Structural steels

No. 3.01

Scope

This Guidance Note gives information on the key physical and mechanical properties of most structural steels commonly used in bridge works. The information should be sufficient to enable a designer to select the appropriate steel grades to achieve the required design characteristics.

Correct specification of the steel material will ensure that the structural performance presumed in the design will be achieved in the completed bridge structure.

Comments on the many and differing grades used in the past are generally outside the scope of this Note.

Key physical/mechanical properties of steels

Steel derives its mechanical properties from a combination of chemical composition, heat treatment and mechanical working. The bridge designer cannot reasonably be expected to understand all the detailed implications of the differences between the various grades, but an understanding of the importance of each of the key properties and the means of achieving them will be of benefit.

The following properties are of particular importance to the bridge designer:

- yield strength
- modulus of elasticity
- coefficient of thermal expansion
- ductility (in plane and through thickness)
- notch toughness (impact strength)
- weldability
- corrosion resistance

The designer has scope to select some of these properties; others (such as modulus) are implicit in the use of structural steel.

European steel specifications

Generally, all new steel for structural purposes should be 'hot-rolled steel' manufactured to a CEN European Standard (EN). These standards are issued in the UK through BSI, and consequently bear the EN designation. In the CEN designation system (see EN 10027 and ECISS IC10), all structural steels have the prefix 'S'.

The following standards are relevant to bridge steelwork:

EN 10025, Parts 1 to 6
EN 10210

A summary of the grades available in these standards is given in Table 1.

The use of cold formed hollow sections is also covered by Eurocode 3 but these sections are rarely used (see further comment about notch toughness, below).

Yield strength

The yield strength is probably the most significant property that the designer will need to use or specify. The achievement of a suitable strength whilst maintaining other properties has been the driving force behind the development of modern steel-making and rolling processes.

In the European Standards for structural steels, the primary designation relates to the yield strength, e.g. S355 steel is a structural steel with a nominal yield strength of 355 N/mm^2. The number quoted in the designation is the value of yield strength for material up to 16 mm thick. Yield strength reduces with increasing plate or section thickness; this is taken into account in the design standards.

The strength grades covered by the above EN standards include the following:

S235, S275, S355, S420 and S460.

Yield strengths above 460 N/mm^2 are available in EN 10025-6. The use of grades above S460, up to S700, is covered by EN 1993-1-12. (Note that the limitation in the UK NA that the ratio of specified ultimate/yield strengths is at least 1.10 is met by these grades of steel to EN 10025-6.)

Steels of 355 N/mm^2 yield strength are predominantly used in bridgeworks applications in the UK because the cost-to-strength ratio of this material is lower than for other grades. However, some of the higher strength grades offer other advantages and may be seen more frequently in the future. (But note that the use of higher strength steels confers no benefits in applications which are fatigue critical or in which instability of very slender members is the overriding design consideration.)

The strength of the steel is achieved by including alloying elements (notably carbon and manganese) and by the production process. The strength depends on the grain structure of the steel alloy and this depends on both the cooling rate and the working of the steel.

There are a number of production processes for hot rolled steels and it is worth explaining briefly what the main ones are.

Normalized steel
When steel is hot-rolled, the temperature of the steel steadily drops (from about 1200°C) during rolling. However, improved properties can be achieved if the steel is subsequently 'normalized' by heating it to about 900°C and allowing it to cool naturally (in still air).

Normalized rolled steel
Similar properties to those of normalized steel can be achieved in a single process if the temperature during rolling is controlled so that all rolling is carried out at or above about 900°C, provided the steel then cools naturally.

Thermomechanically rolled (TMR) steel
In a further refinement of the rolling process, a slightly lower alloy steel (less carbon) can achieve similar properties by rolling in a carefully controlled manner, down to a finishing temperature of between about 700°C and 800°C.

Quenched and tempered (Q&T) steel
Quenching is a process where the steel is heated above 900°C, which allows the formation of an austenitic grain structure. The steel is then cooled rapidly (by immersion in a bath of water, or by passing through a curtain spray). This produces a high strength steel with high hardness, but with low toughness.

Toughness is restored by tempering, heating to between 600°C and 700°C. The Q&T process can achieve much higher yield strengths, but subsequent heating, for example due to welding or prolonged heat treatment, may have an effect on the properties. Specialist advice should be sought if procedures are to be developed for welding or flame straightening of Q&T steels. Stress relieving can be carried out at 30°C below the tempering temperature (see the test certificate for that temperature), but seek the supplier's advice on the effect of this on the properties.

Delivery condition
The 'delivery condition' indicates which of the above processes is to be used and is designated by an alphabetic code. In some standards there is only the one delivery condition; in other standards there are options.

