Critical temperatures for fire design: Part 2 – Columns

Part 1 of this article discussed the calculation of critical temperatures for beams, presented by ASFP and in the UK NA to BS EN 1993-1-2. In this second part, David Brown considers the information provided for columns.

Calculation process

The calculation of critical temperatures for columns is more involved than the process for beams, but is not so complicated that it should be avoided. According to BS EN 1993-1-2, clause 4.2.3.2, the resistance of a column at elevated temperature is given by:

$$N_{b,fi,t,Rd} = \frac{\chi_{fi} A k_{y,\theta} f_y}{\gamma_{M,fi}}$$

χ_{fi} is a reduction factor, which at least looks familiar to anyone who has designed a column.

$k_{y,\theta}$ is the reduction factor for yield strength, taken from Table 3.1 of BS EN 1993-1-2.

t relates to time – the temperature increases with time, so the value of $k_{y,\theta}$ reduces and therefore also the buckling resistance.

The expressions for χ_{fi} are very similar to those used at ambient temperature and presented in the same format:

$$\chi_{fi} = \frac{1}{\varphi_\theta + \sqrt{\varphi_\theta^2 - \bar{\lambda}_\theta^2}}$$

and

$$\varphi_\theta = ½ \left[1 + \alpha\bar{\lambda}_\theta + \bar{\lambda}_\theta^2\right] \text{ with } \alpha = 0.65\sqrt{235/f_y}$$

The final modification is that the non-dimensional slenderness is adjusted to reflect the fire condition:

$$\bar{\lambda}_\theta = \bar{\lambda}\left[k_{y,\theta}/k_{E,\theta}\right]^{0.5}$$

$k_{E,\theta}$ is an adjustment to the modulus of elasticity (Young's modulus), which changes with temperature and like $k_{y,\theta}$, is taken from Table 3.1 of BS EN 1993-1-2.

Buckling length

The most drama is associated with the buckling lengths to be assumed in the fire condition. BS EN 1993-1-2 specifies that for braced frames (the bracing could be a core, shear walls or bracing), the buckling lengths are to be taken as:

- 0.7L for the top storey
- 0.5L for all intermediate storeys

Identical guidance is given in BS EN 1994-1-2, but in that standard the buckling lengths are made a Nationally Determined Parameter. The UK NA to BS EN 1994-1-2 is more cautious than the code and specifies 0.85L for the top storey and 0.7L for all intermediate storeys. There is no opportunity for national choice in BS EN 1993-1-2 with respect to the buckling lengths, leading to an "interesting" difference in assumed behaviour between bare steel and composite columns – composite columns have a longer buckling length than their bare steel cousins.

Tabulated critical temperatures

Just like for beams, both ASFP and the UK NA to BS EN 1993-1-2 present critical temperatures for columns. The presentation is markedly different – the UK NA has a matrix of non-dimensional slenderness and utilisation, whilst the ASFP has values for UC sections and hollow sections in different building types. The ASFP table has no reference to slenderness or utilisation; the UK NA makes no distinction between section types. The following sections demonstrate how the tabulated temperatures have been determined.

ASFP critical temperatures

The relevant part of the ASFP table for Eurocode design is reproduced below (temperatures in °C).

Building type	Hot rolled H section columns in compression	Hot finished/formed structural hollow sections
Office/domestic	536	547
Storage	530	512
Shopping / congregational / car park	539	521

The ASFP temperatures are stated to be based on:

- 60% utilisation in fire (but this is not true);
- S275 steel;
- A "mid-range" UC section;
- Storey height of 3.5 m;
- A top storey column.

The actual utilisations adopted by ASFP, together with the Q_k:G_k ratios are:

- For office loading, Q_k:G_k = 1:1 and η_{fi} = 0.546
- For storage loading, Q_k:G_k = 2:1 and η_{fi} = 0.644
- For shopping loading, Q_k:G_k = 1:1 and η_{fi} = 0.618

The analysis that led to the ASFP critical temperatures considered section sizes between 203 UC 46 and 305 UC 283, in S275 and S355, with some averaging of intermediate values. It was found that the lower steel grade was the more critical, which is the basis for the ASFP values.

The ASFP methodology always uses the more conservative reduced buckling length of 0.7L.

Due to the averaging of intermediate values, the quoted temperatures will not be correct for any particular situation, but should be conservative. The following example shows the calculation process.

254 UC 73, in S275, 3.5 m long, in an office environment.

At ambient temperature, $N_{b,Rd,z}$ = 1977 kN (quoted to three significant figures as 1980 kN in the Blue Book). The non-dimension slenderness is 0.622

Assuming the column was fully utilised at ambient temperature, the reduction in design effects is due only to η_{fi}, given above as 0.546

The critical temperature of 563°C will be satisfactory if the reduced resistance at this temperature is equal to or more than 0.546 of the "cold" resistance.

