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NEW EUROCODE 4 DESIGN RULES FOR COMPOSITE BEAMS WITH PRECAST CONCRETE SLABS

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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 is intended for implementation within the second generation of Eurocode 4. General design and application rules for composite design of precast concrete elements will be presented, with a particular focus on: the effective width of flanges using precast concrete elements for shear lag; design resistance to longitudinal shear; and the design resistance of headed stud connectors in the presence of precast hollow core slabs.*

1 INTRODUCTION

Steel construction has achieved a high market share in buildings and is often used in conjunction with various types of precast concrete floors. A high proportion of multi-storey steel frames use precast concrete floors, which are particularly suited to sectors such as hotels, residential buildings, and car parks. The synergy between the use of precast concrete slabs and steel structures is that they both come from a manufacturing technology rather than a site-based activity, and share the quality control, accuracy, and reliability of factory production.

Whilst industry guidance for designing composite beams with precast concrete slabs is available [1],[2], this form of construction is not currently covered within the scope of EN 1994-1-1 (Eurocode 4) [3]. As a consequence of this, there is a general need to develop harmonized design rules for Europe. This need was identified in the CEN/TC250 response to Mandate M/515 [4],[5] 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 composite beams incorporating precast concrete units.
- Development of design solutions for shallow floor construction.
- Compilation of solutions into codified rules.
- Production of background documentation.

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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 [6].

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 composite beams incorporating precast concrete slabs within Eurocode 4. A companion paper presents the development of the rules for shallow floor construction [7].

2 COMPOSITE BEAMS WITH PRECAST CONCRETE SLABS

The rules are limited to use in buildings. The structural steel beam should be an open cross-section, which may be hot-rolled or welded. The precast concrete slabs may consist of solid composite slabs, together with hollow core slabs or composite hollow core slabs that are square or chamfered-ended (see Figure 1).

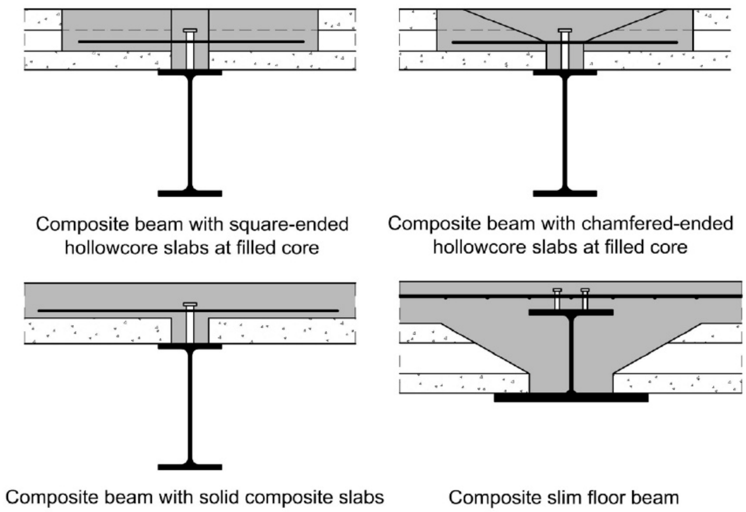

Figure 1. Typical cross-sections of composite beams with precast slabs

The steel beam and precast concrete slabs should be interconnected by mechanical shear connectors, to limit the longitudinal slip between concrete and steel and the separation of one component from the other. A particular design consideration is when precast hollow core slabs are used. In this special case the steel beams may provide ‘flexible supports‘, which result in a reduction to the shear resistance of the slab from the development of transversal shear stresses [8],[9],[10]. For this special case, it is proposed that the designer makes reference to EN 1168 [11].

3 STRUCTURAL ANALYSIS

3.1 Effective width of flanges for shear lag

For floors with solid composite slabs, the effective width of the flanges in the composite beam may be determined using the existing rules given in EN 1994-1-1, 5.4.1.2. From full-scale composite beam tests [13] on floors with hollow core slabs or composite hollow core slabs, the effective width of the flanges may also be determined using EN 1994-1-1, but with the geometric width b_i taken as the smaller of the length of the infill within an open core ℓ_f (see Figure 2), or the distance from the outstand shear connector to a point mid-way between adjacent webs to the supporting steel beams, measured at mid-depth of the concrete flange [1],[2]. In addition, b_0 should be taken as the gap b_g between the ends of the hollow core slabs.

