Localised resource for UK

NCCI: Fire resistance design of composite slabs

The UK National Annex to BS EN 1994-1-2 recommends that informative Annex D should not be used. This NCCI document provides alternative guidance.

Contents

1. Introduction

The BSI committee responsible for the UK National Annex (NA) to BS EN 1994-1-2 considered that Annex D of that Eurocode Part should not be used, and the UK NA therefore does not recommend its use. The UK NA advises that guidance is available on www.steel-ncci.co.uk that offers an alternative to Annex D. This NCCI document provides that advice.

This document provides guidance on calculating suitable design temperatures for composite slabs, to be used in the calculation of moment resistance for composite slabs or composite beams in fire conditions.

The document also provides guidance on how the insulation criterion may be satisfied for composite slabs performing a separating function.

The procedure for calculating the mechanical resistance of a composite slab is based on the general rules for calculating plastic resistance, as given in BS EN 1994-1-2/4.3.1.

The equations presented are valid for trapezoidal shaped profiles with a nominal depth between 60 mm and 80 mm, and bottom flange widths between 100 mm and 130mm. For re-entrant profiled sheeting shapes, the equations are valid for profiles with a nominal depth between 50 mm and 60 mm, and bottom flange widths between 120 mm and 150 mm. These ranges cover the majority of the profiled sheeting shapes available in the UK at the time of writing. Profiles with geometries outside of this range will require specialist calibration.

This document supersedes PN005a-GB. It contains revised values for the thickness of concrete required to satisfy the insulation criterion for slabs constructed with trapezoidal sheeting and normal weight concrete. This document also supersedes PN005b-GB; revised coefficients are presented for calculation of the temperature of reinforcement in a slab constructed with re-entrant sheeting and normal weight concrete.

2. Design Temperatures

The temperature at a point within a composite slab subject to the standard time-temperature curve is generally proportional to the distance from the nearest exposed surface of the profiled steel sheeting (traditionally referred to as decking). However this is not always the case, particularly for profiled sheeting shapes containing large stiffeners or indentations, as is the case in the UK. Modelling has shown that the method given in BS EN 1994-1-2 Annex D would be too conservative to be useful for UK profiled sheeting shapes.

This NCCI presents an alternative method, whereby the temperatures of the strips required for plastic analysis of the section (described in Section 4) are given directly by a series of depth-temperature relationships, presented in Section 2.1.1 and Section 2.2.1 in equation form. A depth-temperature relationship is also provided to calculate the temperature of bar reinforcement within the ribs of the slab.

The equations presented give temperatures at discreet periods of 30, 60, 90 and 120 minutes fire exposure. For intermediate exposures the temperatures can be conservatively found by using the parameters for an exposure time rounded up to the nearest 30 minutes. For exposures greater than 120 minutes, specialist calibration is needed.

The depth-temperature relationships presented in this document have been extensively calibrated against finite element models. The equations are valid as long as the geometry of the profile is within the limits described in Section 1.

2.1 Slabs with trapezoidal profiled sheeting

2.1.1 Concrete Temperatures

When considering the resistance of a composite slab with trapezoidal profiled sheeting, the concrete may be idealised as a number of horizontal strips of uniform temperature, as shown in Figure 2.1.

The number and height of the strips depends on the desired accuracy of the calculated resistance. A greater number of strips means a more accurate answer, but will require more calculation. Limiting strip heights to 10mm will generally provide an answer of sufficient accuracy for design purposes.

Strip heights need not be consistent throughout the profile. Strip heights can be varied to accommodate significant changes in the profile geometry. The height of strips immediately above and below the plastic neutral axis should also be varied, such that the top and bottom of these strips are in line with the PNA. The setting of the location of the PNA is dependent on the temperatures of the strips, meaning this process is iterative.

Two sets of strips are required; one set within the ribs of the profile and one set between the ribs of the profile. There is no requirement for strips to be of consistent height.

For the concrete in and above the ribs of the slab, the design temperature of each strip is assumed to be a constant value that is determined by the vertical distance from the bottom of the rib to the mid-depth of the strip, indicated in Figure 2.1 for a typical strip as z_j. Strips are numbered from j =1 to m (where m is the number of strips).

For the concrete over the top of the profiled sheeting and between the ribs, the design temperature of each strip is determined by the vertical distance to the top flange of the profile, indicated in Figure 2.1 for a typical strip as $(z_k - d_\mathrm{p})$, where z_k is measured from the soffit of the profile. Strips are numbered from k = 1 to l (where l is the number of strips).

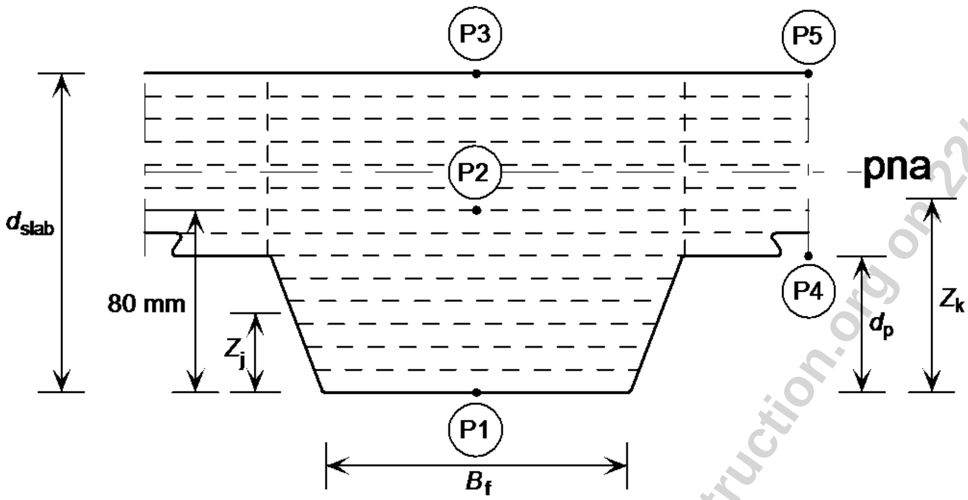


Figure 2.1 Idealised strips of concrete for trapezoidal profiled sheeting

The temperatures within the rib are given by two models, while the temperatures between the ribs are given by a single model. Three zones are therefore considered: within the rib, up to a level 80 mm above the soffit of the rib; within the width of the rib, above 80 mm from the soffit; and between the ribs. Depth-temperature relationships are presented for each of these different parts of the slab, for both normal weight concrete and for lightweight aggregate concrete. In these relationships, the shape of the profile and the slab depth are represented by the following parameters:

$$\beta = \left(\frac{60}{d_p}\right)^{0.4} \qquad \tau = \left(\frac{130}{B_f}\right)^{0.3} \qquad \sigma = \left(\frac{250}{d_{slab}}\right)^{0.5}$$

Normal weight concrete

Within the ribs, up to 80 mm above the soffit.

