the length for calculation of strength of a fillet weld. The Code provides guidance on the determination of effective length.

End returns

The length of end return is specified in the Code. When electrode of grade different from that of the welded parent steel material is used, the lower strength should be used. Table 9.2a and 9.2b of the Code show the combined strength of welded parts in a welded connection.

Steel Bridge Group

Guidance Note

Through thickness properties

No. 3.02

Scope
This Guidance Note gives advice on the need for steel with improved 'through thickness properties' and on the selection of an appropriate quality class where such steel is needed.

Steel is an anisotropic material
Steel plate and sections are produced by a process of rolling, and the mechanical properties that the material attains are influenced by the working of the metal as it cools. Sections are rolled from a compact 'bloom' (a large rectangular piece of steel) into a very long element; any inclusions and non-uniformities in the metal are essentially linear in nature. Plate is rolled from slab, but there is a degree of cross rolling as well as rolling in the longitudinal direction; any inclusions and non-uniformities are therefore essentially planar in extent and parallel to the surface of the plate. The mechanical properties of the material are therefore not the same in all directions; the material is anisotropic.

Material properties for steel sections are specified by reference to test specimens aligned longitudinally in the section. It is presumed that transverse properties (e.g. for bending of the flange) are at least equal to the longitudinal properties. Properties normal to the plane of the flange or web are not specified in the ordinary technical delivery conditions (e.g. in EN 10025-2, Ref 1).

Tensile strength properties for plate are specified by reference to transverse test specimens, unless the plate is less than 600 mm wide, when they are longitudinal. Impact toughness test specimens are usually aligned longitudinally. Again, no properties normal to the plane of the plate are specified in the ordinary technical delivery conditions.

The tensile strength out-of-plane (perpendicular to the surface) is more susceptible (than the in-plane strength) to the influence of rolling imperfections, particularly in plates.

There are two levels of imperfection or defect that affect out-of-plane behaviour:

- macro imperfections - thin layers of inclusion or impurity, extending over an area
- micro imperfections - numerous very small inclusions, usually of sulphides.

Macro defects are termed 'laminations' or 'laminar defects'. Their presence and extent can be checked by ultrasonic testing. Acceptance levels are given in EN 10160 (Ref 2). This type of defect is not the subject of this Guidance Note.

Micro imperfections are significant when the material is subject to through-thickness loading, because they can lead to 'lamellar tearing' as a tear propagates from one inclusion to the next. Since the inclusions are small they cannot readily be revealed by ultrasonic testing, but their effect may be assessed by carrying out through thickness tensile tests in accordance with EN 10164 (Ref 3).

Generally, the requirement for 'through thickness properties' is therefore understood to be a requirement for one of the three quality classes of improved deformation properties (Z15, Z25, Z35) defined in EN 10164.

Evaluation of deformation properties perpendicular to the surface - EN 10164
It is stated in EN 10164 that the reduction of area in a through thickness tensile test is a good general guide to the lamellar tear resistance, i.e. the risk of lamellar tearing decreases with increased reduction of area. Steel normally manufactured to the EN standards (e.g. EN 10025-2) generally has a modest tear resistance (i.e. a modest reduction of area), but this property is not specified or measured. The invoking of EN 10164, as a supplement to the product standard, implies that the steel will have *improved* deformation properties, as a result of additional steelmaking procedures. These improved properties may be specified in terms of a minimum reduction of area in a transverse tensile test; three quality classes are defined, Z15, Z25 and Z35, corresponding to 15%, 25% and 35% average reduction in area at failure, respectively.

The need for steel with improved through-thickness properties
There should be very little need to specify steel with improved (guaranteed) through-thickness properties in typical bridge steelwork, unless the joint details are unusual. The tear resistance of steels from modern steel-making plants is sufficient for most applications. If the source of the steel material is uncertain and/or the manufacturer's or supplier's certification is

incomplete and, especially, if the application is one of those recognised to be critical in this respect, testing to EN 10164 should be called for. The result will indicate in which category the material lies and its suitability for the application can then be assessed.

'Through thickness properties' would, for example, be needed where there is significant load carried through a cruciform detail, or where pieces are welded in positions where they are constrained against weld shrinkage. Good design of connections should ensure that there are rarely any such details.