Interpolating Table 3.1 of BS EN 1993-1-2, for θ = 563°C, then:

$k_{y,\theta}$ = 0.585 and $k_{E,\theta}$=0.417

The modified slenderness, including the reduced buckling length of 0.7L, is given by:

$$\bar{\lambda}_\theta = \bar{\lambda}\left[k_{y,\theta}/k_{E,\theta}\right]^{0.5} = 0.7 \times 0.622 \times \left[0.585/0.417\right]^{0.5} = 0.516$$

$$\alpha = 0.65\sqrt{235/f_y} = 0.65 \times \sqrt{235/275} = 0.6$$

►26

▸24

$$\varphi_\theta = \tfrac{1}{2}\left[1 + \alpha\bar{\lambda}_\theta + \bar{\lambda}_\theta^2\right] = \tfrac{1}{2}\left[1 + 0.6 \times 0.516 + 0.516^2\right] = 0.788$$

$$\chi_{fi} = \frac{1}{\varphi_0 + \sqrt{\varphi_0^2 - \bar{\lambda}_0^2}} = \frac{1}{0.788 + \sqrt{0.788^2 - 0.516^2}} = 0.723$$

$$N_{b,fi,t,Rd} = \frac{\chi_{fi} A k_{y,\theta} f_y}{\gamma_{M,fi}} = \frac{0.723 \times 9310 \times 0.585 \times 275}{1.0 \times 10^3} = 1083 \text{ kN}$$

1083/1977 = 0.548, so at 563°C the column has slightly more resistance that required – the critical temperature is satisfactory.

In S355, the ratio is 0.576, showing that ASFP values are conservative for S355 and S460. The ASFP temperatures are conservative for column lengths above 3.5 m. If the column length is less than 3.5 m, the values are not conservative, but only by a trivial amount.

As the ASFP temperatures are generally conservative, higher temperatures will be calculated if the *actual* design situation is assessed. The following are examples, all using the same 254 UC 73:

245 UC 73, S355, 4.5 m long, Office loading, 100% utilised at ambient: $\theta_{a,cr}$ = 581°C

245 UC 73, S460, 4.5 m long, Office loading, 100% utilised at ambient: $\theta_{a,cr}$ = 592°C

245 UC 73, S355, 4.5 m long, Office loading, 80% utilised at ambient: $\theta_{a,cr}$ = 616°C

245 UC 73, S355, 4.5 m long, Office loading, 60% utilised at ambient: $\theta_{a,cr}$ = 659°C

ASFP provide different temperatures for hollow sections. This is because at ambient temperatures the imperfection factor for UC sections was taken as 0.49 in all cases. For hollow sections the value was taken as 0.21.

180 × 180 × 8 SHS, in S355, 3.5 m long, in an office environment.

At ambient temperature, $N_{b,Rd,z}$ = 1676 kN (quoted to three significant figures as 1680 kN in the Blue Book). The non-dimension slenderness is 0.655

Assuming the column was fully utilised at ambient temperature, the reduction in design effects is due only to η_{fi} , given above as 0.546

The critical temperature of 547°C will be satisfactory if the reduced resistance at this temperature is equal to or more than 0.546 of the "cold" resistance.

Interpolating Table 3.1 of BS EN 1993-1-2, for θ = 547°C, then:

$k_{y,\theta}$ = 0.634 and $k_{E,\theta}$ = 0.464

The modified slenderness, including the reduced buckling length of 0.7*L*, is given by:

$$\bar{\lambda}_\theta = \bar{\lambda}\left[k_{y,\theta}/k_{E,\theta}\right]^{0.5} = 0.7 \times 0.655 \times \left[0.634/0.464\right]^{0.5} = 0.536$$

$$\alpha = 0.65\sqrt{235/f_y} = 0.65 \times \sqrt{235/355} = 0.529$$

$$\varphi_\theta = \tfrac{1}{2}\left[1 + \alpha\bar{\lambda}_\theta + \bar{\lambda}_\theta^2\right] = \tfrac{1}{2}\left[1 + 0.529 \times 0.561 + 0.536^2\right] = 0.786$$

$$\chi_{fi} = \frac{1}{\varphi_0 + \sqrt{\varphi_0^2 - \bar{\lambda}_0^2}} = \frac{1}{0.786 + \sqrt{0.786^2 - 0.536^2}} = 0.735$$

$$N_{b,fi,t,Rd} = \frac{\chi_{fi} A k_{y,\theta} f_y}{\gamma_{M,fi}} = \frac{0.735 \times 5440 \times 0.634 \times 355}{1.0 \times 10^3} = 900 \text{ kN}$$

900/1676 = 0.537 , so at 547°C the column has slightly lower resistance that required – the critical temperature is (just) unsatisfactory. The correct critical temperature is 544°C, which is not considered to be a significant difference.