For the concrete strips between positions P1 and P2 in Figure 2.1, the depth-temperature relationship is given by:

$$\theta_x = ax^2 + bx + c \qquad \text{Eq.(1)}$$

In which parameters a, b and c are given by Table 2.1 and x is the height above the soffit (= z_j for the j-th strip).

Table 2.1 Parameters for use in Equation (1)

Exposure period (min)	*a*	*b*	*c*
30	0.047	$-11.6\,\tau\,\beta^{1.24}$	760
60	0.040	$-11.4\,\tau\,\beta^{1.73}$	910
90	0.040	$-11.3\,\tau\,\beta^{1.73}$	1030
120	0.040	$-11.2\,\tau\,\beta^{1.73}$	1070

Within the width of the ribs, more than 80 mm above the soffit.

For the concrete strips between positions P2 and P3 in Figure 2.1, the depth-temperature relationship is given by:

$$\theta_x = a(x-80)^2 + b(x-80) + c \qquad \text{Eq.(2)}$$

In which parameters a, b and c are given by Table 2.2 and x is the height above the soffit (= z_j for the j-th strip).

Table 2.2 Parameters for use in Equation (2)

Exposure period (min)	*a*	*b*	*c*
30	0.005	$-1.3\,\sigma / \beta^3$	θ_x from Eq.(1) when x = 80 mm
60	0.005	$-2.0\,\sigma / \beta^3$	θ_x from Eq.(1) when x = 80 mm
90	0.005	$-2.5\,\sigma / \beta^3$	θ_x from Eq.(1) when x = 80 mm
120	0.005	$-2.6\,\sigma / \beta^3$	θ_x from Eq.(1) when x = 80 mm

Between the ribs above the profile.

For the concrete strips between positions P4 and P5 in Figure 2.1, the depth-temperature relationship is given by:

$$\theta_x = a(x-d_p)^2 + b(x-d_p) + c \qquad \text{Eq.(3)}$$

In which parameters a, b and c are given by Table 2.3 and x is the height above the rib soffit (= z_k for the k-th strip).

Table 2.3 Parameters for use in Equation (3)

Exposure period (min)	*a*	*b*	*c*
30	0.015	$-5.3\,\sigma^{0.3} / \beta^{0.05}$	$500 / \beta^{0.6}$
60	0.021	$-7.6\,\sigma^{0.7} / \beta^{0.05}$	735
90	0.021	$-8.0\,\sigma^{0.7} / \beta^{0.05}$	845
120	0.021	$-8.7\,\sigma^{0.7} / \beta^{0.05}$	955

Lightweight Concrete

Within the ribs, up to 80 mm above the soffit.

For lightweight concrete the temperatures of the concrete strips between positions P1 and P2 are given by the following relationship:

$$\theta_x = ax^2 + bx + c \qquad \text{Eq.(4)}$$

In which parameters a, b and c are given by Table 2.4 and x is as defined above (= z_j for the j-th strip).

Table 2.4 Parameters for use in Equation (4)

Exposure period (min)	a	b	c
30	0.047	$-11.6\,\tau\,\beta^{1.24}$	760
60	0.040	$-11.4\,\tau\,\beta^{1.73}$	910
90	0.040	$-11.3\,\tau\,\beta^{1.73}$	1030
120	0.040	$-11.2\,\tau\,\beta^{1.73}$	1070

Within the width of the ribs, more than 80 mm above the soffit.

For the concrete strips between positions P2 and P3 in Figure 2.1, the depth-temperature relationship is given by:

$$\theta_{\mathrm{x}} = a(x-80)^2 + b(x-80) + c \qquad \text{Eq.(5)}$$

In which parameters *a*, *b* and *c* are given by Table 2.5 and *x* is as defined above (= z_j for the *j*-th strip).

Table 2.5 Parameters for use in Equation (5)

Exposure period (min)	a	b	c
30	0.005	$-1.3\,\sigma/\beta^3$	θ_{x} from Eq.(4) when x = 80 mm
60	0.005	$-2.0\,\sigma/\beta^3$	θ_{x} from Eq.(4) when x = 80 mm
90	0.005	$-2.5\,\sigma/\beta^3$	θ_{x} from Eq.(4) when x = 80 mm
120	0.005	$-2.6\,\sigma/\beta^3$	θ_{x} from Eq.(4) when x = 80 mm

Between the ribs above the profile.

For the concrete strips between positions P4 and P5 in Figure 2.1, the depth-temperature relationship is given by:

$$\theta_{\mathrm{x}} = a(x-d_{\mathrm{p}})^2 + b(x-d_{\mathrm{p}}) + c \qquad \text{Eq.(6)}$$

In which parameters *a*, *b* and *c* are given by Table 2.6 and *x* is as defined above (= z_k for the *k*-th strip).

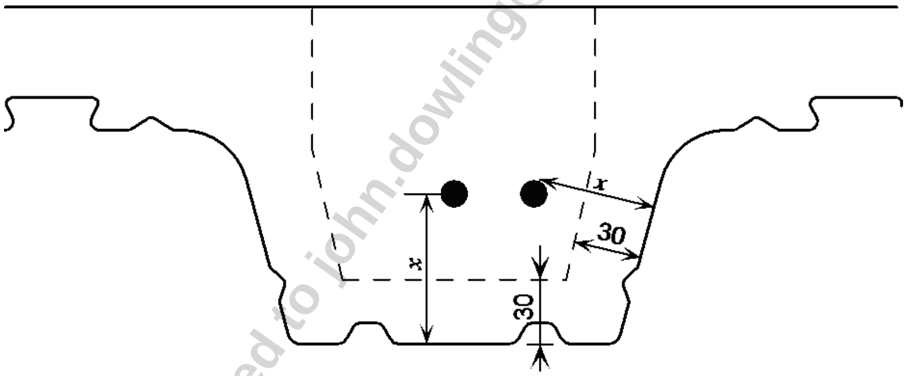
Table 2.6 Parameters for use in Equation (6)

Exposure period (min)	a	b	c
30	0.019	$-7.1\,\sigma^{0.3} / \beta^{0.05}$	$700 / \beta^{0.6}$
60	0.021	$-7.9\,\sigma^{0.9} / \beta^{0.05}$	780
90	0.021	$-8.3\,\sigma^{0.9} / \beta^{0.05}$	895
120	0.021	$-8.8\,\sigma^{0.9} / \beta^{0.05}$	985

2.1.2 Reinforcement temperatures

The temperature of mesh reinforcement may be taken as the temperature of the concrete strip in which it is embedded, given in Section 2.1.1. Different temperatures apply for the stress block above the top flange of the profiled sheeting and the stress block above the rib.

