New Eurocode 4 design rules for shallow floor construction

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Abstract

As members of Project Team SC4.T5, the authors of this paper present the main outcomes from the work that are intended for implementation within EN 1994-1-1 (Eurocode 4). General design and application rules for shallow floor beams will be presented, with a particular focus on: the classification of the composite cross-section; non-linear bending resistance; and the introduction of transverse bars as shear connectors.

Keywords: Eurocode 4; Mandate M/515; slim-floor construction; shallow floor beams; composite beams; precast concrete.

1 Introduction

Shallow floor, or \textit{slim-floor construction}, has become popular throughout Europe as it provides a shallow structural zone, reduced number of beams, and flexibility in the layout of mechanical services. The key feature of slim-floor construction is the steel beams, which are integrated within the floor depth and possess a wide bottom flange to support the floor slabs. The floor slabs, consisting of either precast concrete hollow core slabs or composite slabs with deep profiled steel sheeting, span between the beams in the orthogonal direction. The partial encasement of the steel beams leads to an inherent fire resistance without the application of fire protection materials. Longer fire resistance periods may be achieved by placing longitudinal reinforcing bars within the concrete encasement, or by applying fire protection to the bottom flange of the steel beam.

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variety of different shallow floor beam cross-sections are available, as illustrated in Fig. 1.

![Examples of shallow floor beam (a) open cross-sections (b) closed cross-sections](image)

Fig. 1  *Examples of shallow floor beam (a) open cross-sections (b) closed cross-sections*

Whilst shallow floor solutions have been adopted widely, they have predominantly been developed as proprietary floor systems in the absence of specific design rules given in EN 1994 (Eurocode 4)[1],[2]. As a consequence of this, there is a general need to develop generic design rules that complement the existing proprietary guidance for these different floor systems. This need was identified in the CEN/TC250 response to Mandate M/515[3],[4] in the context of developing the second generation of the Eurocodes. The CEN/TC250 work programme for developing the second generation of the Eurocodes commenced in 2015 and is split into four overlapping phases, which will conclude in 2022. For Eurocode 4 only a single task within the Phase 2 work was undertaken, entitled ‘Development of rules covering shallow floor construction, and other flooring types using precast concrete elements’. Project Team SC4.T5 was made responsible for the task, which was broken down into the following work-packages:

- Development of design solutions for shallow floor construction.
• Development of design solutions for composite beams incorporating precast concrete units.

• Compilation of solutions into codified rules.

• Production of background documentation.

The main deliverable from the task was a new part for Eurocode 4, or proposed revisions to the existing EN 1994-1-1 and EN 1994-1-2.

The membership of Project Team SC4.T5 consisted of the authors of the present paper (with the second author assigned the role of Project Team Leader). This paper presents an overview of the proposed design rules for shallow floor construction within Eurocode 4. A companion paper is currently being prepared, which will present the development of the rules for composite beams incorporating precast concrete units[5].

2 Composite shallow floor beams

The slim-floor beam may be an open or a closed cross-section, which is hot-rolled or welded (see Fig. 1). Composite slim-floor beams are defined as those where the steel section is embedded, or partially embedded, within a concrete slab and acting compositely with it. The slab may be solid in-situ concrete, precast concrete, or a composite slab with profiled steel sheeting. A particular design consideration for shallow floor construction is when precast hollow core slabs are used. In this special case the slim-floor beams provide ‘flexible supports’, which result in a reduction to the shear resistance of the slab from the development of transversal shear stresses[6],[7],[8],[9]. For this special case, it is proposed that the designer makes reference to EN 1168[10].
3 Structural analysis

3.1 Structural modelling for analysis

The effects of slip and separation on calculation of internal forces and moments may be neglected for shallow floor construction, when mechanical shear connectors are used in the form of headed stud connectors, or transverse bars passing through the steel section (see Section 3.4). For other forms of shear connection, non-linear analysis according to the EN 1994-1-1-1, 6.2.1.4 should be used.

3.2 Effective width of flanges for shear lag

Whilst the effective width of slabs that possess a significant bending stiffness has shown to be much larger than for traditional composite beams[11],[12],[13],[14],[15], there was insufficient data to enable general rules to be developed by SC4.T5. As a consequence of this, a lower bound value is proposed through the use of the existing rules for the effective width in EN 1994-1-1, 5.4.1.2.

3.3 Linear elastic analysis and methods considering material non-linearity

During the development of the design rules it was found that no information on the rotation capacity at plastic hinge positions was available, to enable a simple design verification to be developed. As a consequence of this, when plastic global analysis is used it is currently left to the designer to demonstrate whether sufficient rotation capacity exists. Future research investigating the rotation capacity of shallow floor beams is encouraged.

