TATA STEEL

TATA

Celsius® S460NH

Design examples to EN1993-1-1

CONTENTS

CELSIUS® HOT FINISHED HOLLOW SECTIONS

Celsius® offers stronger, lighter, more cost-effective and aesthetically pleasing structures to help meet and exceed the most demanding and challenging applications.

Available in a wide range of circular, square, rectangular and elliptical hollow sections, the strength and weldable qualities of Celsius® mean that it can be used for all structural and mechanical applications, including multi-storey columns, space frames, lattice trusses and beams and frames for cranes, machinery & trailers as well as critical parts like axles.

Made exclusively from normalized, fine grain steel the Celsius® range is fully stress-relieved with uniform mechanical properties and improved weldability thanks to a low Carbon Equivalent Value (CEV) while the controlled silicon content ensures excellent galvanisation.

Alongside the popular S355NH grade, we also manufacture Celsius® fully normalized true hot finished hollow sections in high strength S420NH and S460NH to bring the advantages of Celsius® into a new age of light-weight, sustainable structures. For exceptional toughness in low temperature conditions, we can supply Celsius® in NLH grades too and we even manufacture a range of grades specifically certified for offshore structures. Celsius® is also now available in a weathering grade variant to provide ultimate durability in long-life, low-maintenance structures.

Celsius® - Hot finished hollow sections to EN 10210

- Circular (CHS)
- Square (SHS)
- Rectangular (RHS)
- Elliptical (EHS)

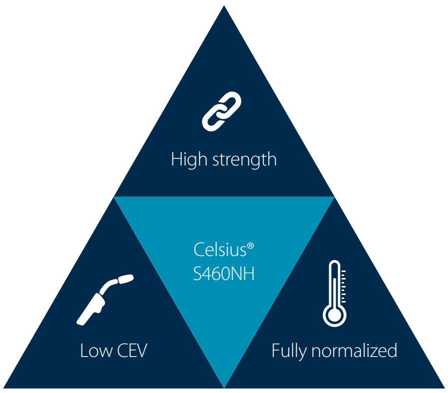
- ✓ S355NH
- ✓ S355NLH
- ✓ S355 Weathering
- ✓ S420NH
- ✓ S460NH

CELSIUS® S460NH

Celsius® S460NH has all the advantages of a true hot finished, fully normalized hollow section, but with an improved yield strength for lean, strong structures.

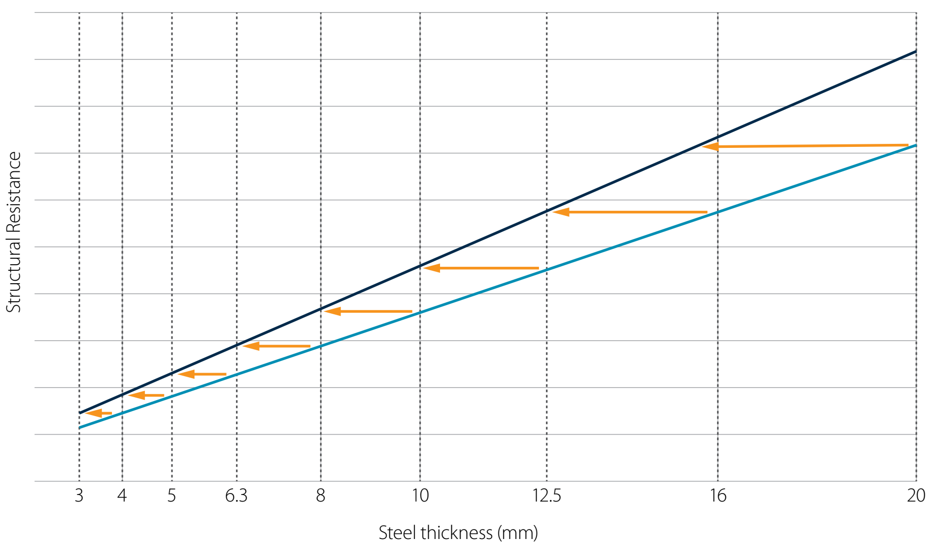
The latest advances in hot finished tube manufacturing now enable us to offer Celsius® true hot finished hollow sections with a minimum yield strength of 460 N/mm² while at the same time maintaining the low CEV of 0.45 max. This unique combination of high strength, fully normalized hollow sections with a low CEV makes this the ideal enabler for stronger, lighter-weight, more economical and more sustainable structures.

Advantages of Celsius® S460NH



Whenever the section size is determined by yield strength, using S460NH enables a thinner standard gauge of Celsius® hollow section to be used. This leads to a saving of at least 20% in steel weight and a saving of at least 20% in associated embodied CO_2-footprint. The total saving in cost and embodied emissions can be much greater since a lighter-weight structure can reduce the demands on other elements such as foundations.

Structural ability versus steel thickness



Key

S460NH
S355NH

DESIGNING TO EN1993-1-1 WITH CELSIUS® S460NH

Most practical structural design is performed in accordance with standards and in the UK and Europe, the relevant standard is EN1993-1-1. This publication reports some typical examples of calculations for the use of Celsius® S460NH hollow sections in accordance with EN1993-1-1 using the relevant UK National Annexes.

The following pages show detailed design calculation examples using Celsius® S460NH true hot finished hollow sections. To enable comparison of S460NH over S355NH and S420NH a summary table for each example shows all the results to demonstrate the potential weight saving using S460NH.

In all calculations, the specific size chosen is the most efficient to achieve the specified loading capacity. Where comparisons between grades S355NH, S420NH and S460NH are made, again the most efficient standard size is chosen, although in some cases comparisons are made by changing the steel thickness and/or cross-sectional size respectively.

In all the examples, it has been demonstrated that a thinner gauge of steel can be specified using S460NH grade rather than S355NH. Of course, this is not the case in all uses of hollow sections, but in most cases using a higher yield-strength steel will be of benefit where the member is in tension, compression or bending. However, where designs are deflection-limited, these benefits may be reduced.

Celsius® hollow sections are manufactured with wall thicknesses of 3.0mm, 4.0mm, 5.0mm, 6.3mm, 8.0mm, 10.0mm, 12.5mm, 14.2mm, 16.0mm and 17.5mm. To show the benefits of using high strength S460NH the comparisons presented, in some cases, use thicker sections (20mm and 22mm) outside of the Celsius® range which are generally significantly more expensive due to manufacturing and fabrication.