The temperature of the bar reinforcement in the rib of the slab depends on the distance *x* from its centre to the nearest exposed face (either the bottom flange or the web). As a minimum, the bar must be placed at least 30 mm from the nearest face, as shown in Figure 2.2.



Note: In this Figure, two bars are shown; for one, the distance to the nearest exposed surface *x* is measured vertically and for the other *x* is measured perpendicular to the side of the profile

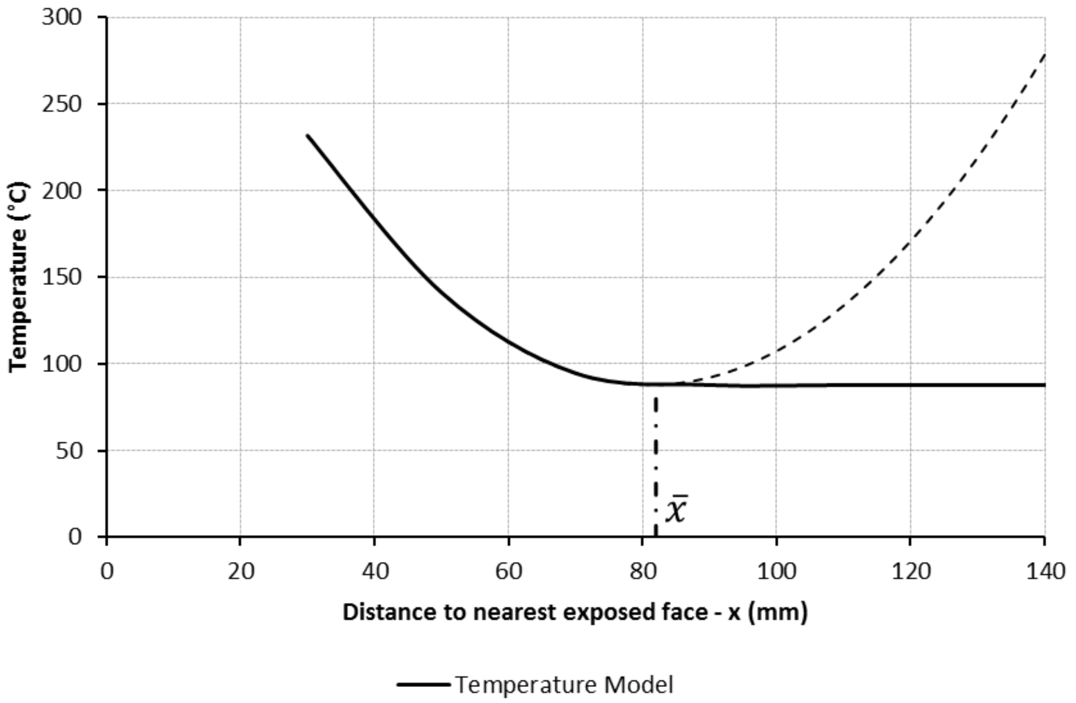
Figure 2.2 Minimum edge distances for placement of bar reinforcement in trapezoidal profiled sheeting

The relationship between the bar temperature and the distance from the exposed surface depends on a quadratic equation, up to the distance $\bar{x}$, at which the quadratic curve reaches its minimum value. For larger distances, the temperature should be taken as that minimum value. A typical temperature-distance curve is shown in Figure 2.3. The value of $\bar{x}$ depends on the parameters of the quadratic equation and should be re-calculated for each exposure period.

Temperature-distance relationships for bar reinforcement are given below. The influence of the depth of slab is represented by the following parameter:

$$\sigma = \left(\frac{250}{d_{\text{slab}}}\right)^{0.5}$$

The shape of the profile is irrelevant to the temperature obtained from the relationships below.



Note: $\bar{x}$ is not a fixed value, as it depends on the values of *a* and *b* given for the appropriate case

Figure 2.3 Typical temperature-distance curve for bar reinforcement

Normal weight concrete

For normal weight concrete, the distance at which the temperature would be a minimum is given by:

$$\bar{x} = \frac{-b}{2a}$$

In which parameters *a* and *b* are given by Table 2.7.

Table 2.7 Parameters for use in Equation (7)

Exposure period (min)	a	b	c
30	0.055	$-8.9\,\sigma^{-0.045}$	450
60	0.048	$-11.2\,\sigma^{-0.05}$	760
90	0.036	$-10.6\,\sigma^{-0.03}$	890
120	0.03	$-10.3\,\sigma^{-0.15}$	985

If the distance to the exposed surface is such that, $x \geq \bar{x}$ the temperature is given by the following equation:

$$\theta_x = a\bar{x}^2 + b\bar{x} + c \qquad \text{Eq.(7a)}$$

If $x < \bar{x}$ then the temperature is given by following equation:

$$\theta_x = ax^2 + bx + c \qquad \text{Eq.(7b)}$$

In which parameters *a*, *b* and *c* are as given in Table 2.7 and *x* is the lesser of the distance to the soffit and that to the side of the profile, as shown in Figure 2.2.

Lightweight concrete

For lightweight concrete, the temperatures are given by the following relationship:

$$\bar{x} = \frac{-b}{2a}$$

In which parameters *a* and *b* are given by Table 2.8.

Table 2.8 Parameters for use in Equation (8)

Exposure period (min)	a	b	c
30	0.07	$-13.24\,\sigma^{-0.05}$	680
60	0.045	$-10.9\,\sigma^{-0.05}$	750
90	0.033	$-10.2\,\sigma^{-0.03}$	870
120	0.028	$-10.0\,\sigma^{-0.15}$	970

If the distance to the exposed surface is such that, $x \geq \bar{x}$ the temperature is given by the following equation:

$$\theta_x = a\bar{x}^2 + b\bar{x} + c \qquad \text{Eq.(8a)}$$

If $x < \bar{x}$ the temperature is given by the following equation:

$$\theta_x = ax^2 + bx + c \qquad \text{Eq.(8b)}$$

In which parameters *a*, *b* and *c* are given by Table 2.8 and *x* is the lesser of the distance to the soffit and that to the side of the profile, as shown in Figure 2.2.