3.4 Classification of shallow cross-sections

From work undertaken on fully encased sections by Schäfer et al.[16], it is recommended that the compression flange of width $b_l$ may be assumed to be Class 2 when the concrete cover is not less than the smaller of 50 mm or $b_l/6$. For open sections which are partially
encased, it is recommended that the compression flange outstands are classified according to EN 1994-1-1, 5.5.3[17].

4 Ultimate limit states

4.1 Bending Resistance

Composite cross-sections may be assumed to remain plane after bending if the shear connection is designed according to EN 1994-1-1, 6.6 together with the rules for transverse bars used as shear connectors (see Section 4.2.3). Both full and partial shear connection design may be used for shallow floor beams.

The bending resistance of the shallow floor composite beam may be evaluated using elastic, plastic or non-linear theory. A unique feature of shallow floor composite beams is the greater likelihood of the plastic neutral axis lying deep within the cross-section, close to the bottom flange; in these circumstances there is the possibility that premature crushing of the concrete can occur before the design yield strength of the steel section is reached[16],[18],[19],[20],[21]. In these situations, the design resistance to bending should be determined using the non-linear bending resistance (see Section 4.1.1), or be based on the elastic bending resistance $M_{el,Rd}$ (from EN 1994-1-1, 6.2.1.5).

Local effects on the composite shallow-floor cross-section should also be considered in the determination of the resistance in bending (e.g. transverse bending of the plate welded to the bottom flange of the steel section)[16],[22],[23].

4.1.1 Non-linear resistance to bending

The non-linear bending resistance of the composite beam should be evaluated by advanced calculation according to EN 1994-1-1, 6.2.1.4. In these cases, the bi-linear stress-strain relationship for the reinforcement and the structural steel should be taken from EN 1992-1-1, 3.2.7 and EN 1993-1-1, 5.4.3(4) (where the latter takes account of the
effects from the method of construction), respectively. For the concrete in compression, the stress-strain relationship given in EN 1992-1-1, 3.1.7 should be used.

Alternatively, the non-linear bending resistance $M_{Rd}$ may be determined using a simplified method[24], when the following conditions are satisfied:

1. the structural steel grade does not exceed S460 and normal weight concrete is used with a strength class up to C50/60;
2. the effective width of the concrete flange $b_{eff} \geq 1000$ mm (see Fig. 2);
3. the concrete cover $c_z$ over the top flange of the steel section fulfils the condition $50$ mm $\leq c_z \leq 150$ mm (see Fig. 2);
4. the depth of the steel section $h_a \geq 160$ mm (see Fig. 2);
5. the ratio of the thickness of the plate welded to the structural steel section $t_p$ to the overall cross-section $h$ fulfils the condition $t_p/h \leq 1/6$ (see Fig. 2);
6. the cross-sectional area of the longitudinal reinforcement $A_s \leq A_p$, where $A_p$ is the cross-sectional area of the plate welded to the structural steel section (see Fig. 2); and
7. the cross-sectional area of the top flange of the structural steel section $A_{f,t}$ in relation to the other steel areas of the composite section are $A_{f,t} / (A_{f,b} + A_p + A_s) \leq 2/3$, where $A_{f,b}$ is the cross-sectional area of the bottom flange of the structural steel section (see Fig. 2).

Where these conditions are satisfied, the bending resistance $M_{Rd}$ may be taken to be:

$$M_{Rd} \geq \beta_{SF} M_{pl,Rd}$$  \hspace{1cm} (1)

where $\beta_{SF}$ is the reduction factor for shallow floor beams given in Fig. 3 and $M_{pl,Rd}$ is the design value of the plastic resistance moment of the composite cross-section.
For $z_{pl}/h$ values greater than the limits shown in Fig. 3, the elastic bending resistance $M_{el,Rd}$ should be used in design (from EN 1994-1-1, 6.2.1.5), or more advanced calculation of the non-linear resistance to bending according to EN 1994-1-1, 6.2.1.4 may be undertaken.

4.2 Shear connection

4.2.1 Limitation on the use of partial shear connection

The mechanical shear connectors in Section 4.2.2 and 4.2.3 may be considered as ductile within the following limits for the degree of shear connection, which is defined by the ratio $\eta = n / n_f$:

For shallow floor beams with steel sections having a bottom flange with an area equal to three times the area of the top flange, EN 1994-1-1, Equation (6.14) and (6.15) may be used.