It is worth noting the conclusion of a study carried out by TWI for TRRL in 1991 (Ref 4): "The review and survey of industry have shown that the principal factors controlling lamellar tearing are well understood, and that instances of this form of cracking in bridge construction are currently very infrequent." The report goes on to say that with the advent of options that offer "a range of through thickness tested grades, there is a risk that such steels will be specified in situations where they are not strictly necessary, thus adding unnecessarily to the overall cost". Refinements in steelmaking since 1991 are likely to have further reduced the instances of tearing.

Avoidance of lamellar tearing

The main cause of lamellar tearing is very high out-of-plane stresses due to restraint of weld shrinkage. Tearing will usually appear during or soon after cooling of the welds; tearing due to applied load occurs rarely, unless tearing has already been initiated, or laminar defects are present.

The best way to avoid tearing is therefore to avoid details that induce high out-of-plane stresses. Where they cannot be avoided, it is recommended to check by ultrasonic testing locally around any critical details *after* welding, to ensure that there are no tears or defects.

Details that avoid the risk of lamellar tearing

A simple corner butt weld can lead to tearing if the weld preparation is to the wrong plate. See Figure 1.

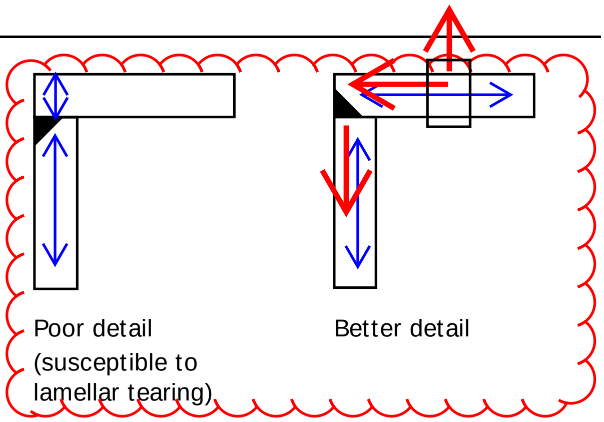


Figure 1 *Corner weld details*

When the upper plate in Figure 1 is prepared (as in the right-hand detail), the preparation cuts across most of any laminar defects.

If a cruciform detail is needed (for example when there are integral crossheads), consider running the thicker web plate through and weld the thinner to it, as in Figure 2. The thinner web is unlikely to require very large welds and thus should not require consideration of through-thickness. In any case, try to remove the need for full penetration welds: fillet welds and partial penetration welds are less likely to give rise to problems.

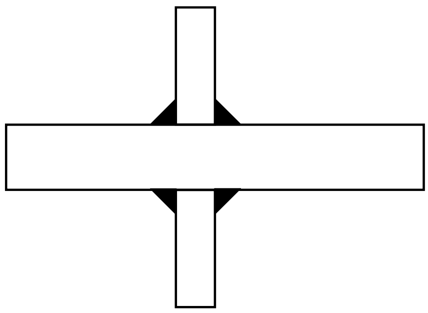


Figure 2 *Cruciform detail*

If a full penetration butt weld detail is needed (perhaps because of its better fatigue classification), there is again a lesser risk of tearing if the thicker plate is passed through; then no requirement for through thickness properties need normally be specified. See Figure 3.

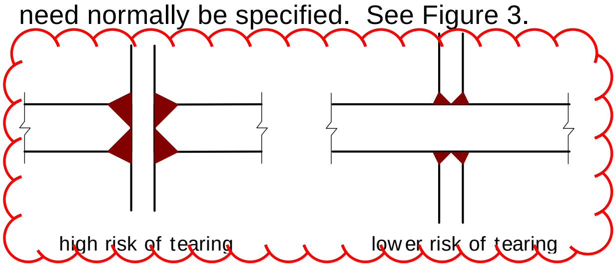


Figure 3 *Cruciform details using butt welds*

Specification of steel with improved deformation properties

Specifying a quality class to EN 10164 will ensure that the steel supplier provides a fine grained steel, with a sulphur level lower than that normally encountered with 'ordinary' structural steels. In addition to the usual properties, the steel will have a 'guaranteed' level of through thickness ductility.

However, steel with improved deformation properties should only be specified if the designer perceives a risk of lamellar tearing. Such a perception should be made after taking a balanced view, not simply as a belt-and-braces safe option. The advice in this Note should aid the designer to make a reasoned judgement.