2.1.3 Profiled Steel Sheeting Temperatures

The profiled steel sheeting is idealised as a single element at the plastic neutral axis of the deck itself (see section 4.1). The temperature of the steel is given by taking the average of the temperature of the top flange and the temperature of the bottom flange of the sheeting, weighted by the width of the top flange and bottom flange respectively. The relationship is presented mathematically as:

$$\theta_s = \frac{(\theta_{bf} \times B_{bf}) + (\theta_{tf} \times B_{tf})}{(B_{tf} + B_{bf})} \qquad \text{Eq.(9)}$$

Where:

θ_s is the temperature of the profiled steel sheeting

θ_{bf} is the temperature of the bottom flange of the profiled steel sheeting

θ_{tf} is the temperature of the top flange of the profiled steel sheeting

B_{bf} is the width of the bottom flange of the profiled steel sheeting

B_{tf} is the width of the top flange of the profiled steel sheeting

The temperature of the bottom flange of the profiled steel sheeting is determined from either equation 1 for normal weight concrete or equation 4 for lightweight concrete, with $x = 0$. The temperature of the top flange of the profiled steel sheeting is determined from either equation 3 for normal weight concrete or equation 6 for lightweight concrete, with $x = d_p$.

2.2 Slabs with re-entrant steel sheeting

2.2.1 Concrete Temperatures

Depth-temperature relationships are presented below for re-entrant steel sheeting. The concrete is again idealised as a number of strips of uniform temperature, as shown in Figure 2.4. As described in Section 2.1, the height of the strips may be varied to accommodate changes in the geometry of the profile and the plastic neutral axis.

For the concrete in and above the ribs of the slab, the design temperature of each strip is assumed to be a constant value that is determined by the vertical distance from the bottom of the rib to the mid-depth of the strip, indicated in Figure 2.4 for a typical strip as z_j. Strips are numbered from $j = 1$ to m (where m is the number of strips).

For the concrete over the top of the profiled sheeting and between the ribs, the design temperature of each strip is determined by the vertical distance to the top flange of the profile, indicated in Figure 2.4 for a typical strip as $(z_k - d_p)$, where z_k is measured from the soffit of the profile. Strips are numbered from $k = 1$ to l (where l is the number of strips).

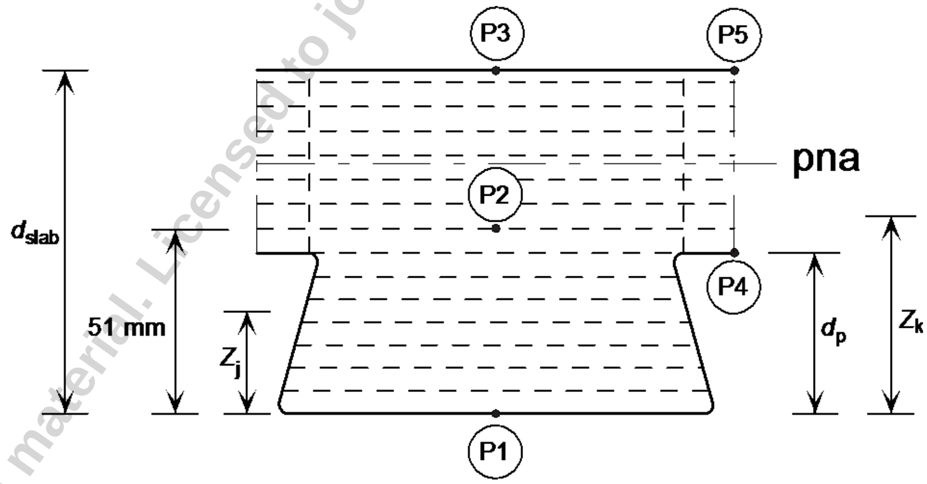


Figure 2.4 Idealised strips of concrete for re-entrant profiled sheeting

The temperatures within the rib are given by two models, while the temperatures between the ribs are given by a single model. Three zones are therefore considered: within the rib, up to a level 51 mm above the soffit of the rib; within the width of the rib, above 51 mm from the soffit; and between the ribs. Depth-temperature relationships are presented for each of these different parts of the slab, for both normal weight concrete and for lightweight aggregate concrete.

For re-entrant profiles, the shape of the profile is irrelevant. The depth of the slab is represented by the following parameter:

$$\sigma = \left(\frac{250}{d_{\text{slab}}} \right)^{0.5}$$

Normal weight concrete

Within the ribs, up to 51 mm above the soffit.

For the concrete strips between positions P1 and P2 in Figure 2.4, the depth-temperature relationship is given by:

$$\theta_{x} = ax^{2} + bx + c \qquad \text{Eq.(10)}$$

In which parameters *a*, *b* and *c* are given by Table 2.9 and *x* is the height above the soffit (= z_j for the *j*-th strip).

Table 2.9 Parameters for use in Equation (10)

Exposure period (min	a	b	c
30	0.047	−12.3	760
60	0.040	−10.0	910
90	0.040	−9.5	1030
120	0.040	−9.0	1070

Within the width of the ribs, more than 51 mm above the soffit.

For the concrete strips between positions P2 and P3 in Figure 2.4, the depth-temperature relationship is given by:

$$\theta_{x} = a(x-51)^{2} + b(x-51) + c \qquad \text{Eq.(11)}$$

In which parameters *a*, *b* and *c* are given by Table 2.10 and *x* is the height above the rib soffit (= z_j for the *j*-th strip).

Table 2.10 Parameters for use in Equation (11)

Exposure period (min)	a	b	c
30	0.01	$-3.0\,\sigma^{0.4}$	θ_x from Eq.(10) when x = 51 mm
60	$0.016\,\sigma^{2.4}$	$-5.5\,\sigma^{1.1}$	θ_x from Eq.(10) when x = 51 mm
90	$0.016\,\sigma^{2.4}$	$-6.3\,\sigma^{1.1}$	θ_x from Eq.(10) when x = 51 mm
120	$0.016\,\sigma^{2.4}$	$-6.6\,\sigma^{1.1}$	θ_x from Eq.(10) when x = 51 mm

Between the ribs above the profile.

For the concrete strips between positions P4 and P5 in Figure 2.4, the depth-temperature relationship is given by:

$$\theta_x = a(x - d_p)^2 + b(x - d_p) + c \qquad \text{Eq.(12)}$$

In which parameters a, b and c are given by Table 2.11 and x is the height above the rib soffit (= z_k for the k-th strip).

Table 2.11 Parameters for use in Equation (12)

Exposure period (min)	a	b	c
30	$0.07\,\sigma^{2.5}$	$-2.6\,\sigma^{1.4}$	270
60	$0.014\,\sigma^{2.8}$	$-5.2\,\sigma^{1.28}$	500
90	$0.016\,\sigma^{2.8}$	$-6.5\,\sigma^{1.28}$	700
120	$0.016\,\sigma^{2.8}$	$-7.0\,\sigma^{1.28}$	800

Lightweight Concrete

Within the ribs, up to 51 mm above the soffit.