From German technical approvals for specific types of shear connectors[25],[26], it is proposed that the following equation may be used for shallow floor beams with steel
sections having a bottom flange with an area larger than three times the area of the top flange:

\[ L_e \leq 18: \quad \eta \leq 1 - \left(\frac{355}{f_y}\right) (0.30 - 0.015L_e) \geq 0.5 \tag{2} \]

where \( L_e \) is the distance in sagging bending between points of zero bending moment in metres, \( f_y \) is the nominal value of the yield strength of the structural steel (for hybrid shallow floor beams, based on the highest steel grade used), \( n_f \) is the number of connectors for full shear connection over the length \( L_e \) and \( n \) is the number of shear connectors provided within that same length.

### 4.2.2 Headed stud connectors in solid slabs and concrete encasement

When headed stud connectors are welded to the top flange of the shallow floor beam (see Fig. 4), it has been shown that the design shear resistance may be evaluated according to EN 1994-1-1, 6.6.3.1[27],[28]. Alternatively, the stud connectors may be welded horizontally to the web as shown in Fig. 4. In these circumstances, the studs will cause splitting forces in the direction of the slab thickness and the design shear resistance should be calculated according to EN 1994-2, 6.6.4[29].

![Fig. 4](image)

**Fig. 4** Mechanical shear connectors which are supported by proposed design rules

### 4.2.3 Transverse bars passing through the web of the shallow floor beam

Whilst transverse bars have been used as shear connectors in the past (see Fig. 4)[17], design rules for calculating the longitudinal shear resistance have not previously been
given in Eurocode 4. From research that has been undertaken since 2006[16],[30],[31],[32],[33],[34],[35],[36],[37], the following design equation is proposed:

\[ P_{rd} = \frac{\pi d^2}{4} \frac{f_{sk}}{\sqrt{3}} \frac{1}{\gamma_v} \]

where:

\( d \) is the diameter of the transversal reinforcement bar, \( 12 \text{ mm} \leq d \leq 20 \text{ mm}; \)

\( f_{sk} \) is the characteristic value of the yield strength of the reinforcement bar, which should have a ductility Class B or C;

\( \gamma_v \) is the partial factor with a recommended value of 1.25.

4.2.4 Design resistance to longitudinal shear

To prevent longitudinal shear failure, transverse reinforcement should be provided so that it crosses potential surfaces for shear failure. In addition to the potential surfaces already given in EN 1994-1-1, Figure 6.15, the surfaces shown in Fig. 5 should be considered for shallow floor beams[26], and the design resistance to longitudinal shear evaluated according to EN 1994-1-1, 6.6.6.

![Fig. 5](image_url)  

*Fig. 5  Potential surfaces of shear failure in shallow floor beams*
5 Tying systems

A floor is often required to provide diaphragm action in order to transfer wind loads to braced walls or concrete core walls. This action may be achieved through the following measures:

- Provision of a continuous in-situ reinforced topping in order to transfer the in-plane forces in both orthogonal directions.
- Ties between the perimeter members and the floor (e.g. attached by headed stud connector and looped bars, etc.).
- Ties to the shear walls or reinforced cores.
- Where an in-situ topping is not used, additional internal ties should be provided.

The same measures are also appropriate to achieve robustness as defined by EN 1991-1-7[38].

Steel beams around the perimeter of the building should be tied into the floor plate for diaphragm action, and for torsional resistance (if they support cladding). Slim-floor beams may also be considered to act as peripheral ties. From the IPHA/ECCS guide[8], the recommended location of these ties for shallow floor construction using precast slabs is shown in Fig. 6.
6 Fire resistance of slim-floor beams

Whilst rules for evaluating the design temperatures within slim-floor beams have been published[39], their basis could not be verified by the present authors. As a consequence of this, a simple calculation method for evaluating the sagging moment resistance of slim-floor beams in fire conditions was developed, and is presented in a companion paper[40]. It is proposed that this simplified method is incorporated within EN 1994-1-2[2].

7 Conclusions

This paper presents the proposed design rules for shallow floor beams that were developed by Project Team SC4.T5 for inclusion within the second generation of Eurocode 4. The rules are intended to complement the existing proprietary guidance for the different floor systems that are currently used widely across Europe. During the development of the proposed design rules it was found that there was sometimes little, or no data available in the public domain for certain design considerations. In these situations, it was either not possible to develop a simple design verification or, alternatively, targeted research needed to be undertaken in parallel with the Project Team work.
The proposed design rules for shallow floor beams are currently being circulated for comment to the 34 National Standardization Bodies (NSBs) that make up the CEN membership and, as a consequence of this, may be subject to change. Any views expressed in this paper may not necessarily reflect those of the members of the Committee responsible for Eurocode 4 (CEN/TC250/SC4).

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