High Strength Steel

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Introduction

There appears to be a gradual trend towards the use of higher strength steel. 20 Years ago, S275 was the norm, and S355 the exception. Now, S355 is the norm, and higher strength steels are available. The use of higher strength steels is facilitated in the Eurocodes, with strengths up to S460 covered in BS EN 1993-1-1 and even higher strengths, up to S700 covered by supplementary rules in BS EN 1993-1-12. As a further indication of emerging trends, it is likely that when BS EN 1993-1-1 is revised, the scope will be increased to cover steels up to S700, with even higher strengths, up to S960, covered in BS EN 1993-1-12.

Table 1 summarises the steel grades and quality covered in the Standards generally cited for building steelwork.

Standard		Steel Grade	Steel Quality
EN 10025-2	Non-alloy structural steels	S275, S355	JR, J0, J2, K2
EN 10025-3	Normalized/normalized rolled weldable fine grain structural steels	S275, S355, S420, S460	N, NL
EN 10025-4	Thermomechanical rolled weldable fine grain structural steels	S275, S355, S420, S460	M, ML
EN 10025-6	Flat products of high yield strength structural steels in the quenched and tempered condition	S460, 500, 550, 620, 690, 890, 960	Q, QL, QL1
EN 10210-1 *	Hot finished structural hollow sections of non-alloy and fine grain steel	Non alloy S275, S355	JRH, J0H, J2H, K2H
		Fine grain S275, 355, 420, 460	NH, NLH,
EN 10219	Cold formed welded structural hollow sections of non-alloy and fine grain steels	Non alloy S275, S355	JRH, J0H, J2H, K2H
		Fine grain S275, 355, 420, 460	NH, NLH
* The next revision of EN 10210 will include steels up to S960.			

Table1: European material specifications for steel

Steel properties like strength and toughness depend both on the chemical composition and processing procedures; steel producers use a wide range of methods to achieve the required balance of properties. Although the easiest way to improve the strength of steel is to increase its carbon content, this reduces other important properties like weldability, toughness and formability. Microalloying with elements like niobium, vanadium or titanium in amounts below 0.1 wt % (1000 grams/tonne) is a cost-effective method of achieving a balanced combination of properties.

Design using high strength steels

Figure 1 demonstrates the changing stress-strain behaviour with increasing steel strength. As the strength increases, the ratio of ultimate to yield strength reduces, and the ductility also reduces, although the reduction is not significant enough to affect the design of the majority of structures. Due to these differences in stress-strain characteristics, a few design rules require modification for the higher strength steels.

BS EN 1993-1-12 relaxes the minimum required ratio of the ultimate

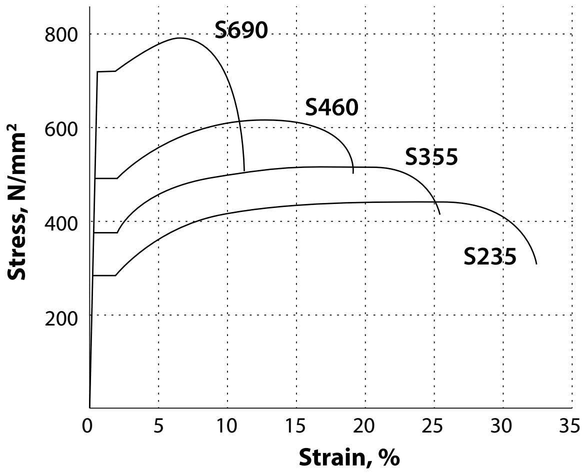

Figure 1: Stress strain characteristics of high strength steels

tensile strength to the yield strength (f_u/f_y) to 1.05 (compared to 1.1 for conventional strength steels) and the elongation at failure is only required to exceed 10% (compared to 15% for conventional strength steels). However, as a result of these restrictions, plastic analysis and semi-rigid joints are not permitted.

Steel strength

For higher strength steels, the 'design strength' does not follow the familiar pattern of a 10 N/mm² reduction at each 'step' in material thickness. The product Standard must be carefully considered when using steels above S355. Table 2 shows the steel strengths for S460.

