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140 m^2 Column Free Space due to Innovative Composite Slim Floor Design

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Abstract

Slim-Floor construction is a well-established and economic solution for steel framed buildings. It is characterized by integrating the principle steel beams into the floor. So far, spans of Slim-Floor beams are generally limited to +/- 8m. With a composite design of Slim-Floor beams, clear spans up to 14m with secondary beam distance of 10m and an overall construction height of only 40cm are achievable. The shear connection is assured by concrete dowels and thus, not related to any significant efforts in fabrication. This beam type leads to economic and flexible construction and fulfils the requirements for sustainability with efficient use of materials in combination with light and slender members. This contribution presents the design of Composite Slim-Floor Beams (CoSFB).

Keywords: Steel, Composite, Slim Floor Construction, Concrete Dowel

1. Introduction

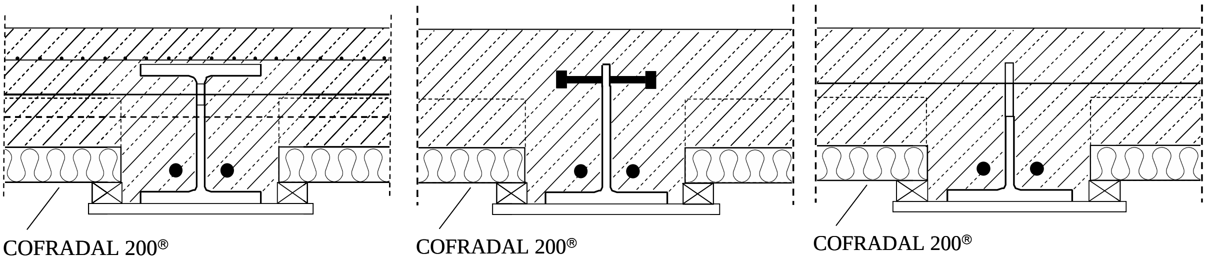
Steel as construction material for high-rise buildings has a long tradition. Since authorities had started to reduce the floor space index of high-rise buildings, the contractors aimed to reduce the height between floors and therefore to increase the total number of storey's as an economic advantage in competition. Consequently Slim-Floor construction became a well-established and economic solution for steel framed buildings. It is characterized by integrating the principle steel beams into the floor, see Fig 1. So far, spans of Slim-Floor Beams (SFB) are generally limited to +/- 8m. However the advantages of steel and composite construction are large spans leading to column-free open spaces. These bright floors are flexible in re-use and consequently sustainable for the future and are not feasible with typical concrete construction. Therefore it has been requested to further develop sophisticated Slim-Floor construction by keeping the construction height constant and to achieve an increase in open floor space with SFBs from 8m spans up to 14m spans. Further the construction speed of steel construction should also been conserved. Floor structures are designed for ultimate limit state and serviceability limit state criteria. For slender floor structures, as made in steel or composite construction, serviceability criteria govern the design. Serviceability limit states are related to deflections and vibrations and hence are governed by stiffness, masses, damping and the excitation mechanisms. Therefore the increase of the inertia of the SFBs has been identified to be the key to achieve the aimed ground floor design. The solution has been found in realizing the SFB as a composite section. Hereby the inertia as well as the damping is increased.

Figure 1: Office building in Esch-sur-Alzette, Luxembourg [1]

2. Composite Slim Floor Beam (CoSFB)

2.1 Introduction

Three sections have been identified to have a further potential, see Fig 2. Hereby the composite action for the CoSFB is activated either by a concrete dowel, case a) and c) or by horizontal shear studs, case b) [4]. In this paper solution a) is focused.



a) CoSFB with concrete dowel

b) Pre-CoSFB with horizontal shear stud

c) Pre-CoSFB with concrete dowel

Figure 2: CoSFB-sections

For the construction stage, the main beam should be propped, whereas the slab rests unpropped. Therefore the construction sequence is kept very effective and economic.