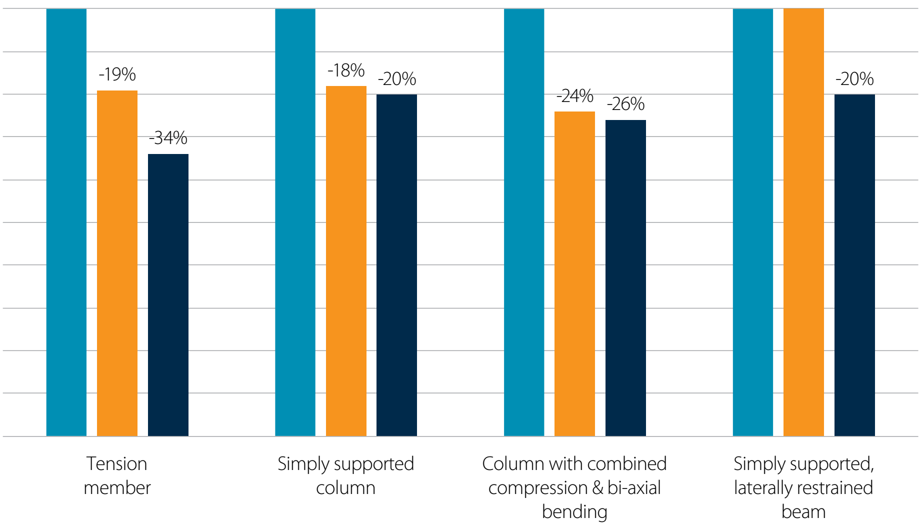
DESIGN EXAMPLES USING CELSIUS® S460NH

The following examples are provided for calculations to EC3.1.1 using Celsius® S460NH hollow sections.

1. Tension Member
2. Simply Supported Column
3. Combined Compression & Bi-Axial Bending Column
4. Simply Supported, Laterally Restrained Beam

The chart below demonstrates the percentage weight savings achieved when using grade S460NH over S420NH and S355NH in the four design examples presented here.

Percentage of weight saving



Key

S355NH S420NH S460NH

Job No:	Ex-01	**Sheet:**	1 of 2
Made by:	KB	**Date:**	10/11/2020
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Job title:	Design examples for Celsius® S460NH (EN10210:S460NH)		
Subject:	Tension Member Design		

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Tension member design

In accordance with EN1993-1-1:2005+A1:2014 incorporating Corrigenda February 2006 and April 2009 and the UK National Annex NA+A1:2014 to BS EN 1993-1-1:2005+A1:2014

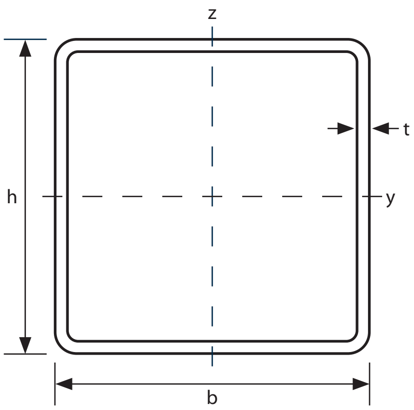
In this example we are checking an SHS for a simple axial load of 2750 kN in a tie member. The section has no fixing holes, welded T-stubs will be used for end fixing.

Figure 1:

Partial factors - Section 6.1

Resistance of cross-sections $\gamma_{M0} = 1.0$

Figure 2:



SHS 200x200x8.0 Tata Steel Celsius® S460 (EN10210:S460NH) Section properties - Tata Steel 'Design data for structural hollow sections' (www.tatasteelbluebook.com)

Steel grade	S460NH
Section depth	h = 200 mm
Section breadth	b = 200 mm
Section thickness	t = 8.0 mm
Section mass	M = 47.7 kg/m
Section area	A = 60.8 cm^2

Material properties - Section 3.2.1(1)

UK National Annex (NA.2.4) requires f_y and f_u to be obtained from the product standard - EN 10210-1:2006;

Minimum yield strength $f_y = 460$ N/mm^2

Member loading

Axial design load $N_{Ed} = 2750$ kN (Tension)

Resistance of cross section - Section 6.2

Tension - Section 6.2.3

Check tension utilisation

$$\frac{N_{Ed}}{N_{t,Rd}} \leq 1.0$$

Design tension resistance (6.2.3(2))

$$N_{t,Rd} = \frac{A\, f_y}{\gamma_{M0}}$$

$$N_{t,Rd} = \frac{60.8 \times 460}{10 \times 1.0} = 2797 \text{ kN}$$

Tension utilisation

$$\frac{N_{Ed}}{N_{t,Rd}} = \frac{2750}{2797} = 0.983 \leq 1.0$$

PASS - Design tension resistance exceeds design tension

Summary of Weight Saving using Celsius® S460NH to EN10210

The table below shows the advantage of using the higher grade EN10210 S460NH compared to EN10210 S355NH & S420NH.

Description	Units	Celsius® S355NH	Celsius® S420NH	Celsius® S460NH
Size	mm	200x200x12.5	200x200x10.0	200x200x8.0
Tension resistance[1)]	kN	3270	3150	2800
Mass	Kg/m	72.3	58.8	47.7
Weight saving	%	**0**	**19**	**34**

[1)] Axial resistance obtained from 'Design data for structural hollow sections' online Tata Steel Blue Book

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Subject:	Simply Supported Column Design		

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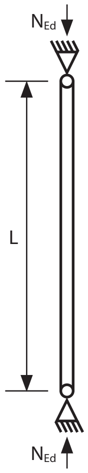
Simply supported column design

In accordance with EN1993-1-1:2005+A1:2014 incorporating Corrigenda February 2006 and April 2009 and the UK National Annex NA+A1:2014 to BS EN 1993-1-1:2005+A1:2014

For this example assume a simply supported 6 m column pinned in both axes and at both ends with an axial load of 8000 kN compression.

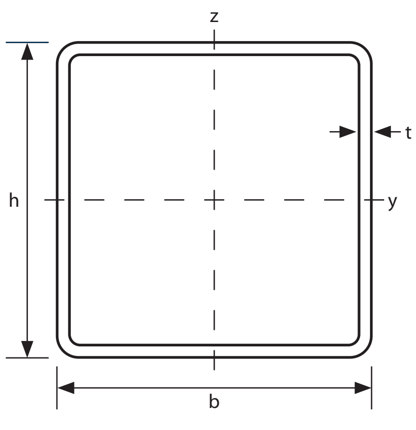
Figure 1: Column



Partial factors - Section 6.1

Resistance of cross-sections	$\gamma_{M0} = 1.0$
Resistance of members to instability	$\gamma_{M1} = 1.0$

Figure 2: Section



SHS 350x350x16.0 Tata Steel Celsius® S460NH (EN10210:S460NH) Section properties - Tata Steel 'Design data for structural hollow sections' (www.tatasteelbluebook.com)

Steel grade	S460NH
Section depth	h = 350 mm
Section breadth	b = 350 mm
Section thickness	t = 16 mm
Section mass	M = 166 kg/m
Section area	A = 211 cm^2
Section radius of gyration	i = 13.6 cm

Material properties - Section 3.2.1(1)

UK National Annex (NA.2.4) requires f_y and f_u to be obtained from the product standard - EN 10210-1:2006;

Minimum yield strength $f_y = 460\ \text{N/mm}^2$

Column loading

Axial load $N_{Ed} = 8000$ kN (Compression)

Buckling length for flexural buckling

System length for buckling, both axes $L = 6000$ mm

Buckling length, both axes $L_{cr} = 1.0\ L$

Buckling length, both axes $L_{cr} = 6000 \times 1.0 = 6000$ mm

Section classification - EN 1993-1-1 Table 5.2 sheet 1

Normally, both the flange and web section classification should be checked. However, in this example the section is only subject to compression, so equally loaded, and being square, is equal section properties, so all sides have equal load. Therefore, only one side need be checked.