EN 1011-2 (Ref 5) provides in its Annex F some guidance on the relationship between the reduction of area in the transverse tensile test and the risk of lamellar tearing in joints of differing restraint. This is presented in tabular form in Table 1.

Annex F also contains advice on the best ways of avoiding lamellar tearing problems.

Table 1 *Relationship between reduction in area and risk of tearing*

Reduction in area	Type of joint at risk
Up to 10%	Some risk in lightly restrained T-joints, e.g. I-beams
Up to 15%	Some risk in moderately restrained joints, e.g. box-columns
Up to 20%	Some risk in highly restrained joints, e.g. node joints, joints between sub-fabrications
Over 20%	Probable freedom from tearing in any joint type

If a designer has concerns in relation to any details, advice could be sought from experienced fabricators prior to contract.

Another simple rule-of-thumb is to expect problems when the size of the attachment by weld to a plate surface matches or exceeds the thickness of that plate.

EN 1993-1-10 (Ref 6) contains a numerical method for determining the required Z-grade according to the weld size, detail type and level of restraint. However, the UK National Annex (Ref 7) indicates that this should not be used. The view of the UK experts is that this method is unduly conservative, required extensive calculations, and would lead to the unnecessary specification of Z-grade material. Instead, the UK National Annex refers designers to PD 6695-1-10 (Ref 8), which gives:

- Options for the fabricator.

  The PD points out that the risk of 'lamellar tearing' can be mitigated by fabrication control measures, notably by procuring material from a modern mill known to produce clean steel.

- Options for the designer.

  The PD implies that Z-grade material need not be specified for low and medium risk situations. For high risk situations it recommends that designers should specify Z35 quality to EN 10164. It defines high risk situations as:

  In T-joints, when t_z > 35mm.

  In cruciform joints, when t_z > 25mm

  Where t_z is the thickness of the incoming plate for butt welds and deep penetration fillet welds, and is the throat size of the largest fillet weld for fillet welded joints.

Material availability

Requirements for improved through-thickness properties are usually very local in nature. However, steel with improved properties is more expensive and less readily available. If restricted portions of web or flange are specified in such steel, it is likely that only small quantities will be needed on any particular project. This may prove difficult for the fabricator, because the supplier may impose minimum order quantities, with a premium for small quantities. These practical considerations should be recognised by the designer; *it is better to design details that do not require the use of steel with improved through thickness properties*.

Avoidance of laminar defects

Wherever load-carrying connections are made to the surface of steel, whether transmitting shear or out-of-plane forces, laminar defects should either be absent or of limited extent, irrespective of any need for through thickness properties. For critical details (such as lifting cleats or bearing stiffener connections to a web), ultrasonic inspection can be carried out before fabrication, as a precaution. Specification of a quality class to EN 10164 invokes a requirement for ultrasonic inspection as well as for through thickness properties.

References

1. EN 10025-2:2004, Hot rolled products of alloy structural steels. Technical delivery conditions for non-alloy steels.
2. EN 10160:1999, Ultrasonic testing of steel flat plate product of thickness equal to or greater than 6 mm (reflection method).
3. EN 10164: 2004, Steel products with improved deformation properties perpendicular to the surface of the product. Technical delivery conditions.
4. Study of through thickness properties of steel for bridge construction, Report 3-4048/3/91, The Welding Institute, 1991 (unpublished)
5. EN 1011-2:2001 Welding. Recommendations for welding of metallic materials. Arc welding of ferritic steels
6. EN 1993-1-10:2005, Eurocode 3: Design of steel structures - Part 1-10 Material toughness and through thickness properties, BSI, 2005
7. NA to EN 1993-1-10: 2005, UK National Annex to Eurocode 3: Design of steel structures – Part 1-10: Material toughness and through-thickness properties, BSI, 2009
8. PD 6695-1-10:2009, Recommendations for the design of structures to BS EN 1993-1-10, BSI 2009.

– for members susceptible to fatigue the size of the flaw should consist of an initial flaw grown by fatigue. The size of the initial crack should be chosen such that it represents the minimum value detectable by the inspection methods used in accordance with EN 1090. The crack growth from fatigue should be calculated with an appropriate fracture mechanics model using loads experienced during the design safe working life or an inspection interval (as relevant).

(4) If a structural detail cannot be allocated a specific detail category from EN 1993-1-9 or if more rigorous methods are used to obtain results which are more refined than those given in Table 2.1 then a specific verification should be carried out using actual fracture tests on large scale test specimens.