Thickness (mm)	≤ 16	> 16 ≤ 40	> 40 ≤ 63	> 63 ≤ 80	> 80 ≤ 100
f_y (N/mm²)	460	440	430	410	400

Table 2: Steel strengths from EN 10025-4 for S460

Member classification

As the yield strength increases, members may move into a higher (more onerous) class. In Table 5.2 of BS EN 1993-1-1, the classification limits are based on ε, which itself is based on the yield strength of the steel.

$\varepsilon = \sqrt{\dfrac{235}{f_y}}$, so as f_y increases, each limit, based on ε, will decrease.

Flexural Buckling

As the steel strength increases, members are less sensitive to imperfections and the residual stresses - they are a smaller proportion of the design strength. This is reflected in BS EN 1993-1-1, where a higher flexural buckling curve is permitted for most section shapes in S460. Notably, there is no improvement for cold formed hollow sections, channels and angles. For hot-rolled sections, the improvement can be significant, in addition to the increase in strength.

A second effect is that slenderness is increased, as the yield strength increases, but this is much less significant than the increase in strength combined with the improved buckling curve.

The increase in resistance is more pronounced at low to medium slenderness. At high slenderness, the improvement is modest, as can be seen in Figure 2.

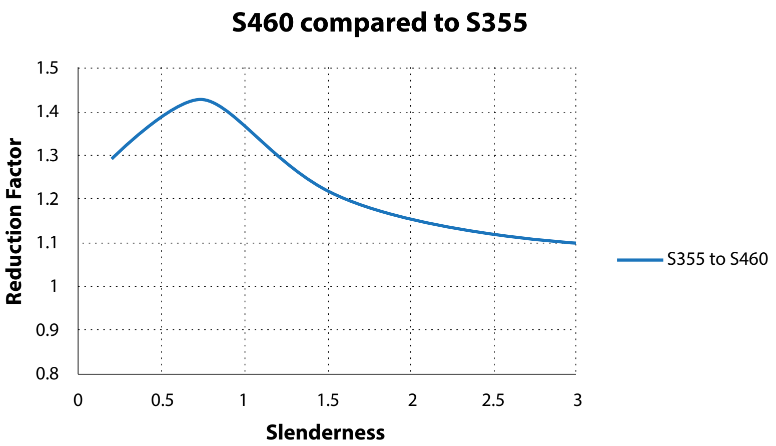

Figure 2 Comparative flexural resistance between S355 and S460 – minor axis

Two examples are shown below to illustrate the values shown in Figure 2. Clause 6.3.1 of BS EN 1993-1-1 should be consulted.

Example 1: 305 UKC 118, 6 m length

$$N_{cr} = \frac{\pi^2 EI}{L^2} = \frac{\pi^2 \times 210000 \times 9060 \times 10^4}{6000^2} \times 10^{-3} = 5216 \text{ kN}$$

In S355, $\bar{\lambda} = \sqrt{\frac{Af_y}{N_{cr}}} = \sqrt{\frac{150 \times 10^2 \times 345}{5216 \times 10^3}} = 0.99$

Note the use of 345 N/mm² as $t_f > 16$ mm

In the minor axis, curve c is to be used, so $\alpha = 0.49$

$$\phi = 0.5\left[1 + \alpha\left(\bar{\lambda} - 0.2\right) + \bar{\lambda}^2\right] = 0.5\left[1 + 0.49\left(0.99 - 0.2\right) + 0.99^2\right] = 1.184$$

$$\chi = \frac{1}{\phi + \sqrt{\phi^2 - \bar{\lambda}^2}} = \frac{1}{1.184 + \sqrt{1.184^2 - 0.99^2}} = 0.545$$

$N_{b,Rd} = 0.545 \times 150 \times 102 \times 345 \times 10^{-3} = 2820$ kN

In S460, $\bar{\lambda} = \sqrt{\frac{Af_y}{N_{cr}}} = \sqrt{\frac{150 \times 10^2 \times 440}{5216 \times 10^3}} = 1.125$

Note the use of 440 N/mm² as $t_f > 16$ mm; design grades in S460 do not follow the usual 10 N/mm² steps.

