Design of composite slab system with integrated installation floor

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ABSTRACT: The paper presents a novel type of composite floor system using cellular beams. A major benefit of the system is the integrated installation floor, providing additional value to the floor. The system is based on half cellular beams made of existing hot-rolled sections. The openings in the cellular beams allow placing installations in all directions, thus providing excellent flexibility to the user when maintaining or changing installations. The paper first presents the general design of the construction of the floor system. Then the results of bending tests on the structural behaviour and the load-carrying capacity are presented and compared to common calculation models for composite slabs. Further, additional information about static analysis and detailing (local buckling, local bending caused by shear stresses, lateral-torsional-buckling, design of the support) are given. Finally, the paper presents some examples of first buildings where the novel type of floor system is used.

1 INTRODUCTION

A large variety of composite floor systems are widely used for buildings throughout the world. They allow fast erection and are light weight. However in central Europe they are mostly not cost efficient in comparison to in situ concrete flat slabs and have therefore a small market share. Floor systems for new modern sustainable buildings must be multifunctional and satisfy high requirements with regard to structural behaviour (stiffness, strength and vibration), sound insulation and fire safety. Especially office buildings require flexibility for installations that need to be regularly checked during use, repaired, changed or replaced. Under this aspect the possibility to integrate installations in common concrete flat slabs is quite limited. The installations can be partially cast into the concrete slab, however after concrete pouring modifications are no more possible and the maintenance of installations becomes difficult. For office buildings a raised installation floor is therefore frequently required.

2 TOPFLOOR INTEGRAL: NOVEL TYPE OF COMPOSITE FLOOR SYSTEM

The Institute of Structural Engineering IBK of ETH Zurich in collaboration with the Chair of Metal Construction of the Technische Universität München is currently developing and testing a novel type of composite slab with integrated installation floor. The novel type of composite floor system called Topfloor Integral is based on half cellular steel beams made of hot-rolled sections cut by torch cutting. The cellular steel beams are cast into the concrete as shown in figure 1. The composite action between cellular beam and concrete slab is provided by reinforcing steel welded to the cellular beam.

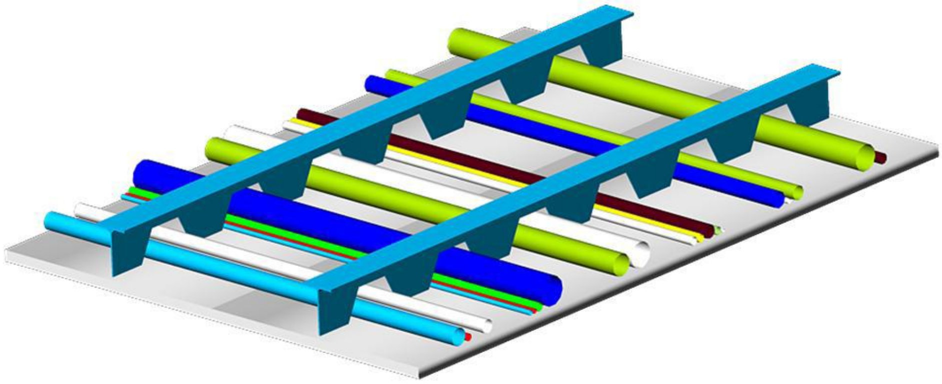

Figure 1 – Novel type of composite slab with integrated installation floor using cellular beams: the concrete slab is placed on the bottom

The composite floor elements are produced in the factory, transported from the factory directly to the site and then joined with bolted connections. The size and form of the prefabricated elements are limited mainly by production, transportation and erection conditions: cross-sections with two steel beams and max. width of 2.5 m are favorable for production and transportation; T-cross-sections are also possible. Size of the cellular steel beams and diameter of the reinforcing steel result from static calculations. The thickness of the concrete slab varies between 8 and 10 cm depending on requirements for fire safety and sound insulation.

The concrete slab on the bottom of the beam seams to be on the wrong site as the concrete is in tension. However, for slabs in bending other aspects than bending resistance can become dominant. The main advantage of the composite floor system is the integration of the raised installation floor into the slab without additional costs. The openings in the cellular beams allow placing installations in the transverse direction, thus providing excellent flexibility during use when maintaining or changing installations. Further, the concrete slab provides fire resistance at no extra cost. In the most cases the steel beams may remain unprotected as the fire load due to installations is small. According to the Swiss fire regulations no fire resistance is required if the fire load due to installations is less than 50 MJ/m^2. The composite action is provided by common reinforcing steel, welded headed studs or other kinds of shear connectors are not required. The steel beams are embedded in the concrete slab and create a frame action permitting to stabilize the compressive flange of the steel beams against lateral-torsional buckling.