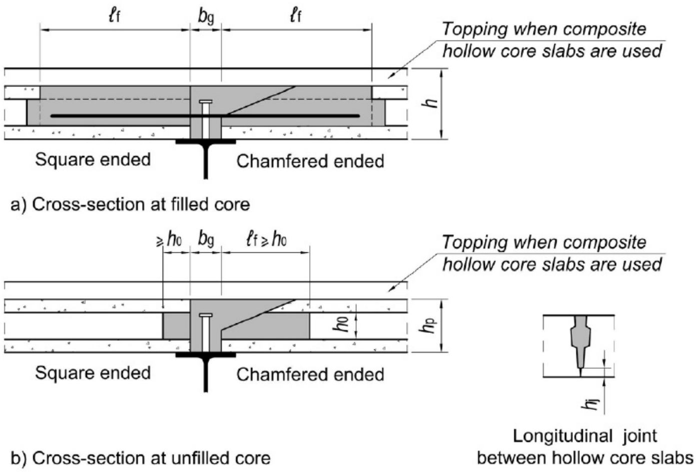

Figure 2. Cross-section of composite beams with precast hollow core slabs at filled and unfilled core positions

4 ULTIMATE LIMIT STATES

4.1 Design resistance of headed studs used with precast floors

4.1.1 Floors using solid composite slabs

From push test evidence reported by Moy and Tayler [12], the nominal thickness of the precast floor plate h_p should not exceed 100 mm and the transverse reinforcement bars should be positioned according to EN 1994-1-1, 6.6.5.1(1). Moreover, the diameter of the shank of the headed stud d should not be less than 19 mm. In these situations, the headed stud shear connector may be deemed to be ductile according to EN 1994-1-1, 6.6.1.1(5), and the design shear resistance should be taken as the resistance in a solid slab given by EN 1994-1-1, Equation (6.18) and (6.19).

For cases when the minimum dimensions given above are not satisfied, the design resistance of the shear connectors should be evaluated from specific tests according to EN 1994-1-1, Annex B.

4.1.2 Floors using precast hollow core slabs

From full-scale composite beam and companion push test evidence [13],[14], the nominal thickness of the hollow core slab excluding topping h_p should not exceed 265 mm and the transverse reinforcement bars should be positioned according to EN 1994-1-1, 6.6.5.1(1). The slabs may be square or chamfered-ended. For the latter case, the depth of the chamfer a_h should not exceed 85 mm, whilst its breadth a_b should not exceed 235 mm (see Figure 3). The diameter of the shank of the headed stud d should be within the range 19 mm $\leqslant d \leqslant$ 22 mm.

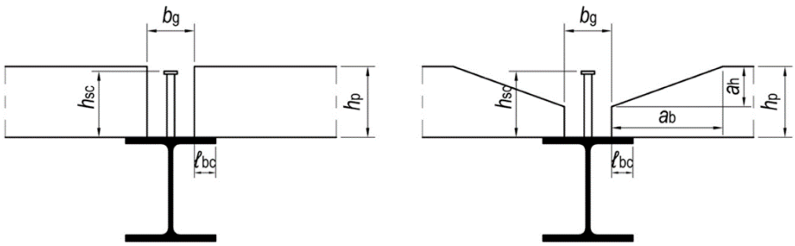

Figure 3. Detailing requirements for precast hollow core slabs.

In these situations, the design shear resistance of headed stud connectors should be taken as the resistance in a solid slab (calculated according to EN 1994-1-1, Equation (6.18) and (6.19)) and multiplied by the reduction factor k given by [15]:

$$k = \beta\varepsilon \leq 1.0 \tag{1}$$

with

$\beta = \dfrac{b_g + 70}{140}$ for 70 mm $\geq b_g \geq$ 50 mm

$\varepsilon = \dfrac{\phi + 20}{40}$ for 20 mm $\geq \phi \geq$ 8 mm

where b_g is the nominal distance between the ends of the hollow core slabs (mm) and ϕ is the diameter of the transverse reinforcing bars (mm).