For the concrete strips between positions P1 and P2 in Figure 2.4, the depth-temperature relationship is given by:

$$\theta_x = ax^2 + bx + c \qquad \text{Eq.(13)}$$

In which parameters a, b and c are given by Table 2.12 and x is the height above the soffit (= z_j for the j-th strip).

Table 2.12 Parameters for use in Equation (13)

Exposure period (min)	a	b	c
30	0.047	−12.9	810
60	0.040	−10.0	950
90	0.040	−9.3	1050
120	0.040	−7.8	1090

Within the width of the ribs, more than 51 mm above the soffit.

For the concrete strips between positions P2 and P3 in Figure 2.4, the depth-temperature relationship is given by:

$$\theta_x = a(x - 51)^2 + b(x - 51) + c \qquad \text{Eq.(14)}$$

In which parameters a, b and c are given by Table 2.13 and x is the height above the soffit (= z_j for the j-th strip).

Table 2.13 Parameters for use in Equation (14)

Exposure period (min)	a	b	c
30	$0.012\,\sigma^{3}$	$-3.2\,\sigma^{1.3}$	θ_{x} from Eq.(13) when x = 51 mm
60	$0.02\,\sigma^{2.5}$	$-6.5\,\sigma^{1.2}$	θ_{x} from Eq.(13) when x = 51 mm
90	$0.02\,\sigma^{2.5}$	$-7.2\,\sigma^{1.2}$	θ_{x} from Eq.(13) when x = 51 mm
120	$0.02\,\sigma^{2.5}$	$-7.8\,\sigma^{1.2}$	θ_{x} from Eq.(13) when x = 51 mm

Between the ribs above the profile.

For the concrete strips between positions P4 and P5 in Figure 2.4, the depth-temperature relationship is given by:

$$\theta_{x} = a(x-d_{p})^{2} + b(x-d_{p}) + c \qquad \text{Eq.(15)}$$

In which parameters *a*, *b* and *c* are given by Table 2.14 and *x* is the height above the soffit (= z_k for the *k*-th strip).

Table 2.14 Parameters for use in Equation (15)

Exposure period (min)	a	b	c
30	$0.012\,\sigma^{3}$	$-4.2\,\sigma^{1.5}$	380
60	$0.02\,\sigma^{3}$	$-7.2\,\sigma^{1.5}$	670
90	$0.02\,\sigma^{3}$	$-7.7\,\sigma^{1.5}$	820
120	$0.02\,\sigma^{2.7}$	$-8.4\,\sigma^{1.3}$	900

2.2.2 Reinforcement temperatures

The temperature of mesh reinforcement may be taken as the temperature of the concrete strip in which it is embedded, given in Section 2.2.1. Different temperatures apply for the stress block above the top flange of the profiled sheeting and the stress block above the rib.

The temperature of the bar reinforcement in the ribs of the slab is given by the relationship below. The distance x is taken as the distance to the bottom of the profile. x is not measured from the web of the profile for re-entrant profiles, as is the case for trapezoidal profiles (described in section 2.1.2). However, the bar should still be kept at least 30mm away from the nearest exposed face of the profile, as shown in Figure 2.5.

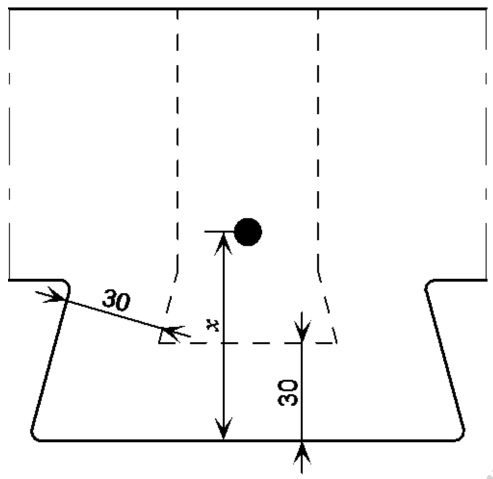


Figure 2.5 Minimum edge distances for placement of bar reinforcement in re-entrant profile

The relationship between the bar temperature and the distance from the exposed surface depends on a quadratic equation, up to the distance $\bar{x}$, at which the quadratic curve reaches its minimum value. For larger distances, the temperature should be taken as that minimum value. A typical temperature-distance curve is shown in Figure 2.3. The value of $\bar{x}$ depends on the parameters of the quadratic equation and should be re-calculated for each exposure period.

Temperature-time relationships for bar reinforcement are given below. The influence of the depth of slab is represented by the following parameter:

$$\sigma = \left(\frac{250}{d_{\text{slab}}} \right)^{0.5}$$

The shape of the profile is irrelevant to the temperature obtained from the relationships below.

Normal weight concrete

For normal weight concrete, the distance at which the temperature would be a minimum is given by:

$$\bar{x} = \frac{-b}{2a}$$

In which parameters a and b are given by Table 2.15 and x is the distance to the soffit, as shown in Figure 2.5.

Table 2.15 Parameters for use in Equation (16)

Exposure period (min)	a	b	c
30	0.042	$-7.5.\sigma^{-0.05}$	400
60	0.049	$-11.0.\sigma^{-0.05}$	695
90	0.04	$-11.1.\sigma^{-0.03}$	855
120	0.039	$-11.5.\sigma^{-0.01}$	970

If the distance to the exposed surface is such that, $x \geq \bar{x}$ the temperature is given by the following equation:

$$\theta_x = a\bar{x}^2 + b\bar{x} + c \quad \text{Eq.(16a)}$$

If $x < \bar{x}$ then the temperature is given by following equation:

$$\theta_x = ax^2 + bx + c \quad \text{Eq.(16b)}$$

In which parameters *a*, *b* and *c* are given by Table 2.15 and *x* is the distance to the soffit, as shown in Figure 2.5.

Lightweight Concrete

For lightweight concrete, the temperatures are given by the following relationship:

$$\bar{x} = \frac{-b}{2a}$$

In which parameters *a* and *b* are given by Table 2.16.

Table 2.16 Parameters for use in Equation (17)

Exposure period (min)	a	b	c
30	0.052	$-9.3\,\sigma^{-0.05}$	470
60	0.049	$-11.5\,\sigma^{-0.05}$	745
90	0.038	$-11.2\,\sigma^{-0.03}$	895
120	0.036	$-11.3\,\sigma^{-0.01}$	995

If the distance to the exposed surface is such that, $x \geq \bar{x}$ the temperature is given by the following equation

$$\theta_x = a\bar{x}^2 + b\bar{x} + c \quad \text{Eq.(17a)}$$

If $x < \bar{x}$ the temperature is given by the following equation:

$$\theta_x = ax^2 + bx + c \quad \text{Eq.(17b)}$$

In which parameters *a*, *b* and *c* are given by Table 2.16 and *x* is the distance to the soffit, as shown in Figure 2.5.