In EN 10025-2 and EN 10025-5, the delivery condition is either 'at the manufacturer's discretion' or is specified as an 'Option'. The two Options available are:
+N   Normalized and normalized rolled
+AR   As rolled
These Options are indicated by adding the code after the grade and quality (toughness) designation (see below for toughness grades), for example S355J2+N.

In each of EN 10025-3 and EN 10025-4 there is only the one delivery condition, indicated by adding N (normalized/normalized rolled) or M (thermomechanically rolled) after the strength grade.

In EN 10025-6, there is only the one delivery condition, indicated by adding Q (quenched and tempered), for example S355Q.

'Flat products' (plate and strip) can be produced by any of the above processes. 'Long products' (sections and bars) are generally supplied 'as rolled'. The as rolled condition for long products is effectively the same as normalized rolled. Long products can be supplied as 'M' steels, by agreement with the supplier.

EN 10210 covers two types of steel, non-alloy and fine grain steel. The delivery of the former is hot finished and of the latter is normalized/normalized rolled (indicated by adding N to the strength grade). Additionally, the letter H is added at the end of the designation (after the quality designation) to indicate hollow sections. EN 10219 also covers non-alloy and fine grain steels, the delivery condition is cold formed and the letter H is added at the end of the quality designation.

Modulus of elasticity and coefficient of thermal expansion

These properties are taken as constant for all structural steels regardless of grade or yield strength. Therefore, the designer need not consider them when selecting an appropriate steel grade. EN 1993-1-1 gives the modulus of elasticity (E) as 210 kN/mm^2, the shear modulus (G) as 80 kN/mm^2, Poisson's ratio ν as 0.3 and the coefficient of thermal expansion as 12×10^{-6} per °C (although EN 1994-1-1 recommends the value of 10×10^{-6} per °C for effects in composite bridges other than change in length).

Ductility

Ductility is of paramount importance to all steels in structural applications. It is a measure of the degree to which the material can strain or elongate between the onset of yield and eventual fracture under tensile loading.

Whether it is realised or not, the designer relies on ductility for a number of aspects of design: redistribution of stress at the ultimate limit state; bolt group design; reduced risk of fatigue crack propagation; and in the fabrication process in welding, straightening, bending, etc.

Ductility tends to reduce with increasing yield strength. Fortunately, this effect is not significant enough to affect the design of the majority of bridges.

Ductility of a steel plate or rolled section is measured in relation to behaviour in the plane of the element (plate, flange or web), either in or normal to the direction of rolling, and in relation to through-thickness behaviour (i.e. perpendicular to the plane of the element). The two measurements have different significance for the designer.

In-plane ductility

The material standards specify minimum elongation at failure under test. Material complying with these standards usually possesses adequate in-plane ductility for the bridge designer's and the fabricator's purposes, hence no additional specification is needed.

Through-thickness ductility

The properties of steel perpendicular to the plane of the element are different to those in-plane. This is particularly true for ductility, which is generally lower in the direction normal to the plane of rolling.

For several reasons, a designer should try to avoid welded joint configurations in which plate material is subjected to high tensile stresses in the through-thickness direction (see GN 3.02). Where there is such a joint carrying significant load, the specification of material with assured through-thickness properties is usually required.

Through thickness ductility may be specified as an 'option' in EN 10025, in terms of one of three 'levels' according to EN 10164. These levels are expressed in terms of the percentage reduction of area obtained during - through-thickness tensile tests on small specimens of plate material. High ductility is indicated by a high percentage (e.g. ≥35% as the average of six test pieces per plate and ≥25% for any single value). See GN 3.02 for detailed advice on specifying through thickness ductility.

Notch toughness (impact strength)

The nature of steel material is that it always contains some imperfections, albeit of very small size. When subject to tensile stress these imperfections (similar to very small cracks) tend to open; if the steel is insufficiently tough, the 'crack' propagates rapidly, without plastic deformation, and failure may result. This is called 'brittle fracture' and is of particular concern because of the sudden nature of failure. Also, the toughness of the steel, and its ability to resist this behaviour, decreases as the temperature decreases. The toughness required, at any given temperature, increases with the thickness of the material.

A convenient measure of toughness is the Charpy V-notch impact test (hence the use of the terms 'Charpy energy' and 'notch toughness' in EN 1993-1-10). This test measures the impact energy (in Joules) required to break a small notched specimen by a single impact blow from a pendulum; the test is carried out with the specimen at a specified (low) temperature. In the material standards, tests are specified typically at –20°C and the required minimum value is typically 27J. Other temperatures and energy values are specified for different grades.