In the minor axis, curve a is to be used, so $\alpha = 0.21$

$$\phi = 0.5\left[1 + \alpha\left(\bar{\lambda} - 0.2\right) + \bar{\lambda}^2\right] = 0.5\left[1 + 0.21\left(1.125 - 0.2\right) + 1.125^2\right] = 1.23$$

$$\chi = \frac{1}{\phi + \sqrt{\phi^2 - \bar{\lambda}^2}} = \frac{1}{1.23 + \sqrt{1.23^2 - 1.125^2}} = 0.579$$

$N_{b,Rd} = 0.579 \times 150 \times 102 \times 440 \times 10^{-3} = 3821$ kN

The resistance of the S460 column is 1.35 that of the S355 column. This corresponds to a slenderness of 1.0 in Figure 2.

Example 2: 305 UKC 118, 12 m length

$$N_{cr} = \frac{\pi^2 EI}{L^2} = \frac{\pi^2 \times 210000 \times 9060 \times 10^4}{12000^2} \times 10^{-3} = 1304 \text{ kN}$$

In S355, $\bar{\lambda} = \sqrt{\frac{150 \times 10^2 \times 345}{1304 \times 10^3}} = 1.99$

$$\phi = 0.5\left[1 + 0.49\left(1.99 - 0.2\right) + 1.99^2\right] = 2.919$$

$$\chi = \frac{1}{2.919 + \sqrt{2.919^2 - 1.99^2}} = 0.198$$

$N_{b,Rd} = 0.198 \times 150 \times 10^2 \times 345 \times 10^{-3} = 1025$ kN

In S460, $\bar{\lambda} = \sqrt{\frac{150 \times 10^2 \times 440}{1304 \times 10^3}} = 2.25$.

In the minor axis, curve a is to be used, so $\alpha = 0.21$

$$\phi = 0.5\left[1 + 0.21\left(2.25 - 0.2\right) + 2.25^2\right] = 3.247$$

$$\chi = \frac{1}{3.247 + \sqrt{3.247^2 - 2.25^2}} = 0.179$$

$N_{b,Rd} = 0.179 \times 150 \times 10^2 \times 440 \times 10^{-3} = 1181$ kN

At this higher slenderness, the improvement in resistance is 15%, illustrating the diminishing advantage shown in Figure 2 at higher slenderness.

Lateral torsional buckling

The relationship between steel strengths and lateral torsional buckling resistance is more complicated than flexural buckling, because of the influence of the shape of the bending moment diagram. As the steel strength increases, the slenderness increases, but the effect is modified by the f factor found in clause 6.3.2.3(2) of BS EN 1993-1-1. The same LTB curves are used for all steel grades.

Until the end of the plateau at a slenderness of 0.4, clearly the full increase in strength can be utilised. As slenderness increases, and buckling behaviour becomes more significant, the advantage of the increased strength diminishes.

Where to consider high strength steel…

The advantages of higher strength steels are lighter weights for similar resistance, so applications where light weight, or where smaller cross sections are required, are situations where higher strength steel may be advantageous. Higher strength steels are used in long span bridges where minimising self weight is important. Reduced self weight can also be a significant benefit in long span roof structures such as stadia and aircraft hangers.

…and where not.

Reduced section sizes mean reduced second moment of area, so any situation where deflection is dominating the design or where fatigue is critical will not benefit from higher strength. Similarly, decreased stiffness may increase the vibration response.

Where might steel strengths be in another 20 years?

Perhaps there is no definitive answer, but it seems likely based on the last two decades that higher strengths will be in more common use. When revised, the Eurocodes will bring some higher strength steels into the 'general rules' indicating their increased use. At present, SCI is co-ordinating a pan-European RFCS project *HILONG*, looking at new technologies to enable a greater proportion of the strength of higher strength steels to be exploited in long span truss structures. The structural performance of innovative cross-sections with greater resistance to local buckling, such as U shapes and polygonal shapes, is also being studied.