Internal compression part subject to compression

Coefficient depending on f_y

$$\varepsilon = \sqrt{\frac{235}{f_y}}$$

$$\varepsilon = \sqrt{\frac{235}{460}} = 0.71$$

Depth between fillets

$c = h - 3 \times t$

$c = 350 - 3 \times 16 = 302.0$ mm

Ratio of c/t

$$\frac{c}{t} = \frac{302}{16} = 18.88$$

Limit for class 1 flange

$$\frac{c}{t} \leq 33 \times \varepsilon$$

$$\frac{302}{16} \leq 33 \times 0.71$$

$18.88 \leq 23.59$

PASS - The section is class 1

Care has been taken to ensure that this information is accurate, but Tata Steel UK, including its subsidiaries, does not accept responsibility or liability for errors or information which is found to be misleading.

Resistance of cross section - Section 6.2
Compression - Section 6.2.4

Check compression utilisation $\frac{N_{Ed}}{N_{c,Rd}} \leq 1.0$

Design resistance (Class 1, 2 or 3) $N_{c,Rd} = N_{pl,Rd} = \frac{A \times f_y}{\gamma_{M0}}$

$$N_{c,Rd} = \frac{211 \times 460}{1.0} \times 10^{-1} = 9707 \text{ kN}$$

Compression utilisation $\frac{N_{Ed}}{N_{c,Rd}} = \frac{8000}{9707} = 0.824 < 1.0$

PASS - The compression design resistance exceeds the design force

Buckling resistance - Section 6.3

Check buckling utilisation $\frac{N_{Ed}}{N_{b,Rd}} \leq 1.0$

Relative slenderness (6.3.1.3)

$\lambda_1 = 93.9\ \varepsilon$
$\lambda_1 = 93.9 \times 0.71 = 66.7$

Non-dimensional slenderness (6.3.1) $\bar{\lambda} = \frac{L_{cr}}{i\ \lambda_1}$

$$\bar{\lambda} = \frac{6000}{13.6 \times 10 \times 66.7} = 0.661$$

Buckling curve (Table 6.2) a_0 (for S460 hot finished)
Imperfection factor (Table 6.1) $\alpha = 0.13$
Parameter Φ

$\Phi = 0.5 \times [1 + \alpha \times (\bar{\lambda} - 0.2) + \bar{\lambda}^2]$
$\Phi = 0.5 \times [1 + 0.13 \times (0.661 - 0.2) + 0.661^2] = 0.748$

Reduction factor $\chi = \frac{1}{\Phi + \sqrt{\Phi^2 - \bar{\lambda}^2}}$ but ≤ 1.0

$$\chi = \frac{1}{0.748 + \sqrt{0.748^2 - 0.661^2}} = 0.911 \text{ but } \leq 1.0$$

$$\chi = 0.911$$

Care has been taken to ensure that this information is accurate, but Tata Steel UK, including its subsidiaries, does not accept responsibility or liability for errors or information which is found to be misleading.

Design buckling resistance

$$N_{b,Rd} = \frac{\chi A f_y}{\gamma_{M1}} \text{ (Class 1, 2 or 3)}$$

$$N_{b,Rd} = \frac{0.911 \times 211 \times 460}{1.0 \times 10} = 8842 \text{ kN}$$

Buckling utilisation

$$\frac{N_{Ed}}{N_{b,Rd}} = \frac{8000}{8842} = 0.905 < 1.0$$

PASS - The axial load buckling resistance exceeds the design axial load

Summary of Weight Saving using Celsius® S460NH to EN10210

The table below shows the advantage of using the higher grade EN10210 S460NH compared to EN10210 S355NH & S420NH.

Description	Units	S355NH	S355NH	S420NH	S460NH
Size	mm	400x400x17.5	350x350x20 [3]	400x400x14.2	350x350x16
Axial resistance at 6 m [1]	kN	8430 [2]	8060 [2]	8290	8840
Mass	Kg/m	208	204	170	166
Weight saving	%	**0**	**2**	**18**	**20**

[1] Axial resistance obtained from 'Design data for structural hollow sections' online Tata Steel Blue Book

[2] UK National Annex (NA.2.4) requires f_y and f_u to be obtained from the product standard, EN 10210-1:2006 gives a reduction over 16 mm thickness

[3] This size not currently available in Celsius® range, included for comparison

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Subject:	Combined Compression & Bi-axial Bending Column Design		

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Combined compression & bi-axial bending column design

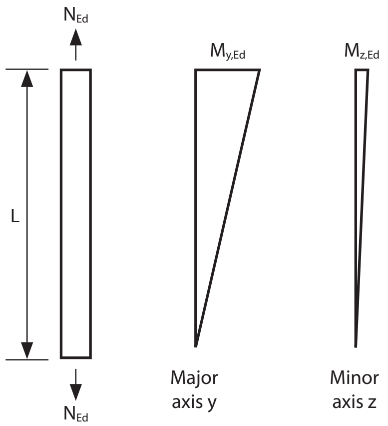
In accordance with EN1993-1-1:2005+A1:2014 incorporating Corrigenda February 2006 and April 2009 and the UK National Annex NA+A1:2014 to BS EN 1993-1-1:2005+A1:2014

This example assumes a simply supported 6 m column, with the base pinned in both axes. Member design bending moment forces at the top of the column are 70 kNm in the major axis and 25 kNm in the minor axis. The coexisting axial force is 7500 kN compression.

There is no shear force present.

The column is not part of a sway frame in either axis.