The material standards designate the available toughness quality in a number of different ways.

Standards EN 10025-2 and EN 10025-5 offer a choice of four qualities, designated by appended a two letter alphanumeric code to the steel strength code, for example S355J2. The four codes are:

JR: 27J impact energy at +20°C
JO: 27J impact energy at 0°C
J2: 27J impact energy at –20°C
K2: 40J impact energy at –20°C

Quality JR is not suitable for bridges because the NA to BS EN 1993-1-10 prohibits the use of steels at temperatures more than 20°C below the test temperature.

EN 10210 also offers qualities J0 and J2 for non-alloy hollow sections.

Standards EN 10025-3 and EN 10025-4 each offer only two qualities, one being differentiated by the addition of 'L' after the strength grade and delivery condition. The two grades are:

40J impact energy at –20°C
L 27J impact energy at –50°C

EN 10210 also offers these two qualities for fine grained steel hollow sections.

Standard EN 10025-6 offers three qualities, two designated by the addition of a code:

30J impact energy at –20°C
L 30J impact energy at –40°C
L1 30J impact energy a –60°C

The designer is thus able to select and specify an appropriate toughness/ impact strength for his structure. He can take advantage of a lesser need for toughness during construction, if it is certain that the component will be subject to only moderate tensile stresses or to less severe minimum temperatures, but it is wise not to rely on this unless absolutely necessary. It is imperative that the rules be rigorously observed for normal service conditions.

For ease of application, toughness requirements can be presented in the form of tables of limiting thickness: for a given minimum service temperature and maximum tensile stress in an element of a particular grade of steel. Such tables give the designer a maximum thickness of component that will have sufficient toughness. Explicit relationships between temperature and toughness are also provided. (It may be noted that the requirements are less onerous in building design as the minimum service temperatures are generally higher.) Tables are given in EN 1993-1-10 but the NA to BS EN 1993-1-10 refers to PD 6695-1-10 for simplified tables that avoid the detailed evaluation of 'reference temperature' required for the use of the EN 1993-1-10 tables.

In the UK most designers are led to the use of toughness grades J2 or K2 (or the lower grades of N and M steels) in recognition that the minimum bridge service temperature of composite bridges in UK does not fall below –20°C. However, toughness is assured up to 20°C below the test temperature, and consequently J0 steels will be satisfactory in many circumstances.

Cold formed hollow sections to EN 10219 can be supplied in qualities J0, J2, K2, N and NL (for J0 it is necessary to specify the Option that toughness be verified). However, it should be noted that for rectangular hollow sections the toughness is only verified at the middle of the flat sides; the toughness is very significantly reduced in the corners by the cold forming process (the reduction in reference temperature $\Delta T_{\varepsilon_{cf}}$ given by EN 1993-1-10, 2.3.1 can be as much as 99°C). Cold formed rectangular hollow sections are therefore unsuitable for bridges.

Weldability

All structural steels are essentially weldable. However, welding involves locally heating the steel material, which subsequently cools. The cooling can be quite fast, because the material offers a large 'heat sink' and the weld (and the heat introduced) is relatively small. This can lead to hardening of the 'heat affected zone' and to reduced toughness. The greater the heat input, the less the reduction; the greater the thickness of material, the greater the reduction of toughness. Thus thick material may need to be preheated.

The susceptibility to embrittlement depends on the alloying elements, principally, but not exclusively, on the carbon content. This susceptibility can be expressed as the 'Carbon Equivalent Value' (CEV), and the standards give an expression for determining this value. Welding standards (such as EN 1011-2) will indicate what preheat, if any, is needed for a given CEV, material thickness and weld size.

EN 10025 gives limiting values for CEV that are automatically invoked when specific inspection is called for. It may be noted that fine grain steels (to Parts 3 and 4 of EN 10025) generally have a lower value of maximum CEV than have non-alloy steels to Part 2.

Corrosion Resistance

All structural steels, with the exception of steels with improved atmospheric corrosion resistance ('weather resistant steels'), have a similar resistance to corrosion. In exposed conditions they need to be protected by a coating system.

Weather resistant steels form a tightly adhering oxidised steel coating or 'patina' that inhibits further corrosion. See GN 1.07 for further advice.