2.2.3 Profiled Steel Sheeting Temperatures

The profiled steel sheeting is idealised as a single element at the plastic neutral axis of the deck itself (see section 4.1). The temperature of the steel is given by taking the average of the temperature of the top flange and the temperature of the bottom flange of sheeting, weighted by the width of the top flange and bottom flange respectively. The relationship is presented mathematically as:

$$\theta_s = \frac{(\theta_{bf} \times B_{bf}) + (\theta_{tf} \times B_{tf})}{(B_{tf} + B_{bf})} \quad \text{Eq.(18)}$$

Where:

θ_s is the temperature of the profiled steel sheeting

θ_{bf} is the temperature of the bottom flange of the profiled steel sheeting

θ_{tf} is the temperature of the top flange of the profiled steel sheeting

B_{bf} is the width of the bottom flange of the profiled steel sheeting

B_{tf} is the width of the top flange of the profiled steel sheeting

The temperature of the bottom flange of the profiled steel sheeting is determined from either equation 10 for normal weight concrete or equation 13 for lightweight concrete, with $x = 0$. The temperature of the top flange of the profiled steel sheeting is determined from either equation 12 for normal weight concrete or equation 15 for lightweight concrete, with $x = d_p$.

3. Insulation

The insulation requirements will be met provided that the minimum thickness of concrete is not less than that specified in Table 3.1 (for composite slabs constructed on profiled sheeting with a trapezoidal profile) or Table 3.2 (for composite slabs constructed on sheeting with a re-entrant profile).

Table 3.1 Minimum thickness of concrete for trapezoidal profiled sheeting

Concrete type	Minimum thickness of concrete (mm) for a fire resistance period (mins) of:			
	I30	I60	I90	I120
NC	60	60	70	80
LC	50	60	70	80

Thickness is measured above the profile (See Figure 3.1)

Table 3.2 Minimum thickness of slab for re-entrant profiled sheeting

Concrete type	Minimum thickness of concrete for a fire resistance period of:			
	I30	I60	I90	I120
NC	100	100	110	125
LC	100	100	105	115

Thickness measured above profiled sheeting soffit (See Figure 3.1)

As noted in the Tables, for trapezoidal profiled sheeting shapes, the insulation depth refers to the depth of concrete above the profiled sheeting (h_s-h_p) and for re-entrant profiled sheeting the depth is the slab depth. Both depths are shown in Figure 3.1.

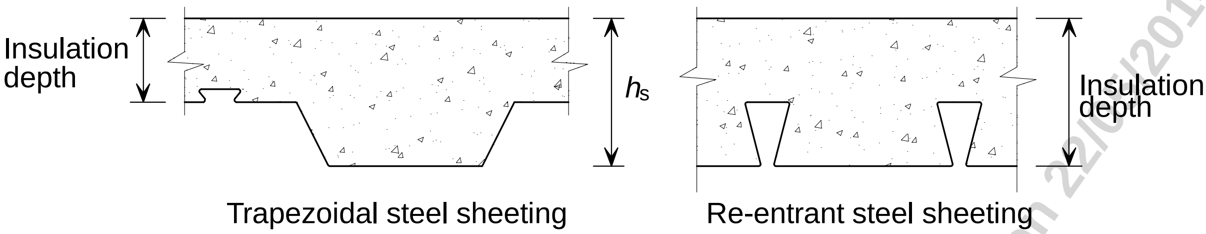


Figure 3.1 Insulation depth

4. Structural design method

4.1 Contribution of sheeting to design resistance

For both fibre and mesh reinforced composite slabs, the strength of the steel sheeting in tension will control the bending resistance for fire resistance periods in excess of 40 minutes. This view is supported by back analysis of bending tests, which demonstrated that 100% of the elevated temperature sheeting resistance may be considered to contribute to the bending resistance in sagging moment regions of the slab.

For fire resistance periods of 40 minutes or less, the bending resistance of the composite slab may be determined using the room temperature design methods and ignoring the mesh or fibre reinforcement. Most mesh or fibre reinforced composite slabs designed to BS EN 1994-1-1 should be able to achieve up to 40 minutes fire resistance without further verification of their bending resistance.

In hogging moment regions, the contribution of the sheeting should be ignored and the bending resistance should be based on the tensile resistance of any reinforcement present in the slab.

Any end anchorage of the sheeting that is provided by shear connectors does not appear to affect the contribution of the sheeting to the bending resistance in fire conditions.

The profiled steel sheeting is represented in equations 20 and 21 by a single element at the plastic neutral axis of the steel sheeting, as supplied by the decking manufacturer. The element temperature is determined using either equation 9 or equation 18, depending on the concrete type.

4.2 Mesh reinforced slabs

The load bearing capacity of mesh reinforced slabs should be based on a plastic design model, provided that the composite slab has sufficient rotational capacity to allow plastic redistribution of moments (for continuous slabs). The bending resistance of the slab may be based on the design model given in BS EN 1994-1-2, 4.3.

4.2.1 Sagging moment regions

The position of the plastic neutral axis of the composite slab in sagging moment regions should be determined such that:

$$A_{\mathrm{p}} k_{\mathrm{y},\theta}\left(\frac{f_{\mathrm{py}}}{\gamma_{\mathrm{M,fi,a}}}\right) + \sum_{i=1}^{n} A_{\mathrm{i}} k_{\mathrm{y},\theta,\mathrm{i}}\left(\frac{f_{\mathrm{sy,i}}}{\gamma_{\mathrm{M,fi,s}}}\right) + \sum_{j=1}^{\mathrm{m}} A_{\mathrm{j}} k_{\mathrm{c},\theta,\mathrm{j}}\left(\frac{\alpha_{\mathrm{slab}}\, f_{\mathrm{c,j}}}{\gamma_{\mathrm{M,fi,c}}}\right) + \sum_{k=1}^{\mathrm{l}} A_{\mathrm{k}} k_{\mathrm{c},\theta,\mathrm{k}}\left(\frac{\alpha_{\mathrm{slab}}\, f_{\mathrm{c,k}}}{\gamma_{\mathrm{M,fi,c}}}\right) = 0 \quad \text{Eq.(19)}$$

Where:

α_{slab} is the coefficient to account for the assumption of a rectangular stress block in concrete, given by BS EN 1994-1-2 Section 4.3.1

A_{p} is the gross area of the profiled steel sheeting

A_{i} is the area of the reinforcement element, *i*.