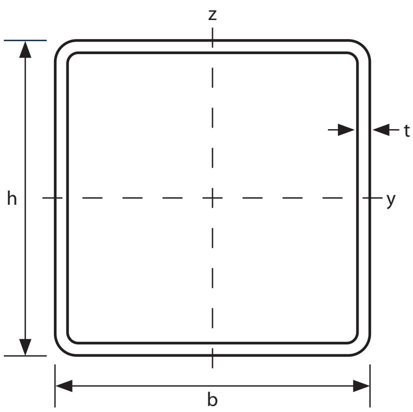
Figure 1: Column member forces



Partial factors - Section 6.1

Resistance of cross-sections	$\gamma_{M0} = 1.0$
Resistance of members to instability	$\gamma_{M1} = 1.0$

Figure 2: Section



SHS 350x350x16.0 Tata Steel Celsius® S460NH (EN10210:S460NH) Section properties - Tata Steel 'Design data for structural hollow sections' (www.tatasteelbluebook.com)

Steel grade	S460NH
Section depth	$h = 350$ mm
Section breadth	$b = 350$ mm
Section thickness	$t = 16$ mm
Section mass	$M = 166$ kg/m
Section area	$A = 211$ cm^2
Second moment of area, both axes	$I_y = I_z = 38900$ cm^4
Section plastic modulus, both axes	$W_{pl,y} = W_{pl,z} = 2630$ cm^3

Material properties - Section 3.2.1(1)

UK National Annex (NA.2.4) requires f_y and f_u to be obtained from the product standard - EN 10210-1:2006;

Minimum yield strength	$f_y = 460\ \text{N/mm}^2$
Minimum tensile strength	$f_u = 540\ \text{N/mm}^2$
Modulus of elasticity	$E = 210\ \text{kN/mm}^2$

Column loading

Axial load	$N_{Ed} = 7500$ kN (Compression)
Major axis moment at end 1 - Bottom	$M_{y,Ed1} = 0.0$ kNm
Major axis moment at end 2 - Top	$M_{y,Ed2} = 70.0$ kNm
	Major axis bending is single curvature
Minor axis moment at end 1 - Bottom	$M_{z,Ed1} = 0.0$ kNm
Minor axis moment at end 2 - Top	$M_{z,Ed2} = 25.0$ kNm
	Minor axis bending is single curvature
Major axis shear force	$V_{y,Ed} = 0$ kN
Minor axis shear force	$V_{z,Ed} = 0$ kN

Buckling length for flexural buckling

System length for buckling, both axes	$L_y = L_z = 6000$ mm
Buckling length, both axes	$L_{cr,y} = L_{cr,z} = 6000$ mm

Web section classification (Table 5.2) – Simplified Method

Conservatively, check webs as internal compression parts, subject to compression;

Coefficient depending on f_y — $\varepsilon = 0.71$

Alternatively from calculation

$$\varepsilon = \sqrt{\frac{235}{f_y}}$$

$$\varepsilon = \sqrt{\frac{235}{460}} = 0.71$$

Depth between fillets

$$c_w = h - 3 \times t$$

$$c_w = 350 - 3 \times 16 = 302.0\text{mm}$$

Ratio of c/t (web)

$$\text{ratio}_w = \frac{c_w}{t}$$

$$\text{ratio}_w = \frac{302}{16} = 18.88$$

Limit for class 1 web

$$\text{Limit}_{1w} = 33\ \varepsilon$$

$$\text{Limit}_{1w} = 33 \times 0.71 = 23.43$$

Class 1 web check

$$\text{ratio}_w \leq \text{Limit}_{1w}$$

$$18.88 \leq 23.43$$

Flange section classification (Table 5.2)
The flange should be checked as an internal compression part, subject to compression. However, an SHS section is equal about both axes, so the calculations will be the same as the check above for the webs as internal compression parts, subject to compression.

PASS - The compression design resistance exceeds the design force

Overall section classification

The overall section classification is class 1

Resistance of cross section (cl. 6.2)
Compression (cl. 6.2.4)

Check compression utilisation $\frac{N_{Ed}}{N_{c,Rd}} \leq 1.0$

Design resistance $N_{c,Rd} = N_{pl,Rd} = \frac{A \times f_y}{\gamma_{M0}}$ (Class 1, 2 or 3)

$$N_{c,Rd} = N_{pl,Rd} = \frac{211 \times 460}{1.0} \times 10^{-1} = 9706 \text{ kN}$$

Compression utilisation $\frac{N_{Ed}}{N_{c,Rd}} = \frac{7500}{9706} = 0.773 < 1.0$

PASS - The compression design resistance exceeds the design force

Combined bending and axial force (cl. 6.2.9)

Check bending and axial force utilisation $\frac{M_{Ed}}{M_{N,Rd}} \leq 1.0$ (Class 1, 2 or 3)

Ratio design axial to design plastic resistance $n = \frac{N_{Ed}}{N_{pl,Rd}}$

$$n = \frac{7500}{9706} = 0.773$$

Reduced bending resistance due to axial force - Major axis (cl. 6.2.9.1 (5))

Plastic design resistance $M_{pl,y,Rd} = \frac{M_{pl,y} f_y}{\gamma_{M0}}$

$$M_{pl,y,Rd} = \frac{2630 \times 460}{1.0} \times \frac{1}{1000} = 1209.8 \text{ kN}$$

Ratio web area to gross area

$$a_w = \frac{A - 2b\,t}{A} \quad \text{but} \quad \leq 0.5$$

$$a_w = \frac{211 - (2 \times 350 \times 16)/10^2}{211} = 0.469 \quad \text{but} \quad \leq 0.5$$

$$a_w = 0.469$$

Modified design resistance

$$M_{N,y,Rd} = M_{pl,y,Rd} \times \frac{1 - n}{1 - 0.5\,a_w} \quad \text{but} \quad \leq M_{pl,y,Rd}$$

$$M_{N,y,Rd} = 1209.8 \times \frac{1 - 0.773}{1 - 0.5 \times 0.469} = 358.8 \quad \text{but} \quad \leq 1209.8 \text{ kNm}$$

$$M_{N,y,Rd} = 358.8 \text{ kNm}$$

Bending and axial force utilisation

$$\frac{M_{y,Ed}}{M_{N,y,Rd}} = \frac{70}{358.8} = 0.195 \quad \leq 1.0$$

PASS - Bending resistance in presence of axial load exceeds design moment

Reduced bending resistance due to axial force - Minor axis (cl. 6.2.9.1 (5))

Plastic design resistance

$$M_{pl,z,Rd} = \frac{W_{pl,z}\,f_y}{\gamma_{M0}}$$

$$M_{pl,z,Rd} = \frac{2630 \times 460}{1.0} \times \frac{1}{1000} = 1209.8 \text{ kN}$$