UK NA Critical temperatures

The relevant part of the UK NA table is shown on p27.

In contrast to ASFP, the values of critical temperatures for columns in the UK NA are based on S355 steel and do not apply the reduction to the buckling length.

For a non-dimensional slenderness of 0.8, the reduction factor at ambient temperature can be calculated as 0.663

For those interested, an alternative way to calculate the reduction factor without any reference to the section is to use the following expressions:

Non-dimensional slenderness	Critical temperature (°C) for utilisation factor μ_0					
	0.7	0.6	0.5	0.4	0.3	0.2
$\bar{\lambda} = 0.4$	485	526	562	598	646	694
$\bar{\lambda} = 0.6$	470	548	554	590	637	686
$\bar{\lambda} = 0.8$	451	510	546	583	627	678
$\bar{\lambda} = 1.0$	434	505	541	577	619	672
$\bar{\lambda} = 1.2$	422	502	538	573	614	668
$\bar{\lambda} = 1.4$	415	500	536	572	611	666
$\bar{\lambda} = 1.6$	411	500	535	571	620	665

$$\chi = \frac{T_1 - T_2}{2\bar{\lambda}^2}$$

Where $T_1 = 2\phi$ and $T_2 = (T_1{}^2 - 4\bar{\lambda}^2)^{0.5}$

Using these expressions with $\bar{\lambda} = 0.8$ and $\alpha = 0.49$, then $\phi = 0.967$

$T_1 = 2 \times 0.967 = 1.934$

$T_2 = (1.934^2 - 4 \times 0.8^2)^{0.5} = 1.086$

$$\chi = \frac{1.934 - 1.086}{2 \times 0.8^2} = 0.663 \text{ as above}$$

The buckling stress at ambient temperature is therefore 0.663 × 355 = 235 N/mm²

If the utilisation in the fire condition was 0.6, the buckling stress in the fire condition would be 0.6 × 235 = 141 N/mm²

The objective then is to determine at what temperature the buckling stress is 141 N/mm² – the UK NA states this to be 510°C. Following the same process as demonstrated for the ASFP values (but omitting the 0.7*L* reduction in buckling length), the steps are shown below.

Interpolating Table 3.1 of BS EN 1993-1-2, for θ = 510°C, then:

$k_{y,\theta} = 0.749$ and $k_{E,\theta} = 0.571$

The modified slenderness is given by:

$\bar{\lambda}_\theta = \bar{\lambda}[k_{y,\theta}/k_{E,\theta}]^{0.5} = 0.8 \times [0.749/0.571]^{0.5} = 0.916$

$\alpha = 0.65\sqrt{235/f_y} = 0.65 \times \sqrt{235/355} = 0.529$

$\varphi_\theta = ½\,[1 + \alpha\bar{\lambda}_\theta + \bar{\lambda}_\theta{}^2] = ½\,[1 + 0.529 \times 0.916 + 0.916^2] = 1.162$

$T_1 = 2 \times 1.162 = 2.324$

$T_2 = (2.324^2 - 4 \times 0.916^2)^{0.5} = 1.430$

$$k_{y,\theta}\chi = 0.749 \times \frac{2.324 - 1.430}{2 \times 0.916^2} = 0.399$$

The buckling stress at the temperature of 510°C is therefore 0.399 × 355 = 142 N/mm²

The UK NA is not conservative for columns in S275 steel. The largest difference is at highly utilised sections and large slenderness (for example $\mu_0 = 0.7$; $\bar{\lambda} = 1.6$, where the difference is about 6%)

Comparison between ASFP and UK NA for columns

The calculation process is identical, although the results are presented in quite different formats. The UK NA does not apply the 0.7*L* reduction in buckling length, so for a given utilisation will be more conservative. If the ASFP approach is applied to a 254 UC 73 in S355, 3.5 m long, fully utilised at ambient temperatures, in an office loading condition, the critical temperature is 572°C. The UK NA approach would show a more onerous critical temperature of 534°C, simply because of the longer buckling length.

The UK NA has the advantage that actual utilisations can be calculated, including the 0.5*L* or 0.7*L* buckling length reduction and allowing for surplus resistance in the ambient condition. ■