When bending resistance is the dominant requirement, the composite floor system can also be used in a classical configuration, i.e. with the concrete slab on top. In this case prefabricated panels can be placed between the steel beams forming a suspended ceiling.

3 EXPERIMENTAL ANALYSIS

Two bending tests performed with composite beams showed that the reinforcing steel welded to the steel beam was able to guarantee a rigid full composite action between steel beam and concrete slab. For both tests high ductility was observed due to yielding of the steel beam and steel reinforcing. Simple analytical model considering plastic bending moment distribution and cracking of concrete led to adequate results for the stiffness and the ultimate resistance compared to the test results.

4 CASE STUDIES

The novel type of floor system was used for the construction of a platform with the dimensions of 10.0x6.7m for a work space located in the ETH testing laboratory. In summer 2009 the floor system with the concrete slab placed on the top was used for the enlargement of a store of garden furnitures in Kanton Aargau, Switzerland. The construction of the first 7 storeys residential building located in the city of Lugano, Switzerland using the new floor system with the concrete slab placed on the top is planned for spring 2010.

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1 INTRODUCTION

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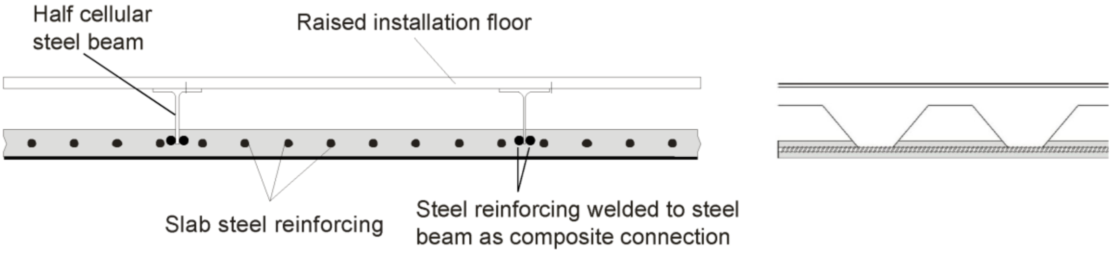

Figure 1 – Novel type of composite slab with integrated installation floor using cellular beams: the concrete slab is placed on the bottom

The composite floor elements are produced in the factory, transported from the factory directly to the site and then joined with bolted connections. The size and form of the prefabricated elements are limited mainly by production, transportation and erection conditions: cross-sections with two steel beams and max. width of 2.5 m are favorable for production and transportation; T-cross-sections are also possible. Size of the cellular steel beams and diameter of the reinforcing steel result from static calculations. The thickness of the concrete slab varies between 8 and 10 cm depending on requirements for fire safety and sound insulation.

The concrete slab on the bottom of the beam seams to be on the wrong site as the concrete is in tension. However, for slabs in bending other aspects than bending resistance can become dominant. The main advantage of the composite floor system is the integration of the raised installation floor into the slab without additional costs. The openings in the cellular beams allow placing installations in the transverse direction, thus providing excellent flexibility during use when maintaining or changing installations. Further, the concrete slab provides fire resistance at no extra cost. In the most cases the steel beams may remain unprotected as the fire load due to installations is small. According to the Swiss fire regulations no fire resistance is required if the fire load due to installations is less than 50 MJ/m^2. The composite action is provided by common reinforcing steel, welded headed studs or other kinds of shear connectors are not required. The steel beams are embedded in the concrete slab and create a frame action permitting to stabilize the compressive flange of the steel beams against lateral-torsional buckling.

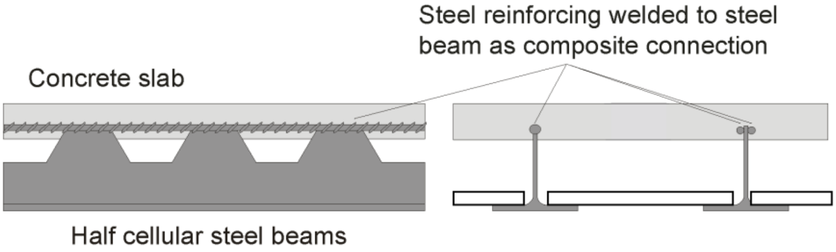

Figure 2 – Novel type of composite slab with integrated installation floor using cellular beams: the concrete slab is placed on top

When bending resistance is the dominant requirement, the composite floor system can also be used in a classical configuration, i.e. with the concrete slab on top (see Figure 2). In this case prefabricated panels can be placed between the steel beams forming a suspended ceiling.