Open cores should be provided to receive transverse reinforcement bars, which should be positioned below the heads of the stud shear connectors according to EN 1994-1-1, 6.6.5.1 (see Figure 4). Where the minimum dimensions above are not satisfied, the design shear resistance of the shear connectors should be evaluated from specific tests for precast hollow core slabs according to the proposed push test arrangement given in Annex B (see Section 7).

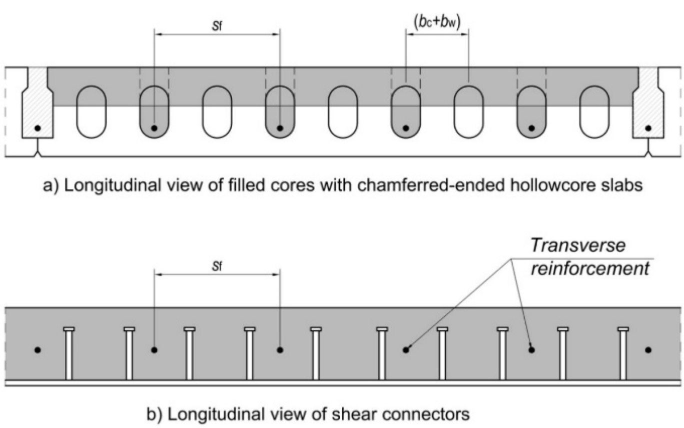

Figure 4. Longitudinal detailing requirements for precast hollow core slabs.

4.2 Longitudinal shear in precast concrete slabs

To prevent longitudinal shear failure, transverse reinforcement bars should be provided so that they cross potential surfaces for shear failure, and the design resistance to longitudinal shear evaluated according to EN 1994-1-1, 6.6.6. Whilst design rules for composite beams with precast concrete slabs are generally not provided in the existing Eurocode 4, information on the potential surfaces of shear failure in solid composite slabs is given in EN 1994-1-1, Figure 6.15.

For cases when hollow core slabs or composite hollow core slabs are used, the length of the potential shear surface c-c shown in Figure 5 should be taken as equal to $2h_{sc}$, where h_{sc} is the height of the studs. The transverse reinforcement should be placed in alternate cores (see Figure 4) [1],[2].

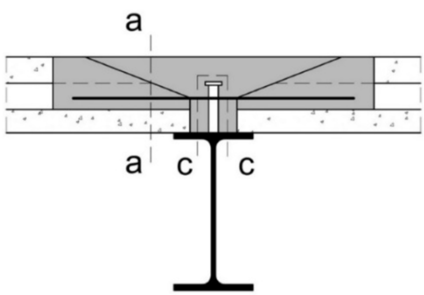

Figure 5. Typical potential surfaces of shear failure where precast hollow core slabs are used.

The transverse reinforcement should be provided in accordance with EN 1994-1-1, 6.6.6 and fully anchored within each open core, with the length of the concrete infill ℓ_f not being less than 500 mm (see Figure 2). As shown in Figure 2(b), cores without transverse reinforcement should be filled with concrete such that $\ell_f \geqslant h_0$.

5 BOLTED SHEAR CONNECTORS

In the interest of improving the sustainability of composite beams through encouraging re-use, design rules for bolted shear connectors are also proposed. Two types of bolted shear connector are considered *viz*. pre-stressed bolts and non-preloaded bolts.

5.1 Preloaded bolts

Given their use in Switzerland [16] and the UK [17], it is proposed that the earlier design rules previously given in ENV 1994-1-1 [18] for class 8.8 bolts are reintroduced. At the ultimate limit state, the design shear resistance per bolt should be taken as:

$$P_{Rd} = \frac{\mu_k F_{pr,Cd}}{\gamma_V} \tag{2}$$

where $F_{pr,Cd}$ is the preloading force in the bolt, based on $F_{p,Cd}$ given by EN 1993-1-8 (reduced to take account of the effects of creep and shrinkage of the concrete), μ_k is the characteristic coefficient of friction and γ_V is the partial factor (with a recommended value of 1.25).

