Composite beam design at elevated temperature: comparisons between different temperature distributions in the concrete flange

Several resources give guidance on the temperature profile through composite slabs; BS 5950-8, EN 1994-1-2 and NCCI PN005C-GB. Ricardo Pimentel of the SCI discusses the impact of these alternative profiles on the design of composite beams at elevated temperature.

Composite beams are one of the most common structural elements in the UK construction market. Steel and concrete are connected by mechanical devices (shear connection – usually studs), allowing the two materials to work together. Composite beams are usually simply supported elements, allowing the steel to be mainly in tension and the concrete in compression.

The fire design of composite beams is often required, which demands an assessment of resistance of the concrete, steel and studs at elevated temperature. The main topic of this article is to evaluate the impact of alternative temperature distributions in the slab to obtain the critical temperature or the allowable fire exposure period of composite beams. For a composite beam design at elevated temperature, there are three possible ways to model the temperature distribution in the slab in the UK: (i) EN 1994-1-2 Annex D Table D.5; (ii) BS 5950-8 Table 12; (iii) NCCI PN005C-GB. However, note that the UK National Annex to EN 1994-1-2 states that Annex D should not be used, recommending the use of non-contradictory complementary information (NCCI).

The effect of different temperature profiles will be assessed based on two worked examples, comprising 6 m and 12 m span beams, both optimized for an adequate performance under Serviceability Limit States, Ultimate Limit States and Fire Design. The geometry and design conditions for the two worked examples are summarized in the data presented in Figure 1 and Table 1.

h_1 [mm]	70
h_2 [mm]	60
l_1 [mm]	175
l_2 [mm]	125
l_3 [mm]	125

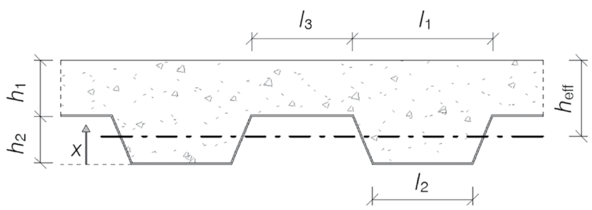


Figure 1 – Composite slab geometry.

Characteristic	Description/value
Steel section for the 6 m beam:	UB 203 x 133 x 25
Steel section for the 12 m beam:	UB 406 x 178 x 67
Effective slab breath to 12 m span:	3000 mm
Effective slab breath to 6 m span:	1500 mm
Floor usage:	Office
Beam spacing [m]	3.50
Slab weight [kN/m²]	2.65
Additional permanent loads [kN/m²]	2.00
Imposed Load [kN/m²]	2.70
Steel:	S355 JR
Concrete:	C30/37
Slab mesh:	A142
Ribs direction:	Perpendicular to the steel beam.
Fire protection:	Yes
Temperature gradient:	Uniform temperature in the steel profile.
Fire rating:	90 minutes
Steel Critical temperature – 6 m span:	620°C
Steel Critical temperature – 12 m span:	621°C
Miscellaneous:	Cambered beam; restrained by steel sheet in construction stage.

Table 1 – Design conditions

According to EN 1994-1-2, to take into account the ribs of a trapezoidal deck, an effective slab depth can be calculated (h_{eff} - Figure 1), allowing a more realistic uniform temperature distribution in the concrete flange. According to equations D.15a and D.15b of EN 1994-1-2, an effective depth of 100 mm can be obtained for the slab shown in Figure 1 (h_{eff} = 100 mm). Basically, this effective depth means that the temperature of the top concrete fibre is obtained assuming a depth of 100 mm in table D.5 of EN 1994-1-2.

There are no recommendations in the NCCI or BS 5950-8 for assessing an effective slab depth for composite floors. When estimating the resistance of the concrete flange at elevated temperature using NCCI, a weighted average between temperatures above ribs and between ribs can be considered (using l_2 and l_3 to calculate the weighted average). If BS 5950-8 is used, the approach of equations D.15a and D.15b of EN 1994-1-2 can be assumed to be valid. An alternative (and conservative) measure can be to disregard the ribs, i.e., assuming that $h_{eff} = h_1$ = 70 mm.

The temperature on the unexposed (top) side of the slab is required to be no more than approximately 140°C to fulfil insulation requirements[6]. A minimum slab thickness is imposed to fulfil this requirement. For the beam analysis, according to EN 1994-1-2, 4.3.4.2.2 (16), it may be assumed that for concrete temperatures below 250°C, no strength reduction is necessary. For these reasons, according to some references[7], assuming room temperature for assessing the sagging bending resistance of composite slabs and beams is suggested, as, in general, only a modest depth at the top of the slab will be necessary to obtain section equilibrium at elevated temperature. Thus, an example assuming room temperature in the slab will also be considered (note that if floor screed is considered for the minimum insulation thickness, the temperature in the top concrete fibre can be slightly higher).