Ratio flange area to gross area

$$a_f = \frac{A - 2h\,t}{A} \quad \text{but} \quad \leq 0.5$$

$$a_f = \frac{211 - (2 \times 350 \times 16)/10^2}{211} = 0.469 \quad \text{but} \quad \leq 0.5$$

$$a_f = 0.469$$

Modified design resistance

$$M_{N,z,Rd} = M_{pl,z,Rd} \times \frac{1 - n}{1 - 0.5\,a_f} \quad \text{but} \quad \leq M_{pl,z,Rd}$$

$$M_{N,z,Rd} = 1209.8 \times \frac{1 - 0.773}{1 - 0.5 \times 0.469} = 358.8 \quad \text{but} \quad \leq 1209.8 \text{ kNm}$$

$$M_{N,z,Rd} = 358.8 \text{ kNm}$$

Bending and axial force utilisation

$$\frac{M_{z,Ed}}{M_{N,z,Rd}} = \frac{25}{358.8} = 0.070 \quad \leq 1.0$$

PASS - Bending resistance in presence of axial load exceeds design moment

Biaxial bending (cl. 6.2.9.1 (6))

Bending and axial force utilisation

$$\left[\frac{M_{y,Ed}}{M_{N,y,Rd}}\right]^{\alpha} \times \left[\frac{M_{z,Ed}}{M_{N,z,Rd}}\right]^{\beta} \leq 1.0$$

Effect of biaxial bending parameter (RHS)

$$\alpha = \beta = \frac{1.66}{1 - 1.13\, n^2} \quad \text{but} \quad \leq 6$$

$$\alpha = \beta = \frac{1.66}{1 - 1.13 \times 0.773^2} = 5.111 \quad \text{but} \quad \leq 6$$

$$\alpha = \beta = 5.111$$

Bending moments are zero at bottom of column (End 1), so only need to check section utilisation for biaxial bending at top of column (End 2).

Section utilisation, End 2

$$\left[\frac{M_{y,Ed}}{M_{N,y,Rd}}\right]^{\alpha} + \left[\frac{M_{z,Ed}}{M_{N,z,Rd}}\right]^{\beta} \leq 1.0$$

$$\left[\frac{70}{358.8}\right]^{5.11} + \left[\frac{25}{358.8}\right]^{5.11} = 0.00 \leq 1.0$$

PASS - The cross-section resistance is adequate

Buckling resistance (cl. 6.3)
Uniform members in compression (cl. 6.3.1.1)

Check buckling utilisation

$$\frac{N_{Ed}}{N_{b,Rd}} \leq 1.0$$

Flexural buckling - Major axis

Elastic critical buckling force

$$N_{cr,y} = \frac{\pi^2 E I_y}{L_{cr,y}^2}$$

$$N_{cr,y} = \frac{\pi^2 \text{ x } 210 \times 38900}{6000^2} \times 10^4 = 22395 \text{ kN}$$

Non-dimensional slenderness

$$\bar{\lambda}_y = \sqrt{\frac{A f_y}{N_{cr,y}}}$$ (Class 1, 2 or 3)

$$\bar{\lambda}_y = \sqrt{\frac{211 \text{ x } 460}{22395} \times \frac{1}{10}} = 0.658$$

Buckling curve (Table 6.2) a_0 (hollow sections, hot finished, S460)

Imperfection factor (Table 6.1) $a_y = 0.13$

Parameter Φ

$$\Phi_y = 0.5 \times [1 + \alpha_y \times (\bar{\lambda}_y - 0.2) + \bar{\lambda}_y^2]$$

$$\Phi_y = 0.5 \times [1 + 0.13 \times (0.658 - 0.2) + 0.658^2] = 0.746$$

Reduction factor for buckling, Major axis

$$\chi_y = \frac{1}{\Phi_y + \sqrt{\Phi^2 - \bar{\lambda}_y^2}} \text{ but} \leq 1.0$$

$$\chi_y = \frac{1}{0.746 + \sqrt{0.746^2 - 0.658^2}} = 0.911 \text{ but} \leq 1.0$$

$$\chi_y = 0.911$$

Design buckling resistance, Major axis

$$N_{b,y,Rd} = \frac{\chi_y A f_y}{\gamma_{M1}} \quad \text{(Class 1, 2 or 3)}$$

$$N_{b,y,Rd} = \frac{0.911 \times 211 \times 460}{1.0} \times \frac{1}{10} = 8842 \text{ kN}$$

Buckling utilisation, Major axis

$$\frac{N_{Ed}}{N_{b,y,Rd}} = \frac{7500}{8842} = 0.848 \leq 1.0$$

PASS - The cross-section resistance is adequate

Flexural buckling - Minor axis

Elastic critical buckling force

$$N_{c,z} = \frac{\pi^2 E I_z}{L_{cr,z}^2}$$

$$N_{c,y} = \frac{\pi^2 \times 210 \times 38900}{6000^2} \times 10^4 = 22395 \text{ kN}$$

Non-dimensional slenderness

$$\bar{\lambda}_z = \sqrt{\frac{A f_y}{N_{cr,z}}} \quad \text{(Class 1, 2 or 3)}$$

$$\bar{\lambda}_z = \sqrt{\frac{211 \text{ x } 460}{22395}} \times \frac{1}{10} = 0.658$$

Buckling curve (Table 6.2) a_0 (hollow sections, hot finished, S460)

Imperfection factor (Table 6.1) $\alpha_z = 0.13$

Parameter Φ

$$\Phi_z = 0.5 \times [1 + \alpha_y \times (\bar{\lambda}_z - 0.2) + \bar{\lambda}_z^2]$$

$$\Phi_z = 0.5 \times [1 + 0.13 \times (0.658 - 0.2) + 0.658^2] = 0.746$$

Reduction factor for buckling, Minor axis

$$\chi_z = \frac{1}{\Phi_z + \sqrt{\Phi^2 - \bar{\lambda}_z^2}} \text{ but} \leq 1.0$$

$$\chi_z = \frac{1}{0.746 + \sqrt{0.746^2 - 0.658^2}} = 0.911 \text{ but} \leq 1.0$$

$$\chi_z = 0.911$$

Design buckling resistance, Minor axis $N_{b,z,Rd} = \dfrac{\chi_z A f_y}{\gamma_{M1}}$ (Class 1, 2 or 3)

$$N_{b,z,Rd} = \frac{0.911 \times 211 \times 460}{1.0} \times \frac{1}{10} = 8842 \text{ kN}$$

Buckling utilisation, Minor axis $\dfrac{N_{Ed}}{N_{b,z,Rd}} = \dfrac{7500}{8842} = 0.848 \leq 1.0$

PASS - The cross-section resistance is adequate

Minimum flexural buckling resistance

Minimum flexural buckling resistance $N_{b,Rd} = \min(N_{b,y,Rd}, N_{b,z,Rd}) = 8842$ kN

Flexural buckling utilisation $\dfrac{N_{Ed}}{N_{b,Rd}} = \dfrac{7500}{8842} = 0.848 < 1.0$