Both HR and HV systems according to EN 14399 [19] may be used. The characteristic coefficient of friction may be taken to be the slip factor μ_k for a particular surface treatment given in the execution standard EN 1090-2 [20]. For other surface treatments, the coefficient of friction may be based on test results, with the characteristic value determined in accordance with EN 1990, Annex D [21].

The reduction in the preloading force in the bolt due to creep and shrinkage of the concrete should either be determined by long-term tests, or should be assumed to be not less than 40% of $F_{p,Cd}$.

5.2 Non-preloaded bolts

Non-preloaded bolts with embedded nuts may also be used as shear connectors. Preloaded bolts according to EN 14399 [19] may be used, provided that the preloading force is not higher than $F_{p,C}$ according to EN 1993-1-8 [22], and that the preloading is only applied within the region b between the embedded and outer nut (see Figure 6).

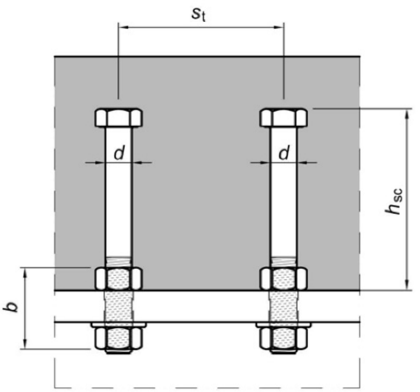

Figure 6. Shear connection with preloaded high-strength bolts

The design shear resistance of a non-preloaded bolt, with one or two embedded nuts, should be determined from [23]:

$$P_{b,Rd} = \frac{\alpha_b A_s f_{ub}}{\gamma_V} \tag{3}$$

or

$$P_{c,Rd} = \frac{55\alpha_c d^{1.9}\left(f_{ck}\frac{h_{sc}}{d}\right)^{0.4} + 22000}{\gamma_V} \tag{4}$$

whichever is smaller, with:

$$\alpha_b = 0.6\left(\frac{34}{d}\right)^{0.23} \tag{3}$$

$$\alpha_c = \frac{22.5}{d+3} \leq 1.0 \tag{4}$$

where d is the bolt diameter in mm (12 mm $\leq d \leq$ 24 mm), A_s is the tensile stress area of the bolt in mm² ($A_s \approx 0.785\pi d^2/4$), h_{sc} is the overall nominal height of the non-preloaded bolted shear connector above the flange in mm, f_{ub} is the ultimate tensile strength in N/mm² for bolt classes 8.8 and 10.9, f_{ck} is the characteristic cylinder compressive strength of concrete at the age considered, of density not less than

1750 kg/m³ that is cast in-situ around the shear connector and γ_V is the partial factor (with a recommended value of 1.25).

5.2.1 Slip capacity

The characteristic slip capacity for non-preloaded bolts may be calculated to be:

$$\delta_{uk} = 0.56e^{2.45 P_{b,Rd} / P_{c,Rd}} \tag{5}$$

where $P_{b,Rd}$ is the design value of shear resistance from bolt failure (Equation (3)), and $P_{c,Rd}$ is the design value of shear resistance to concrete failure (Equation 4).

According to Equation (7), a non-preloaded bolt may be taken as ductile according to EN 1994-1-1, 6.6.1.1(5), when $P_{b,Rd}/P_{c,Rd} > 0.97$.

6 TYING SYSTEMS

A floor is normally 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 [24]. The 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). The steel beams may also be considered to act as peripheral ties. From the IPHA/ECCS guide [25], the recommended location of these ties for hollow core floors is shown in Figure 7.