For 90 minutes of fire exposure, the minimum insulation thickness according to EN 1994-1-2 Annex D would be $h_{eff} \geq$ 100 mm (note that the profile falls outside the scope of Annex D of EN 1994-1-2, which limits l_3 to 115 mm, compared to the actual value of 125 mm). According to the NCCI, a minimum thickness of $h_1 \geq$ 70 mm is imposed, while BS 5950-8 suggests $h_1 \geq$ 70 mm for

▶28

▶26

lightweight concrete and $h_1 \geq 80$ mm for normal weight concrete.

In Figure 2, for 90 minutes of fire exposure, the different temperature distributions in the concrete flange according to the three different UK resources can be found for normal weight concrete. Slab depth is measured from the face exposed to fire.

For 90 minutes of fire exposure, the temperatures in the top (Table 2) and the bottom (Table 3) fibres of the concrete flange above the steel sheet can be obtained (i.e. X = 130 mm, and X = 60 mm, respectively, according to Figure 1). Eight possible approaches are presented. Once the temperatures have been obtained, the respective concrete resistance reduction factors (K_c) according to Table 3.3 of EN 1994-1-2 can be obtained. In the top concrete fibres, according to EN 1994-1-2 and BS 5950-8 approaches, the top temperature is in fact close to 140°C (Cases 2 and 3). Even with conservative approaches (Cases 5, 6 and 7), the temperature in the top concrete fibre is generally below 250°C, so no concrete strength reduction would be needed for the top concrete fibres. On the other hand, for lower concrete fibres, the strength reduction can be up to 29 % for Cases 2 and 3 and 83 % for Case 6. Thus, depending of the depth of the concrete flange required for section equilibrium, the concrete resistance may have some significant reductions.

To evaluate the impact of different temperature distributions in the slab, the critical steel temperatures shown in Table 1 were assumed as fixed. The plastic bending resistance under fire, for each slab profiles temperatures (Cases 1 to 8) were then evaluated, and are presented in Table 4 and Table 5 for the two worked examples. The degree of shear connection (η) can vary between 0 and 1 in a composite beam. Results for different degrees of shear connection are presented in steps of 0.25 between those two extreme cases, obtained through a stress block analysis. Partial interaction curves are presented for both worked examples in Figure 3, for 6 m and 12 m worked examples.

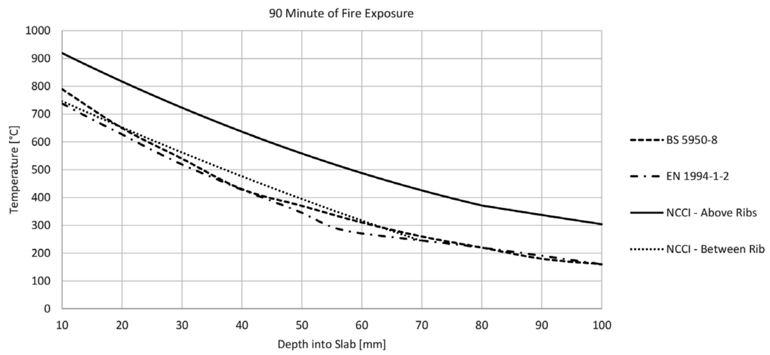


Figure 2 - Temperature distribution according to different UK resources.

Case	Methodology (90 minutes of fire exposure)	$\theta_{c,top}$	K_c
1	Room Temperature	20	1.00
2	EN 1994-1-2 Annex D (h_{eff} = 100 mm)	160	0.97
3	BS 5950-8 with EN 1994-1-2 Annex D ($h_{eff} \geq$ 100 mm)	160	0.97
4	Medium value according to NCCI (weighted average)	224	0.93
5	Ignoring Ribs According to EC (h_{eff} = 70 mm)	246	0.90
6	Ignoring Ribs According to BS 5950-8 (h_{eff} = 70 mm)	260	0.89
7	Ignoring Ribs According to NCCI (h_{eff} = 70 mm)	244	0.91
8	Assuming 40% of steel top flange temperature (θ_{top} flange = 620°C) EN 1994-1-2, 4.3.4.2.5 (2) – for shear studs resistance.	248	0.90

Table 2 – Top concrete fibre temperature according to different approaches (X = 130 mm).