A_{j} is the area of concrete strip within the ribs, *j*.

A_{k} is the area of concrete strip between the ribs, *k*.

f_{py} is the yield strength of the profiled steel sheeting at room temperature

f_{sy} is the yield strength of the reinforcement at room temperature

f_{c} is the design compressive strength of the concrete at room temperature $f_{\mathrm{c}} = f_{\mathrm{ck}} / \gamma_{\mathrm{M}}$ (with $\gamma_{\mathrm{M}} = 1.2$ according to BS EN 1992-1-2 Table 2.1N)

$k_{\mathrm{y},\theta}$ is the strength retention of the steel elements at elevated temperature (given by BS EN 1994-1-2 Table 3.2 and Table 3.4)

$k_{\mathrm{c},\theta}$ is the strength retention of the concrete strips at elevated temperature (given by BS EN 1994-1-2 Table 3.3)

$\gamma_{\mathrm{M,fi,a}}$ is the partial factor for the strength of structural steel in the fire situation (= 1.0, according to BS EN 1994-1-2 Section 2.3)

$\gamma_{\mathrm{M,fi,s}}$ is the partial factor for the strength of concrete in the fire situation (= 1.0, according to BS EN 1994-1-2 Section 2.3)

$\gamma_{\mathrm{M,fi,c}}$ is the partial factor for the strength of reinforcing bars in the fire situation (= 1.0, according to BS EN 1994-1-2 Section 2.3)

Adopting the sign convention of compression as negative and tension as positive, the resistance of the cross section may be determined by taking moments about the plastic neutral axis. Concrete in tension is ignored. The bending moment resistance is then given as follows.

$$M_{\mathrm{fi,t,Rd}} = A_{\mathrm{p}} k_{\mathrm{y},\theta}\left(\frac{f_{\mathrm{py}}}{\gamma_{\mathrm{M,fi,a}}}\right) z_{\mathrm{p}} + \sum_{i=1}^{n} A_{\mathrm{i}} k_{\mathrm{y},\theta,\mathrm{i}}\left(\frac{f_{\mathrm{sy},i}}{\gamma_{\mathrm{M,fi,s}}}\right) z_i + \sum_{j=1}^{\mathrm{m}} A_j k_{\mathrm{c},\theta,j}\left(\frac{\alpha_{\mathrm{slab}}\, f_{\mathrm{c},j}}{\gamma_{\mathrm{M,fi,c}}}\right) z_j + \sum_{k=1}^{\mathrm{l}} A_k k_{\mathrm{c},\theta,k}\left(\frac{\alpha_{\mathrm{slab}}\, f_{\mathrm{c},k}}{\gamma_{\mathrm{M,fi,c}}}\right) z_k \quad \text{Eq.(20)}$$

Where:

z_{p} is the distance from the plastic neutral axis to the plastic neutral axis of the profile

z_{i} are the distances from the plastic neutral axis to the centroid of each reinforcement element

z_{j}, z_{k} are the distances from the plastic neutral axis to the centroid of each of the concrete areas

Note: All dimensions of z in Section 4 are measured from the PNA, not from the soffit; this differs from the convention in Section 2.

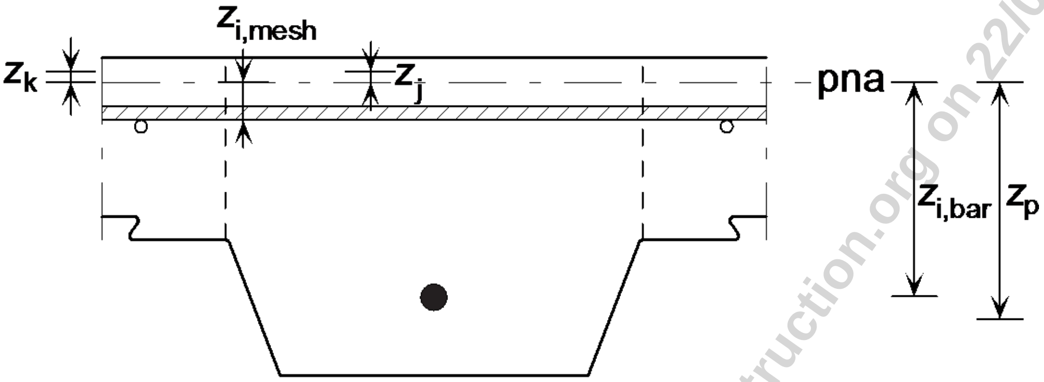


Figure 4.1 Dimensions for slab in sagging bending

The cross section in sagging bending is shown in Figure 4.1. In most cases, the temperature of the concrete in the compressive stress block will be such that the strength need not be reduced, meaning the concrete can be treated as a single strip. The lever arm of the mesh may be measured to the mid depth of the mesh ($z_{i,mesh}$), as shown.

4.2.2 Hogging moment regions

In hogging moment regions, the resistance of the steel profiled sheeting and bar reinforcement is ignored when calculating the plastic bending resistance of the composite slab. The neutral axis position of the composite slab in hogging moment regions should be determined such that:

$$\sum_{i=1}^{n} A_i k_{y,\theta,i}\left(\frac{f_{sy,i}}{\gamma_{M,fi,s}}\right) + \sum_{j=1}^{m} A_j k_{c,\theta,j}\left(\frac{\alpha_{slab}\ f_{c,j}}{\gamma_{M,fi,c}}\right) + \sum_{k=1}^{l} A_k k_{c,\theta,k}\left(\frac{\alpha_{slab}\ f_{c,k}}{\gamma_{M,fi,c}}\right) = 0 \qquad \text{Eq.(21)}$$

Calculating the lever arm for each concrete strip and adopting the sign convention of compression negative and tension positive, the bending moment resistance can be calculated by taking moments about the plastic neutral axis. Concrete in tension is ignored. The bending moment resistance is then given as follows.

$$M_{fi,t,Rd} = \sum_{i=1}^{n} A_i k_{y,\theta,i}\left(\frac{f_{sy,i}}{\gamma_{M,fi,s}}\right) z_i + \sum_{j=1}^{m} A_j k_{c,\theta,j}\left(\frac{\alpha_{slab}\ f_{c,j}}{\gamma_{M,fi,c}}\right) z_j + \sum_{k=1}^{l} A_k k_{c,\theta,k}\left(\frac{\alpha_{slab}\ f_{c,k}}{\gamma_{M,fi,c}}\right) z_k \qquad \text{Eq.(22)}$$