2.2 Concrete Dowel Technology

For a controlled shear transmission between the SFB and the concrete chord, concrete dowels have been chosen. These are openings in the steel section interspersed by concrete. The resistance of the dowel is depending on the projection area of the compressed steel surface from the opening in the concrete chord and the 3-dimensional stress state concrete resistance activated. The first application of concrete dowels for Slim-Floor slab systems has been for the Korean high rise building market [2]. Hereby T-sections with cut-outs (concrete dowels), have been placed on the lower flange of an SFB, bearing sheetings for a composite slab. Reinforcement has been put through holes in the web of the SFB and the overall system has been calculated as a compact composite slab solution for the SLS. Subsequently the concrete dowel technology has been used for the PreCoBeam solution [5] based on T-sections with a prefabricated concrete chord. For the design of the dowel and further information it is references to [3] and [5]. Finally the economic potential of combining the concrete dowel technology with the SFB-technology has been identified and developed by ArcelorMittal.

3. Design of Composite Slim Floor Beams

3.1 General design considerations

The Slim-Floor beam (types, see Fig. 3) is designed according to the elasto-plastic analysis. Therefore the section has to be minimum class 2 according to EN 1993-1-1 (2005), Table 5.2. [8], in order to avoid local instability for full plastic moment design.

3.2 Ultimate Limit State (ULS)

For ULS design the following checks have to be performed: maximum bending moment at mid-span, maximum vertical shear at the supports and load bearing capacity of the bottom plate.

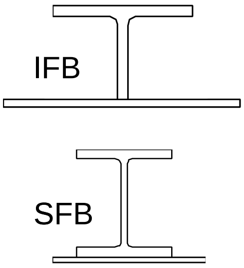


Figure 3: Slim-Floor beam types

Further, the resistance for longitudinal shear has to be verified, see chapter 2.2. Generally, with the concrete dowel technology, full shear connection is present. Stability checks, such as for lateral torsional buckling (LTB) for the construction and the final stage are not covered by this paper.

Bottom Plate

The slab elements, e.g. COFRADAL 200®, are supported by the bottom plate of the steel section, see Fig. 4. The plate is working as a cantilever with a rectangular cross section, on which concentrated loads are acting. As shear and bending become maximal near the support, an M/V interaction is required. If the shear force is less than 50% of the plastic shear resistance, interaction has not to performed, see EN 1993-1-1 (2005), 6.2.8 (2) [8].

Steel Section

The static theorem from the plastic theory allows the assumption of any stress distribution (as simple as possible), as long as the following two conditions are fulfilled: (1) the equivalent von-Mises stress cannot exceed the yield strength in any point of the section and (2) the stress distribution must be in equilibrium. The equivalent von-Mises stress, neglecting the shear stresses ($\tau_{xy} \approx \tau_{xz} \approx \tau_{yz} \approx 0$), is expressed in Eq. (1).

$$\sigma_{vM} = \sqrt{\sigma_x^2 + \sigma_y^2 - \sigma_x * \sigma_y} \leq f_{y,d} \qquad (1)$$

From Eq. 1 it can be derived, that if the stresses σ_x and σ_y are simultaneously positive or negative, they can both reach the yield strength without violating the yield condition. If they are of different sign, one of them has to go to zero, if the other one goes towards the yield strength. The application of these rules leads to a model, in which the lower area of the bottom plate is exclusively reserved for transversal bending while, for longitudinal bending, only a reduced beam section is available.

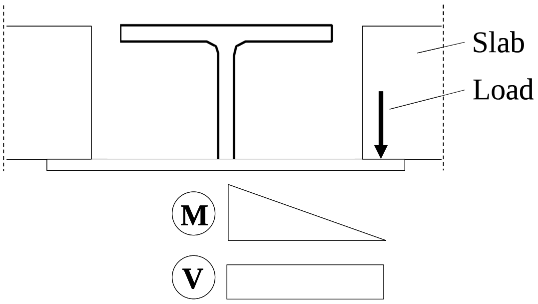


Figure 4: Inner Forces Bottom Plate

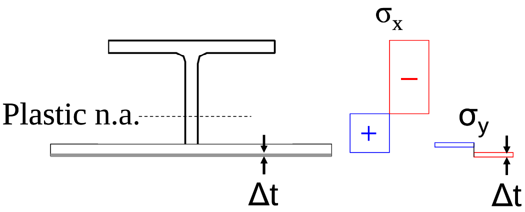


Figure 5: Plastic stress distribution

In Fig. 5 the full plastic stresses for longitudinal (σ_x) and transversal (σ_y) bending are shown. The thickness reduction Δt of the bottom plate is derived with Eq. 2:

$$t_{red} = t - \Delta t \tag{2}$$

with $\Delta t = 0.5 * t * \left(1 - \sqrt{1 - M_{Ed,plate} / M_{pl,Rd,plate}}\right)$ and $M_{pl,Rd,plate} = 0.25 * b * t^2 * f_{y,d}$.