PASS - The axial load buckling resistance exceeds the design axial load

Uniform members in bending (cl. 6.3.2)
Buckling resistance moment (cl. 6.3.2.1)

Check buckling resistance utilisation $\dfrac{M_{Ed}}{M_{b,Rd}} < 1.0$

Square hollow section not subject to lateral torsional buckling therefore;

Reduction factor for lateral torsional buckling $\chi_{LT} = 1.0$ (Table 6.7 Note)

Design LTB resistance moment $M_{b,Rd} = \chi_{LT} W_y \dfrac{f_y}{\gamma_{M1}}$

Appropriate section modulus $W_y = W_{pl,y}$ (cl. 6.3.2.1(3) Class 1 or 2)

$$M_{b,Rd} = 1.0 \times 2630 \times \frac{460}{1.0} \times \frac{1}{1000} = 1210 \text{ kN}$$

Design bending moment $M_{y,Ed} = \max(M_{y,Ed1}, M_{y,Ed2}) = 70.0$ kNm

Buckling resistance utilisation $\dfrac{M_{Ed}}{M_{b,Rd}} = \dfrac{70}{1210} = 0.058 < 1.0$

PASS - The buckling resistance moment exceeds the maximum design moment

Combined bending and axial compression (cl. 6.3.3)
Uniform members in bending and axial compression (cl. 6.3.3)

Check combined bending and axial compression utilisation;

Eq. (6.61)
$$\frac{N_{Ed}}{\left(\frac{\chi_y N_{Rk}}{\gamma_{M1}}\right)} + k_{yy}\frac{M_{y,Ed}+\Delta M_{y,Ed}}{\chi_{LT}\left(\frac{M_{y,Rk}}{\gamma_{M1}}\right)} + k_{yz}\frac{M_{z,Ed}+\Delta M_{z,Ed}}{\left(\frac{M_{z,Rk}}{\gamma_{M1}}\right)} \leq 1.0$$

and

Eq. (6.62)
$$\frac{N_{Ed}}{\left(\frac{\chi_z N_{Rk}}{\gamma_{M1}}\right)} + k_{zy}\frac{M_{y,Ed}+\Delta M_{y,Ed}}{\chi_{LT}\left(\frac{M_{y,Rk}}{\gamma_{M1}}\right)} + k_{zz}\frac{M_{z,Ed}+\Delta M_{z,Ed}}{\left(\frac{M_{z,Rk}}{\gamma_{M1}}\right)} \leq 1.0$$

From Table 6.7;

Characteristic resistance to compression $N_{Rk} = f_y \times A_i = f_y \times A$ (Class 1, 2 & 3)

$$N_{Rk} = 460 \times 211 \times \frac{1}{10} = 9706 \text{ kN}$$

Characteristic bending resistance, Major axis $M_{y,Rk} = f_y \times W_y = f_y \times W_{pl,y}$ (Class 1 & 2)

$$M_{y,Rk} = 460 \times 2630 \times \frac{1}{1000} = 1210 \text{ kN}$$

Characteristic bending resistance, Minor axis $M_{z,Rk} = f_y \times W_z = f_y \times W_{pl,z}$ (Class 1 & 2)

$$M_{z,Rk} = 460 \times 2630 \times \frac{1}{1000} = 1210 \text{ kN}$$

Moments due to shift of y-y axis $\Delta M_{y,Ed} = 0$ (Class 1, 2 & 3)

Moments due to shift of z-z axis $\Delta M_{z,Ed} = 0$ (Class 1, 2 & 3)

From Table B.1 (circular and square hollow sections are not susceptible to LTD);

Interaction factor k_{yy} $k_{yy} = C_{my}\left(1 + (\bar{\lambda}_y - 0.2)\frac{N_{Ed}}{\chi_y N_{Rk}/\gamma_{M1}}\right)$ but $\leq C_{my}\left(1 + 0.8\frac{N_{Ed}}{\chi_y N_{Rk}/\gamma_{M1}}\right)$ (Class 1 & 2)

Moment distribution factor, Major axis $\psi_y = \frac{M_{y,Ed1}}{M_{y,Ed2}} = \frac{0}{70} = 0.00$

Moment factor, Major axis $C_{my} = 0.6 + 0.4 \times \psi_y$ but ≥ 0.4 (Table B.3)

$C_{my} = 0.6 + 0.4 \times 0 = 0.60$

Care has been taken to ensure that this information is accurate, but Tata Steel UK, including its subsidiaries, does not accept responsibility or liability for errors or information which is found to be misleading.

Interaction factor k_{yy} $\quad k_{yy} = 0.60 \left(1 + (0.658 - 0.2)\ \dfrac{7500}{0.911 \times 9706 / 1.0}\right) \text{but} \leq 0.60 \left(1 + 0.8\dfrac{7500}{0.911 \times 9706 / 1.0}\right)$

$k_{yy} = 0.833$ but ≤ 1.007

$k_{yy} = 0.833$

Interaction factor k_{zy} $\quad k_{zy} = 0.6 \times k_{yy} = 0.6 \times 0.833 = 0.500$

Interaction factor k_{zz} $\quad k_{zz} = C_{mz} \left(1 + (\bar{\lambda}_z - 0.2)\ \dfrac{N_{Ed}}{\chi_z N_{Rk}/\gamma_{M1}}\right)$ but $\leq C_{mz} \left(1 + 0.8\dfrac{N_{Ed}}{\chi_z N_{Rk}/\gamma_{M1}}\right)$ (Class 1, 2 RHS)

Moment distribution factor, Minor axis $\quad \psi_z = \dfrac{M_{z,Ed1}}{M_{z,Ed2}} = \dfrac{0}{25} = 0.00$

Moment factor, Minor axis $\quad C_{mz} = 0.6 + 0.4 \times \psi_z$ but ≥ 0.4 (Table B.3)

$C_{mz} = 0.6 + 0.4 \times 0 = 0.60$

$$k_{zz} = 0.60 \left(1 + (0.658 - 0.2)\ \frac{7500}{0.911 \times 9706 / 1.0}\right) \text{but} \leq 0.60 \left(1 + 0.8\frac{7500}{0.911 \times 9706 / 1.0}\right)$$

$k_{zz} = 0.833$ but ≤ 1.007

$k_{zz} = 0.833$

Interaction factor k_{yz} $\quad k_{yz} = 0.6 \times k_{zz} = 0.6 \times 0.833 = 0.500$ (Class 1 & 2)

Combined bending and axial compression utilisation;