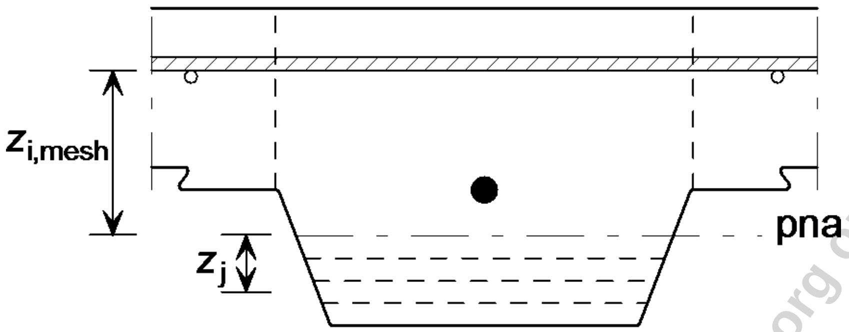


Figure 4.2 Dimensions for slab in hogging bending

The cross section in hogging bending is shown in Figure 4.2. When calculating the hogging moment resistance of a composite slab, the compressive resistance is generally derived from the concrete in the rib of the slab. This concrete is at elevated temperature and must be divided into strips to determine its design temperature (as discussed in Section 2) and to assign strength reductions. In the unlikely case that the plastic neutral axis is higher than the height of the profile, strips will be required both within and between the ribs.

4.2.3 Rotation capacity of composite slabs

Composite slabs must have adequate rotation capacity at plastic hinge positions to allow moments to be redistributed adequately. This is achieved by limiting the depth of the concrete stress block to ensure that premature crushing of the concrete does not occur. The limiting depth of the compressive stress block depends on the amount of redistribution that is required, up to a maximum value of 30%.

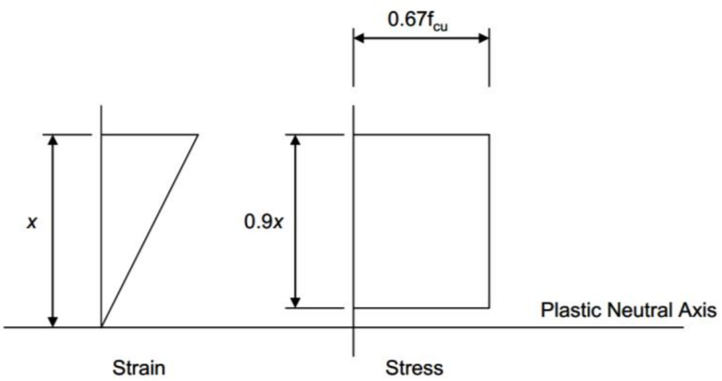


Figure 4.3 Equivalent rectangular concrete stress block (BS 8110-1 Figure 3.3)

The depth of the concrete stress block is equal to $0.9\,x$, as shown in Figure 4.3. The ratio between the depth to the neutral axis and the effective depth of the section varies depending on the degree of moment redistribution.

The relationship between the effective depth of the section (d) and the size of the assumed stress block (x) is:

$$\frac{x}{d} \leq \left(\beta_{\mathrm{b}} - 0.4\right)$$

Where:

x is the depth to the plastic neutral axis of the section

d is the effective depth of the section

β_b is the redistribution factor

The redistribution factor is given as follows:

$$\beta_b = \frac{M_{C,pl}}{M_{el}}$$

Where:

$M_{C,pl}$ is the moment at the cross section after redistribution

M_{el} is the moment at the cross section before redistribution

4.2.4 Plastic mechanism

Using the above limitations to ensure adequate rotational capacity of the slab, the load bearing capacity may be predicted by assuming that a plastic mechanism develops in the slab, as described by the following equations.

Considering the collapse mechanism of a propped cantilever slab, the following expression for minimum collapse load is obtained.

$$W = \frac{2\alpha^2 M_{\text{fi,Rd}^+}}{l} \frac{\sqrt{1+\alpha}}{\left(\sqrt{1+\alpha}-1\right)\left(\alpha+1-\sqrt{1+\alpha}\right)}$$

With:

$$\alpha = \frac{M_{\text{fi,Rd}^-}}{M_{\text{fi,Rd}^+}}$$

Where:

l is the span of the slab

$M_{\text{fi,Rd}}{}^+$ is the sagging resistance moment at elevated temperature

$M_{\text{fi,Rd}}{}^-$ is the hogging resistance moment at elevated temperature

W is the total load on the span

Re-writing the above equation in terms of a uniformly distributed load *w*, the maximum clear span is given by the following expression.

$$l_{\max} = \left(\frac{2\alpha^2 M_{\text{fi,Rd}^+}}{w} \frac{\sqrt{1+\alpha}}{\left(\sqrt{1+\alpha}-1\right)\left(\alpha+1-\sqrt{1+\alpha}\right)} \right)^{\frac{1}{2}}$$

Where:

w is the uniformly distributed load on the span.

5. Design situations outside the scope of this NCCI

5.1 Fibre reinforced slabs

The fire design of composite slabs constructed with fibre reinforced concrete needs specialist calibration and software, the theory of which is outside the scope of PN005c-GB. SCI should be contacted for further information. The contribution of the profiled sheeting to the bending resistance of the composite slab should be based upon the guidance given in Section 4.1.

5.2 Future fire testing

As noted in Section 1, the depth-temperature relationships given in Section 2.1 and Section 2.1.3 are valid for a limited range of profile geometries. While this covers the majority of trapezoidal profiles available in the UK at the time of writing, the model is not valid for 'deep deck' profiles, where the nominal depth exceeds 80 mm. Profiled sheeting with geometries outside of these limits will require specialist temperature model calibration. SCI should be contacted for further information.

6. Reference standards

BS EN 1992-1-1:2004. Eurocode 2: Design of concrete structures. General rules and rules for buildings. BSI.

NA to BS EN 1992-1-1:2004. UK National Annex to Eurocode 2: Design of concrete structures. General rules and rules for buildings. BSI

BS EN 1994-1-1:2004. Eurocode 4: Design of composite steel and concrete structures. General rules and rules for buildings. BSI.

NA to BS EN 1994-1-1:2004. UK National Annex to Eurocode 4: Design of composite steel and concrete structures. General rules and rules for buildings. BSI

BS EN 1994-1-2:2005. Eurocode 4: Design of composite steel and concrete structures. General rules. Structural fire design. BSI.

NA to BS EN 1994-1-2:2004. UK National Annex to Eurocode 4: Design of composite steel and concrete structures. General rules. Structural fire design. BSI

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Amendment 1, 20/10/12
Updated introduction to cover amendments in this version of the document (page 2).
Updated Table 3.1 to reduce minimum concrete thicknesses for normal weight concrete (page 16).

Amendment 2, 12/08/13
Updated coefficients in Table 2.15 (page 16).