Based on a simplified plastic stress distribution, shown in Fig. 6, the resistance design moment of the reduced steel section is calculated. The composite action is taken into account, the concrete part in tension and the slab reinforcement in compression is neglected.

For example, for the CoSFB specified in Fig. 6 with concrete class C30/37 the following values are determined: $M_{Ed,plate}$ = 3.25kNm/m, Δt_{plate} = 0.50mm, I_0 = 65000cm^4, $M_{pl,Rd}$ = 1270kNm. The values of the pure steel section are: I_y = 24000cm^4 and $M_{pl,Rd}$ = 600kNm. Therefore 100% plastic moment resistance has been gained due to the composite action. The shear resistance of the concrete dowel according to [3] is hereby P_{Rd} = 790kN/m; therefore full shear connection is present. For the plastic design of composite SFB, the moment rotation capacity of the composite section has to be taken into account.

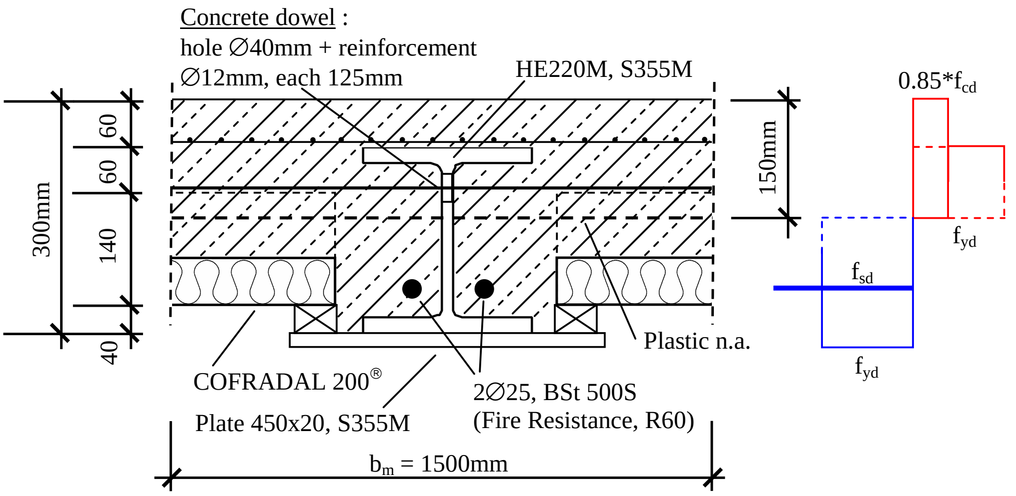


Figure 6: CoSFB + plastic stress distribution

3.3 Serviceability Limit State (SLS)

The stresses in the beam have to remain elastic under service loads (safety factors = 1.0). Based on this elastic behavior, the global beam deflection can be estimated as for a standard composite beam. Shrinkage and creeping of the concrete has to be taken into account. Additionally the local deflection due to bending of the bottom plate must be checked – a deflection limit of 1.5 mm has been proved to be adequate.

3.4 Vibration Comfort

There is no direct limitation of the natural frequency, velocity or acceleration given by the Eurocodes, see EN 1993-1-1 (2005), 7.2.3 (1) [8]. To close this lack, ArcelorMittal has published a “Design Guide for Floor vibrations” [6]. With this guide, a quick evaluation of the vibration behavior of floors and the vibration comfort is possible. The slab solution with a CoSFB span of 10m and beam distance of 7.5m has e.g. been assessed into class D (OS-RMS$_{90}$ = 2.4 mm/s), suitable for office buildings according to [6], Table 2.