NOTE The numerical evaluation of the test results may be undertaken using the methodology given in Annex D of EN 1990.

3 Selection of materials for through-thickness properties

3.1 General

(1) The choice of quality class should be selected from Table 3.1 depending on the consequences of lamellar tearing.

Table 3.1: Choice of quality class

Class	Application of guidance
1	All steel products and all thicknesses listed in European standards for all applications
2	Certain steel products and thicknesses listed in European standards and/or certain listed applications

NOTE The National Annex may choose the relevant class. The use of class 1 is recommended.

(2) Depending on the quality class selected from Table 3.1, either:

– through thickness properties for the steel material should be specified from EN 10164, or

– post fabrication inspection should be used to identify whether lamellar tearing has occurred.

(3) The following aspects should be considered in the selection of steel assemblies or connections to safeguard against lamellar tearing:

– the criticality of the location in terms of applied tensile stress and the degree of redundancy.

– the strain in the through-thickness direction in the element to which the connection is made. This strain arises from the shrinkage of the weld metal as it cools. It is greatly increased where free movement is restrained by other portions of the structure.

– the nature of the joint detail, in particular welded cruciform, tee and corner joints. For example, at the point shown in Figure 3.1, the horizontal plate might have poor ductility in the through-thickness direction. Lamellar tearing is most likely to arise AC_2 if the strain in the connection acts AC_2 through the thickness of the material, which occurs if the fusion face is roughly parallel to the surface of the material and the induced shrinkage strain is perpendicular to the direction of rolling of the material. The heavier the weld, the greater is the susceptibility.

– chemical properties of transversely stressed material. High sulfur levels in particular, even if significantly below normal steel product standard limits, can increase the lamellar tearing.

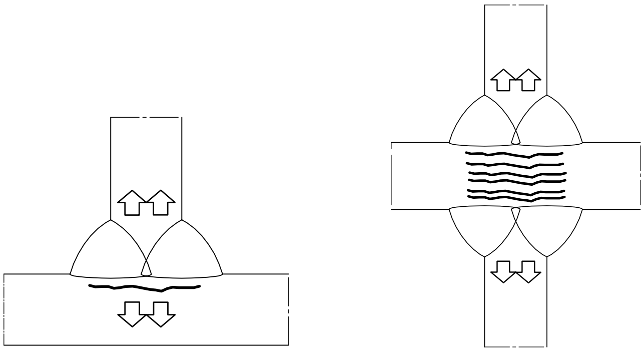


Figure 3.1: Lamellar tearing

(4) The susceptibility of the material should be determined by measuring the through-thickness ductility quality to EN 10164, which is expressed in terms of quality classes identified by Z-values.

NOTE 1 Lamellar tearing is a weld induced flaw in the material which generally becomes evident during ultrasonic inspection. The main risk of tearing is with cruciform, T- and corner joints and with full penetration welds.

NOTE 2 Guidance on the avoidance of lamellar tearing during welding is given in EN 1011-2.

3.2 Procedure

(1) Lamellar tearing may be neglected if the following condition is satisfied:

$$Z_{Ed} \leq Z_{Rd} \qquad (3.1)$$

where Z_{Ed} is the required design Z-value resulting from the magnitude of strains from restrained metal shrinkage under the weld beads.

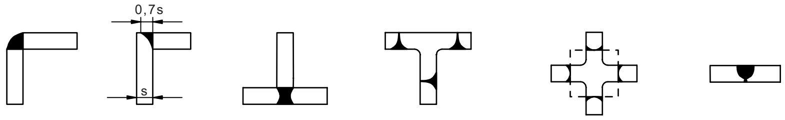
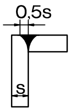
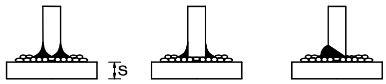
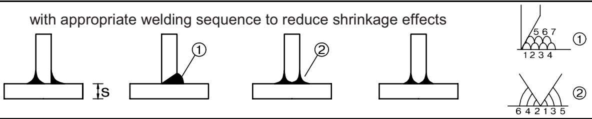
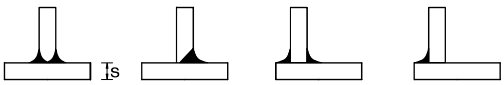
Z_{Rd} is the available design Z-value for the material according to EN 10164, i.e. Z15, Z25 or Z35.