Eq. (6.61)

$$\frac{N_{Ed}}{\left(\dfrac{\chi_y N_{Rk}}{\gamma_{M1}}\right)} + k_{yy}\ \frac{M_{y,Ed} + \Delta M_{y,Ed}}{\chi_{LT}\left(\dfrac{M_{y,Rk}}{\gamma_{M1}}\right)} + k_{yz}\ \frac{M_{z,Ed} + \Delta M_{z,Ed}}{\chi_{LT}\left(\dfrac{M_{z,Rk}}{\gamma_{M1}}\right)} \leq 1.0$$

$$\frac{7500}{\left(\dfrac{0.911 \times 9706}{1.0}\right)} + 0.833\ \frac{70 + 0}{1.0\left(\dfrac{1210}{1.0}\right)} + 0.50\ \frac{25 + 0}{\left(\dfrac{1210}{1.0}\right)} \leq 1.0$$

and $\quad 0.907 \leq 1.0$

Eq. (6.62)

$$\frac{N_{Ed}}{\left(\dfrac{\chi_z N_{Rk}}{\gamma_{M1}}\right)} + k_{zy}\ \frac{M_{y,Ed} + \Delta M_{y,Ed}}{\chi_{LT}\left(\dfrac{M_{y,Rk}}{\gamma_{M1}}\right)} + k_{zz}\ \frac{M_{z,Ed} + \Delta M_{z,Ed}}{\chi_{LT}\left(\dfrac{M_{z,Rk}}{\gamma_{M1}}\right)} \leq 1.0$$

$$\frac{7500}{\left(\dfrac{0.911 \times 9706}{1.0}\right)} + 0.500\ \frac{70 + 0}{1.0\left(\dfrac{1210}{1.0}\right)} + 0.833\ \frac{25 + 0}{\left(\dfrac{1210}{1.0}\right)} \leq 1.0$$

$0.894 \leq 1.0$

PASS - The buckling resistance is adequate

Summary of checks and utilisation

Check	Utilisation
Bending and axial compression (y-y)	0.907
Bending and axial compression (z-z)	0.894

Summary of Weight Saving using Celsius® S460NH to EN10210
The table below shows the advantage of using the higher grade EN10210 S460NH compared to EN10210 S355NH & S420NH.

Description	Units	S355NH	S355NH	S420NH	S460NH
Size	mm	350x350x22 [1)]	400x400x16	400x400x14.2	350x350x16
Utilisation factor	-	0.938	0.994	0.955	0.907
Mass	Kg/m	223	191	170	166
Weight saving	%	**0**	**14**	**24**	**26**

[1)] Celsius® SHS 350x350 only available up to 17.5 mm thick in S355 grade, included for comparison with other manufacturers

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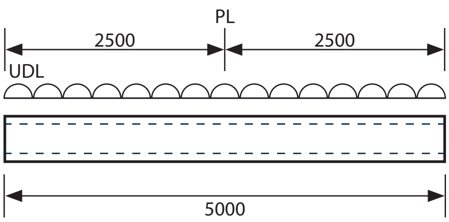
Simply supported, laterally restrained beam design

In accordance with EN1993-1-1:2005+A1:2014 incorporating Corrigenda February 2006 and April 2009 and the UK National Annex NA+A1:2014 to BS EN 1993-1-1:2005+A1:2014. References are to this standard and NA unless otherwise stated.

This example is for a 5 m span, simply supported beam, fully laterally restrained along its length. The chosen size RHS 250x150x6.3 grade S460 is checked for structural suitability and deflection.

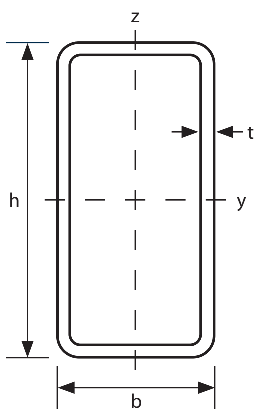
Figure 1: Beam and actions diagram



Partial factors - Section 6.1

Resistance of cross-sections $\gamma_{M0} = 1.0$

Figure 2: Section



RHS 250x150x6.3 Tata Steel Celsius® S460NH (EN10210:S460NH) Section properties - Tata Steel 'Design data for structural hollow sections' (www.tatasteelbluebook.com)

Steel grade	S460NH
Section depth	$h = 250$ mm
Section breadth	$b = 150$ mm
Section thickness	$t = 6.3$ mm
Section mass	$M = 38.0$ kg/m
Section area	$A = 48.4$ cm^2
Second moment of area, both axes	$I_y = 4140$ cm^4
Section plastic modulus, both axes	$W_{pl,y} = 402$ cm^3

Material properties - Section 3.2.1(1)

UK National Annex (NA.2.4) requires f_y and f_u to be obtained from the product standard - EN 10210-1:2006;

Minimum yield strength $f_y = 460$ N/mm^2

Modulus of elasticity $E = 210$ kN/mm^2

Beam actions (loading)

For this example assume the following loading; $F_{d,1} = 9.7$ kN/m
Combination of uniformly distributed loads (UDL): $F_{d,2} = 113.7$ kN
Combination of concentrated loads (PL): (EN1990:2002 cl 6.4.3.2)

Design bending moments and shear forces (ULS)

Span of beam $L = 5000$ mm

The maximum design bending moment value occurs at mid-span:

$$M_{Ed} = \frac{F_{d,1}\,L^2}{8} + \frac{F_{d,2}\,L}{4} = \frac{9.7 \times 5^2}{8} + \frac{113.7 \times 5}{4} = 172.4 \text{ kNm}$$

The maximum design shear value occurs at the supports:

$$V_{Ed} = \frac{F_{d,1}\,L}{2} + \frac{F_{d,2}}{2} = \frac{9.7 \times 5}{2} + \frac{113.7}{2} = 81.1 \text{ kNm}$$

The design shear force at mid-span is:

$$V_{Ed,mid} = V_{Ed} - \frac{F_{d,1}\,L}{2} = 81.1 - \frac{9.7 \times 5}{2} = 56.9 \text{ kNm}$$

Section classification (Table 5.2)
Web section classification

Check webs as internal compression parts, subject to bending;

Coefficient depending on f_y $\varepsilon = 0.71$ (From Table 5.2)

Alternatively from calculation

$$\varepsilon = \sqrt{\frac{235}{f_y}}$$

$$\varepsilon = \sqrt{\frac{235}{460}} = 0.71$$

Depth between fillets $c_w = h - 3t$

$c_w = 250 - 3 \times 6.3 = 231.1$ mm

Depth between fillets $ratio_w = \dfrac{c_w}{t} = \dfrac{231.1}{6.3} = 36.68$

Limit for class 1 web $Limit_{1w} = 72\varepsilon = 72 \times 0.71 = 51.12$

Class 1 web check $ratio_w \leq Limit_{1w}$

$36.68 \leq 51.12$

PASS - The web section is class 1

Flange section classification (Table 5.2)

Check the flange as internal compression part, subject to compression;