Reference Standards

EN 1011-2:2001, Welding. Recommendations for welding of metallic materials. Arc welding of ferritic steels.
EN 1993 Eurocode 3: Design of steel structures
EN 1993-1-1:2005, General rules and rules for buildings
EN 1993-1-10:2005, Material toughness and through-thickness properties
EN 1993-1-12:2007, Additional rules for the extension of EN 1993 up to steel grades S700
EN 1994-2:2005, Eurocode 4: General rules and rules for bridges
EN 10025: 2004, Hot rolled products of structural steels.
Part 1: 2004, General technical delivery conditions.
Part 2: 2004, Technical delivery conditions for non-alloy structural steels.
Part 3: 2004, Technical delivery conditions for normalized/normalized rolled weldable fine grain structural steels.
Part 4: 2004, Technical delivery conditions for thermomechanical rolled weldable fine grain structural steels.
Part 5: 2004, Technical delivery conditions for structural steels with improved atmospheric corrosion resistance.
Part 6: 2004, Technical delivery conditions for flat products of high yield strength structural steels in the quenched and tempered condition.
EN 10027, designation systems for steel
Part 1: 1992, Steel names, principal symbols.
EN 10210, Hot finished structural hollow sections of non-alloy and fine grain structural steels.
Part 1: 2006, Technical delivery requirements.
EN 10219, Cold formed welded structural hollow sections of non-alloy and fine grain steels.
Part 1: 2006 Technical delivery conditions
PD 6622:1998, CR 10260:1998, Designation systems for steel. Additional symbols.
PD 6695-1-10:2009, Recommendations for the design of structures to BS EN 1993-1-10

Table 1 *Summary of grades available*

EN 10025-2: Hot rolled products of non-alloy structural steels		
Designation	Impact strength t = 10 150mm	Max CEV t = 40 -150mm
S275JO S275J2	27J @ 0°C 27J @ –20°C	0.42 0.42
S355J0 S355J2 S355K2	27J @ 0°C 27J @ –20° 40J @ –20°C	0.47 0.47 0.47
Grade S235 is available, but is not used for bridge work. Delivery conditions: may be specified as normalized/ normalized rolled (+N) or as rolled (+AR).		

EN 10025-3: Hot rolled products in weldable fine grain structural steels: normalized/ normalized rolled steels		
Designation	Impact strength t = 10 150mm	Max CEV t = 63 – 100mm
S275N S275NL	40J @ –20°C 27J @ –50°C	0.40 0.40
S355N S355NL	40J @ –20°C 27J @ –50°C	0.45 0.45
S420N S420NL	40J @ –20°C 27J @ –50°C	0.50 0.50
S460N S460NL	40J @ –20°C 27J @ –50°C	0.54 0.54
Delivery conditions: normalized/normalized rolled		

EN 10025-4: Hot rolled products in weldable fine grain structural steels: thermomechanical rolled steels		
Designation	Impact strength t = 10 150mm	Max CEV t = 63 – 150mm
S275M S275ML	40J @ –20°C 27J @ –50°C	0.38 0.38
S355M S355ML	40J @ –20°C 27J @ –50°C	0.45 0.45
S420M S420ML	40J @ –20°C 27J @ –50°C	0.47 0.47
S460M S460ML	40J @ –20°C 27J @ –50°C	0.48 0.48
Delivery conditions: thermomechanical rolled		

EN 10025-5: Structural steels with improved atmospheric corrosion resistance		
Designation	Impact strength	Max CEV
S355J0W S355J2W S355K2W	27J @ 0°C 27J @ –20°C 40J @ –20°C	0.52 0.52 0.52
Grade S235 is available, but is not used for bridge work, nor is subgrade P of S355. Delivery conditions: may be specified as normalized/ normalized rolled (+N) or as rolled (+AR).		

EN 10025-6: Flat products in the quenched and tempered condition		
Designation	Impact strength	Max CEV t = 50 -100mm
S460Q S460QL S460QL1 S690 S690QL S690QL1	30J @ –20°C 30J @ –40°C 30J @ –60°C 30J @ –20°C 30J @ –40°C 30J @ –60°C	0.48 0.48 0.48 0.77 0.77 0.77
Other strength grades are available but S460 and S690 are most commonly used. Grades up to S700 are covered by EN 1993-1-12. Delivery conditions: quenched and tempered		

EN 10210: Hot finished structural hollow sections of non-alloy and fine grain structural steels		
Designation	Impact strength	Max CEV* t = 16 – 40mm
Non-alloy S275JOH S275J2H	 27J @ 0°C 27J @ –20°	 0.43 0.43
S355J0H S355J2H	27J @ 0°C 27J @ –20°C	0.47 0.47
Fine grain S275NH S275NLH	 40J @ –20°C 27J @ –50°C	 0.40 0.40
S355NH S355NLH	40J @ –20°C 27J @ –50°C	0.45 0.45
S460NH S460NLH	40J @ –20°C 27J @ –50°C	
Delivery conditions: J0, J2, hot finished N, normalized/normalized rolled * Max CEV values apply only if agreed at the time of order		