(2) The required design value Z_{Ed} may be determined using:

$$Z_{Ed} = Z_a + Z_b + Z_c + Z_d + Z_e \qquad (3.2)$$

in which Z_a, Z_b, Z_c, Z_d and Z_e are as given in Table 3.2.

Table 3.2: Criteria affecting the target value of Z_{Ed}

a)	Weld depth relevant for straining from metal shrinkage	AC2 Effective weld depth a_{eff} (see Figure 3.2) AC2	AC2 Throat thickness a of fillet welds AC2	$\mathbf{Z_i}$
		$a_{eff} \leq 7$mm	a = 5 mm	$\mathbf{Z_a = 0}$
		$7 < a_{eff} \leq 10$mm	a = 7 mm	$\mathbf{Z_a = 3}$
		$10 < a_{eff} \leq 20$mm	a = 14 mm	$\mathbf{Z_a = 6}$
		$20 < a_{eff} \leq 30$mm	a = 21 mm	$\mathbf{Z_a = 9}$
		$30 < a_{eff} \leq 40$mm	a = 28 mm	$\mathbf{Z_a = 12}$
		$40 < a_{eff} \leq 50$mm	a = 35 mm	$\mathbf{Z_a = 15}$
		$50 < a_{eff}$	a > 35 mm	$\mathbf{Z_a = 15}$
b)	Shape and position of welds in T- and cruciform- and corner-connections			$\mathbf{Z_b = -25}$
		corner joints		$\mathbf{Z_b = -10}$
		single run fillet welds $Z_a = 0$ or fillet welds with $Z_a > 1$ with buttering with low strength weld material		$\mathbf{Z_b = -5}$
		multi run fillet welds		$\mathbf{Z_b = 0}$
		partial and full penetration welds		$\mathbf{Z_b = 3}$
		partial and full penetration welds		$\mathbf{Z_b = 5}$
		corner joints		$\mathbf{Z_b = 8}$
c)	Effect of material thickness *s* on restraint to shrinkage	$s \leq 10$mm		$\mathbf{Z_c = 2^*}$
		$10 < s \leq 20$mm		$\mathbf{Z_c = 4^*}$
		$20 < s \leq 30$mm		$\mathbf{Z_c = 6^*}$
		$30 < s \leq 40$mm		$\mathbf{Z_c = 8^*}$
		$40 < s \leq 50$mm		$\mathbf{Z_c = 10^*}$
		$50 < s \leq 60$mm		$\mathbf{Z_c = 12^*}$
		$60 < s \leq 70$mm		$\mathbf{Z_c = 15^*}$
		$70 < s$		$\mathbf{Z_c = 15^*}$
d)	Remote restraint of shrinkage after welding by other portions of the structure	Low restraint:	Free shrinkage possible (e.g. T-joints)	$\mathbf{Z_d = 0}$
		Medium restraint:	Free shrinkage restricted (e.g. diaphragms in box girders)	$\mathbf{Z_d = 3}$
		High restraint:	Free shrinkage not possible (e.g. stringers in orthotropic deck plates)	$\mathbf{Z_d = 5}$
e)	Influence of preheating	Without preheating		$\mathbf{Z_e = 0}$
		Preheating ≥ 100°C		$\mathbf{Z_e = -8}$

* May be reduced by 50% for material stressed, in the through-thickness direction, by compression due to predominantly static loads.

Figure 3.2: Effective weld depth a_{eff} for shrinkage

(3) The appropriate Z_{Rd}-class according to EN 10164 may be obtained by applying a suitable classification.

NOTE For classification see EN 1993-1-1 and EN 1993-2 to EN 1993-6.

3 Prevention of lamellar tearing in welded structural steelwork (BS EN 1993-1-10:2005, Clause 3)

3.1 General

Lamellar tearing is only a risk when building up large deposits of weld metal in the tee, cruciform and corner joints in steels which contain inclusions, particularly sulfur. The measures which the steelwork fabricator can take to minimize this risk are given in **3.2**.