Case	Methodology (90 minutes of fire exposure)	$\theta_{c,top}$	K_c
1	Room Temperature	20	1.00
2	EN 1994-1-2 Annex D (h_{eff} = 100 mm)	428	0.71
3	BS 5950-8 with EN 1994-1-2 Annex D ($h_{eff} \geq$ 100 mm)	430	0.71
4	Medium value according to NCCI (weighted average)	559	0.51
5	Ignoring Ribs According to EC (h_{eff} = 70 mm)	738	0.24
6	Ignoring Ribs According to BS 5950-8 (h_{eff} = 70 mm)	790	0.17
7	Ignoring Ribs According to NCCI (h_{eff} = 70 mm)	747	0.23
8	Assuming 40% of steel top flange temperature (θ_{top} flange = 620°C) EN 1994-1-2, 4.3.4.2.5 (2) – for shear studs resistance.	248	0.90

Table 3 – Bottom concrete fibre temperature according to different approaches (X = 60 mm).

Conclusions

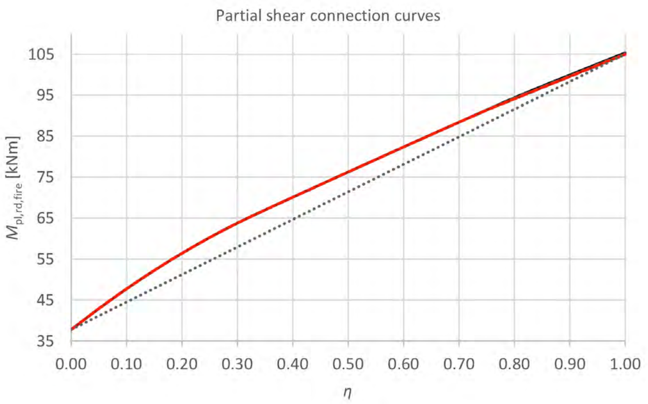
1. The UK NCCI gives temperature profiles at/above ribs and between ribs for composite slabs; in the paper, a weighted average temperature is suggested to assess the sagging bending resistance of the composite beams design under fire.
2. The temperature distribution profile in the composite slab has generally minimal impact in the composite beam sagging plastic bending resistance because: (i) only the top concrete strips are usually needed to obtain section equilibrium, which are not significantly affected by the slab temperature; (ii) differences in the position of the plastic neutral axis are usually small between the approaches; (iii) as the concrete flange tends to be more resistant at elevated temperature than the steel, even if the slab temperature is actually higher than considered,

$M_{pl,rd,fire}$ [kNm]	Slab temperature profile case							
η	1	2	3	4	5	6	7	8
0.00	37.71	37.71	37.71	37.71	37.71	37.71	37.71	37.71
0.25	60.22	60.22	60.22	60.22	60.22	60.22	60.22	60.22
0.50	76.24	76.24	76.24	76.24	76.24	76.24	76.24	76.24
0.75	91.41	91.41	91.41	91.41	91.35	91.30	91.36	91.34
1.00	105.37	105.25	105.25	105.08	105.00	104.95	105.01	104.99

Table 4 – Results for 6 m span beam: UB 203 x 133 x 25; Steel critical temperature: 621°C.

$M_{pl,rd,fire}$ [kNm]	Slab temperature profile case							
η	1	2	3	4	5	6	7	8
0.00	199.13	199.13	199.13	199.13	199.13	199.13	199.13	199.13
0.25	284.60	284.60	284.60	284.60	284.60	284.60	284.60	284.60
0.50	335.08	335.08	335.08	335.08	335.08	335.08	335.08	335.08
0.75	375.67	375.44	375.44	375.10	374.93	374.82	374.95	374.92
1.00	413.06	412.83	412.83	412.49	412.33	412.22	412.34	412.31

Table 5 – Results for 12 m span beam: UB 406 x 178 x 67; Steel critical temperature: 620°C



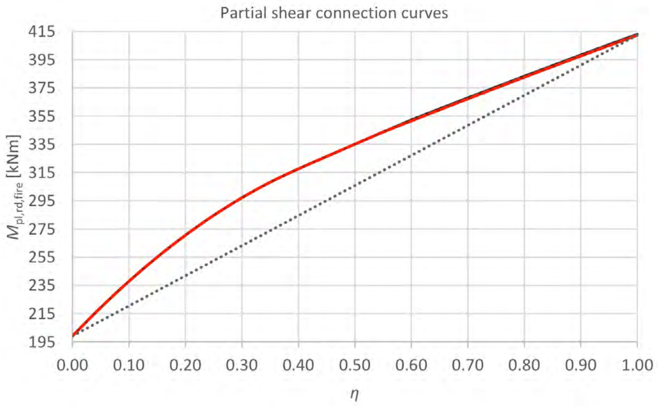


Figure 3 – Partial shear connection curves for the 6 m (left) and 12 m (right) worked examples.

only small changes in the neutral axis are expected, as a small increase in the assumed slab depth increases considerably the slab resistance.

3. For assessing the resistance of the slab, generally no reduction in strength is needed (ambient temperature may be assumed). An alternative often used, which is to assume the slab temperature is equal to 40% of the steel top flange temperature (a rule used to assess studs resistance under fire), can be seen as a conservative solution.

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