Depth between fillets $c_f = b - 3t$

$c_f = 150 - 3 \times 6.3 = 131.1$ mm

Ratio of c/t (flange) $ratio_f = \dfrac{C_f}{t} = \dfrac{131.1}{6.3} = 20.81$

Limit for class 1 flange $Limit_{1f} = 33\ \varepsilon$

$Limit_{1f} = 33 \times 0.71 = 23.43$

Class 1 flange check $ratio_f \leq Limit_{1f}$

$20.81 \leq 23.43$

Pass - The flange internal compression part, subject to compression is class 1

Overall section classification

The overall section classification is class 1

Alternatively, section classification from Tata Steel Blue Book;
Section class, about major axis (y-y) = Class 1 (Bending resistance tables)
The overall section classification is class 1

Resistance of cross section (cl. 6.2)
Shear resistance 6.2.6(1)

Ratio of c/t (flange) $\dfrac{V_{Ed}}{V_{c,Rd}} \leq 1.0$

For plastic design we use the desgn plastic shear resistance $V_{pl,Rd}$ given in:

Design plastic shear resistance $V_{c,Rd} = V_{pl,Rd} = \dfrac{A_v\ (f_y / \sqrt{3})}{\gamma_{M0}}$ (6.2.6(2))

For a rectangular hollow section with load parallel to the depth:

Shear area $A_v = \dfrac{A\ h}{b + h} = \dfrac{48.4 \times 250}{150 + 250} = 30.25\ \text{cm}^2$ (6.2.6(3)f)

Design plastic shear resistance $V_{c,Rd} = V_{pl,Rd} = \dfrac{30.25\ (460 / \sqrt{3})}{1.0} \times \dfrac{1}{10} = 803$ kN (6.2.6(2))

Alternatively, shear resistance from Tata Steel Blue Book;
Shear resistance $V_{c,Rd} = 803$ kN (Bending resistance tables)

Maxiumum design shear is at the ends — $V_{Ed} = 81.1$ kN

Shear utilisation — $\frac{V_{Ed}}{V_{c,Rd}} = \frac{81.1}{803} = 0.10 \leq 1.0$

PASS - The web section is class 1

Bending 6.2.5(1)

Check bending utilisation — $\frac{M_{Ed}}{M_{c,Rd}} \leq 1.0$

Assuming no fastener holes so no reduction in section area.
Check for reduction of section bending resistance due to shear force at point of maximum bending moment, mid-span in this case.

Check — $V_{Ed,mid} < \frac{V_{c,Rd}}{2} = \frac{803}{2}$ (6.2.8(2))

56.9 kN < 401.5 kN

Pass – The shear force is less than half the plastic shear resistance, effect on bending moment can be neglected

For Class 1 and 2 cross-sections bending about one principle axis, 'y' in this case, is:

Design resistance for bending — $M_{c,Rd} = M_{pl,Rd} = \frac{W_{pl,y} f_y}{\gamma_{M0}}$ (6.2.5(2))

$M_{c,Rd} = \frac{402 \times 460}{1.0} \times \frac{1}{1000} = 185$ kNm

Alternatively from Tata Steel Blue Book;
Moment resistance — $M_{c,y,Rd} = 185$ kNm (Bending resistance tables)

$\frac{M_{Ed}}{M_{c,Rd}} = \frac{172.4}{185} = 0.93 < 1.0$

Pass – The maximum design bending moment is less than the design bending resistance

Shear buckling 6.2.6(6)
In addition, the shear buckling resistance of webs without intermediate stiffeners should be checked to EN 1993-1-5 section 5.1 if:

$\frac{h_w}{t_w} > 72 \frac{\varepsilon}{\eta}$

Design resistance for bending — $h_w = h - 2t_w$

$h_w = 250 - 2 \times 6.3 = 237.4$ mm

$\frac{h_w}{t_w} = \frac{237.4}{6.3} = 36.7$

Maxiumum design shear is at the ends

$\eta = 1.0$ (NA to BS EN 1993-1-5:2006, NA.2.4)

$$72\ \frac{\varepsilon}{\eta} = 72 \times \frac{0.71}{1.0} = 51.1$$

$36.7 < 51.1$

PASS - The shear buckling resistance of the webs does not need to be checked

Lateral torsional buckling

As the beam is laterally restrained lateral torsional buckling need not be checked.

Serviceability limit states for buildings

Vertical deflection

Reference to UK NA+A1:2014 to BS EN 1993-1-1:2005+A1:2014 table NA.2 gives vertical deflection limits. For this example we shall consider the deflection limit as;

Vertical deflection limit

$$\delta_{lim} = \frac{L}{360}$$ (UK NA to BS EN 1993-1-1)

$$\delta_{lim} = \frac{5000}{360} = 13.9 \text{ mm}$$

In this example the permanent actions occur during the construction process, so for the servicability check only the variable actions need to be considered, therefore;

Uniformly distributed actions $F_{d,1,ser} = 4$ kN/m

Concentrated actions $F_{d,2,ser} = 30$ kN

Therefore, vertical deflection

$$\delta_{ser} = \left(\frac{5F_{d,1,ser}\ L^4}{384} + \frac{F_{d,2,ser}\ L^3}{48} \right) \frac{1}{E\ I_y}$$

$$\delta_{ser} = \left(\frac{5 \times 4 \times 5000^4}{384} + \frac{30 \times 10^3 \times 5000^3}{48} \right) \times \frac{1}{210000 \times 4140 \times 10^4}$$

$\delta_{ser} = 12.7$ mm

$\delta_{ser} \leq \delta_{lim}$

$12.7 \text{ mm} < 13.9 \text{ mm}$

Pass – The deflection is less than the deflection limit which is satisfactory

The Tata Steel Blue Book does not include deflection values so it has to be checked by hand as above.

Summary of checks and utilisation

Check	Units	Resistance Provided	Resistance Required	Utilisation
Shear resistance (y-y)	kN	803	81.1	0.10
Bending resistance (y-y)	kNm	184.9	172.4	0.93

	Units	Deflection	Deflection Limit	Utilisation
Serviceability for vertical deflection	mm	12.7	13.9	0.91

Summary of Weight Saving using Celsius® S460NH to EN10210

The table below shows the advantage of using the higher grade EN10210 S460NH compared to EN10210 S355NH & S420NH.

Description	Units	S355NH	S420NH	S460NH
Size	mm	250x150x8.0	250x150x8.0	250x150x6.3
Mass	Kg/m	47.7	47.7	38.0
Utilisation factor	-	0.97	0.82	0.93
Deflection (Allowable 13.9 mm)	mm	10.3	10.3	12.7
Weight saving	%	**0**	**0**	**20.3**

When deflection is the critical factor, higher stengths give less benefit as the increase in yield allows thinner sections with reduced moment of inertia which increases deflection.

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