3.2 Options for the fabricator

The risk of lamellar tearing can be mitigated by the following fabrication control measures:

a) procurement of steel from a mill known to produce clean steel, particularly with low sulfur levels. Such material is likely to exhibit a reasonable level of through-thickness properties (Z15, Z25 or even Z35) as a matter of course;

b) checking of the mill certificates on delivery to identify material with higher sulfur levels, particularly where steel is from an unknown source. Ultrasonic inspection may help to identify some areas of higher material susceptibility, but this is not foolproof;

c) ordering steel with a maximum specified sulfur level;.

d) use of favourable weld preparation geometries;

e) use of assembly sequences and jigging to minimize long range restraint;

f) use of welding run sizes and balanced sequence to minimize local shrinkage stresses;

g) use of reduced strength buttering runs on the surfaces of the transversely stressed (or "through") material, and if necessary increasing the buttering depths by prior excavation;

h) control of heat input to avoid high differential thermal strains.

3.3 Options for the designer

In low- and medium-risk situations, the measures recommended in **3.2** should be followed to avoid lamellar tearing.

Through-thickness (Z) testing (which usually requires ultrasonic plate testing as well) is expensive and is often unnecessary. The designer needs to specify Z35 quality to BS EN 10164 only in high-risk situations. This option should apply only to the material with welds on its surface, i.e. the through material not the incoming material (see Figure 1 and Figure 2).

The following situations are considered to be high risk:

- tee joints, t_z >35 mm;
- cruciform joints, t_z >25 mm.

Where t_z for all butt welds and deep penetration fillet welds should be taken as the thickness of the incoming material (see Figure 1). For fillet welded joints, t_z should be the throat size of the largest fillet weld.

In the case of corner joints the risk of lamellar tearing can normally be overcome by preparing the corner of the through material (see Figure 2). Where this cannot be achieved, a value of t_z greater than 20 mm for the incoming material should be taken as high risk, and through-thickness testing or the use of Z steel for the through material might be more appropriate.

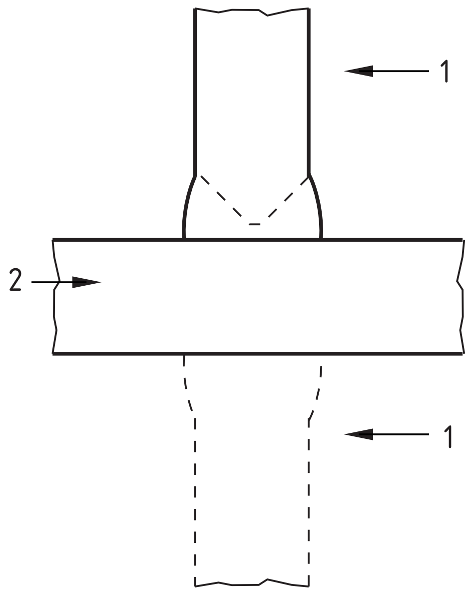
Z35 quality should not be difficult to obtain for plates. However in the case of open sections, (not welded hollow sections made from plates), it may be difficult to find a supplier. In which case specification of a maximum sulfur level of 0.005% for the through material should be used.

In high-risk situations the following measures are also recommended.

a) Do not over-specify the weld throat size.

b) Reduce the weld volume to a minimum. In heavy tee/cruciform joints, double partial penetration butt welds with reinforcing fillet welds may be preferable to full penetration butt welds or large fillet welds (provided that fatigue through the throat is not the governing mode of failure).

Figure 1 **Tee and cruciform joints**

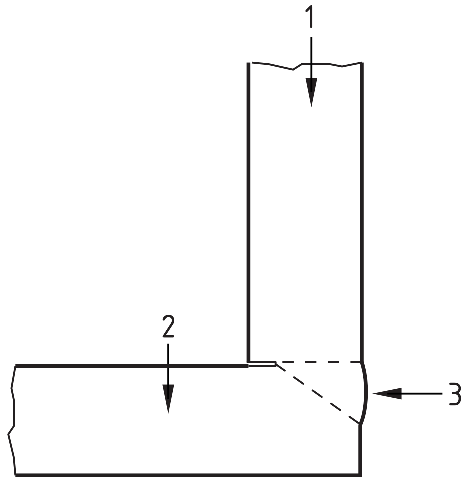


Key

1 "Incoming" material

2 "Through" material

Figure 2 **Corner joint**



Key

1 "Incoming" material

2 "Through" material

3 Preparation on "through" material

Bibliography

For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

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BS EN 10164, *Steel products with improved deformation properties perpendicular to the surface of the product – Technical delivery conditions*