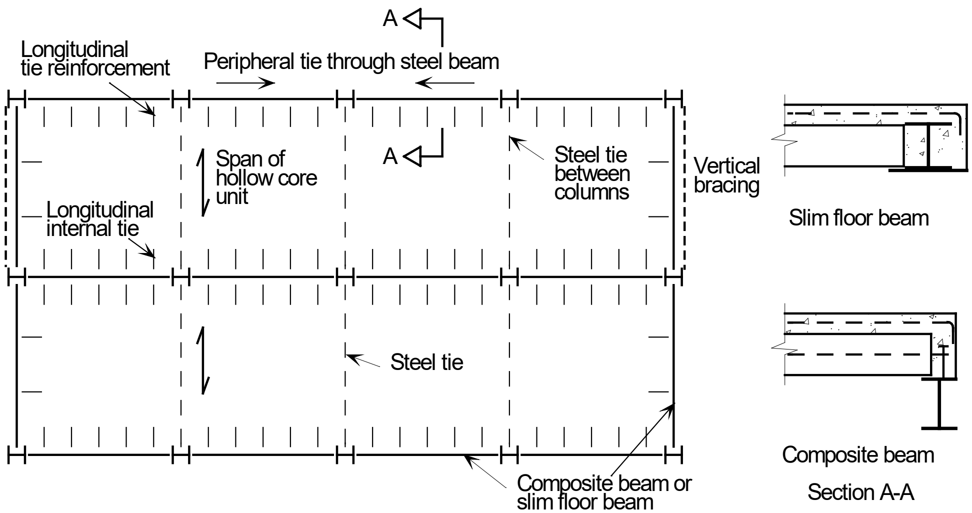

Figure 7. Tying action in the floor plate using precast slabs.

7 TESTS ON SHEAR CONNECTORS IN HOLLOW CORE SLABS

To ensure that the experimental resistance of shear connectors in hollow core slabs is determined consistently, a specific test is proposed for inclusion within EN 1994-1-1, Annex B (see Figure 8). As can be seen from Figure 8, due to the practicalities of testing shear connectors with hollow core slabs using the standard push specimen, a one-sided arrangement is proposed. This arrangement has been successfully used by Lam *et al.* [14], where the results from tests using this type of specimen formed the basis of Equation (1).

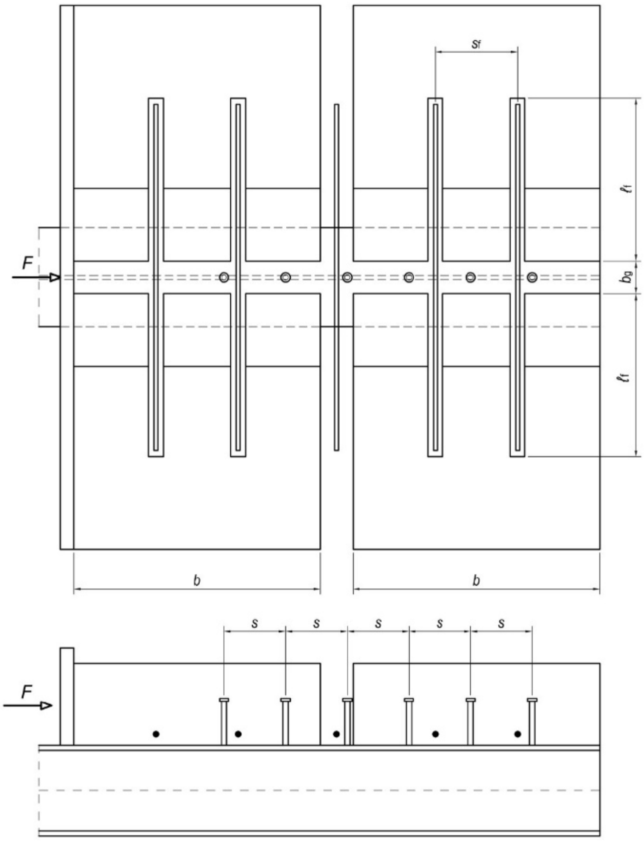

Figure 8. Test specimen for headed stud connectors within hollow core slabs or composite hollow core slabs.

8 CONCLUSIONS

This paper presents the proposed design rules for composite beams with precast concrete slabs, which were developed by Project Team SC4.T5 for inclusion within the second generation of Eurocode 4. The rules are intended to complement the existing industry guidance that has been used widely across Europe. The proposed design rules for composite beams using precast concrete slabs 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 other members of CEN/TC250 Subcommittee 4 (CEN/TC250/SC4).

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