3.5 Fire Resistance

The fire resistance of the composite section shown in Fig. 6 has numerically been investigated FEA [7]. The analysis is done in two steps: (1^{st}) the temperature distribution in the cross section by using the “nominal temperature time curve”, see EN 1991-1-2 [8] is calculated; (2^{nd}) a structural calculation with the static loads taking into account the mechanical properties of the materials at elevated temperature is performed.

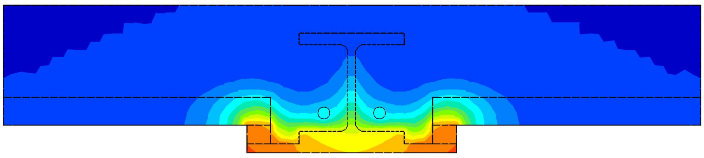


Figure 7: Temperatures at 60 minutes

Hereby the beam span L = 10m, Distance of beams a = 7.5m, Dead Load (DL) 5.0kN/m^2 and Live Load (LL) 3.0kN/m^2 (office building $\Rightarrow \psi_1 = 0.5$) has been assumed. The temperature distribution at 60min is shown in Fig. 7. The section is classified in resistance class R60 (exact calc. fire resistance is about 72 minutes) of “Iso-Fire” without any passive fire protection. A higher fire resistance class can be attained by increasing the reinforcement in the chambers.

4. Application Example

One of the applications of CoSFB has been the 11000m^2 office building “Espace Pétrusse” in Luxembourg (EPL) designed by the architect Marc WERNER, built from CDC in 2006, see Fig. 8 to Fig. 10. The main arguments to choose the CoSFB solution have been:

- Reduction of the overall building height,
- Decrease of the foundation reaction forces (the building was built above an existing underground parking – 2 additional floors could be constructed because of the “light” system),
- Increased erection speed (1000m^2/month),
- Fire resistance w/o passive protection (R90).

However in this application the composite action has only been applied for the SLS design.

Since the application at the Espace Pétrusse, 2 additional applications have been realized; the Ecole d’architecture de Nantes, Nantes (2007) and the Lycée technique Galliéni, Toulouse (2007). Further projects are in sight.

Figure 8: EPL

Figure 9: EPL – SFB and Cofradal

Figure 10: EPL – Ground floor design

5. Conclusions

With a composite design of SFBs, clear spans up to L = 14m with a beam distance a = 10m and an overall construction height of only h = 40cm are achievable. The shear connection of the steel beam to the concrete is assured by innovative concrete dowels and therefore not related to any significant efforts in fabrication.

The comparison between the SFB and the CoSFB in Fig. 11 outlines the technical advantage of this construction type. The CoSFB leads to economic and flexible construction and fulfils the requirements for sustainable structures with efficient use of raw material in combination with light and slender members.

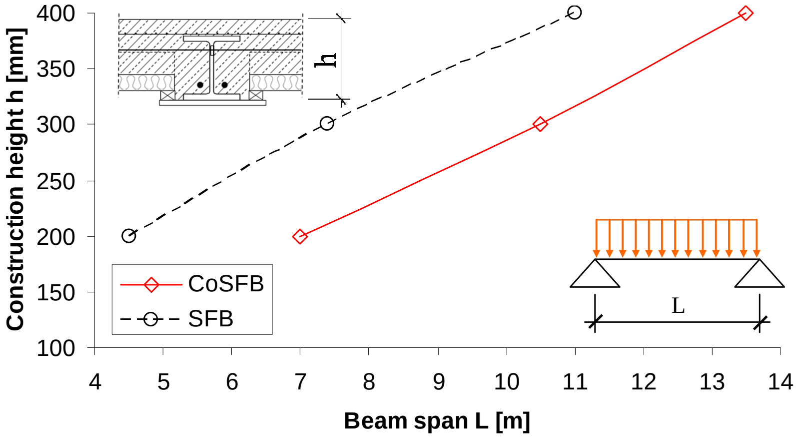


Figure 11: Comparison SFB / CoSFB (DL = 5.0 kN/m^2, LL = 3.0 kN/m^2, a = 7.50 m)

A ratio construction height over span greater than 35 is achievable with this construction technique by respecting all relevant design criteria as well as comfort criteria for vibration. Further research in this technique is presently ongoing with the aim to proof a ground floor design with a secondary beam span of 14m in a distance of the of 10m, which has already been designed.

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