3 BENDING TESTS

The load-carrying behaviour of the composite floor system was experimentally analysed using two test specimens [3]. The composite floor elements with a total length of 7.4 m were manufactured as T-beams by the industrial partner and transported to the ETH testing laboratory. The composite floor elements consisted of half cellular steel beams WPE360 (beam height = 270 mm) with steel quality S235 according to EN 10025-1 [4]. One element ("beam I") was tested with the concrete slab on top (see Figure 3), the other beam ("beam II") with the concrete slab on the bottom (see Figure 4). As shear connectors for beam I two rebars with diameter of 16 mm were welded to the steel beam, for beam II two rebars with diameter of 20 mm were used. The 80 mm thick concrete slab was reinforced with a steel mesh diameter of 10 mm and spacing of 150 mm for both directions. In the slab of beam II 3 additional reinforcing rebars with diameter of 10 mm were placed through each of the cavities. Normal concrete C25/30 according to the EN 1992-1-1 [5] and common reinforcing steel with steel quality B500 according to the Swiss Standard SIA 262 [6] were used. Stiffeners with thickness of 15 mm were welded on both side of the steel beam at the supports and for the introduction of the concentrated vertical test loads. Figures 3 and 4 show longitudinal and cross-section of the composite beams.

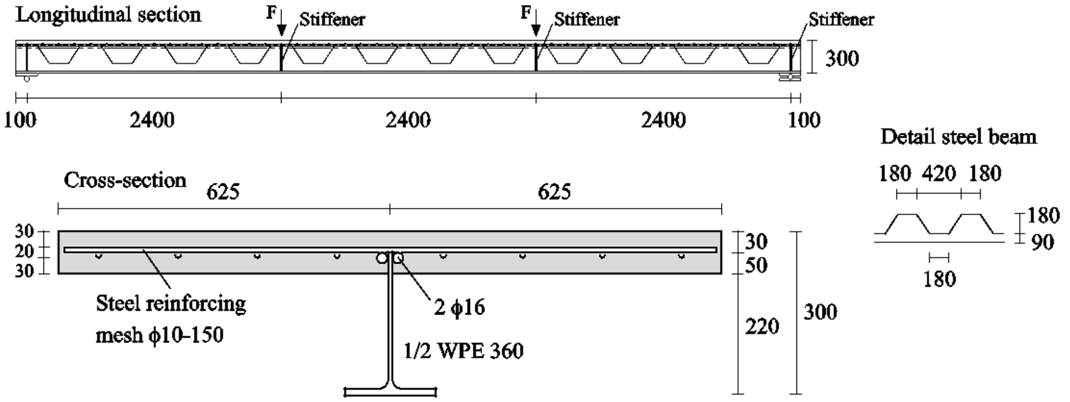

Figure 3 – Steel-concrete composite beam with concrete slab on top (“beam I”)

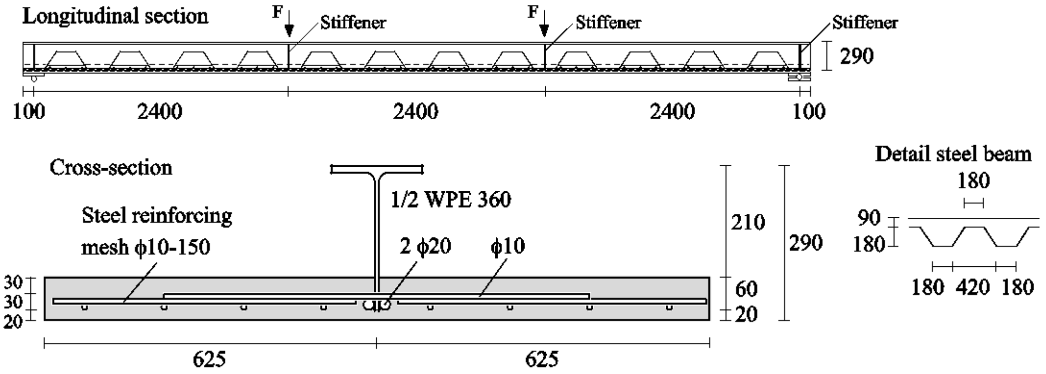

Figure 4 – Steel-concrete composite beam with concrete slab on the bottom (“beam II”)

The concrete compressive strength of each composite beam was tested using 3 cubes with dimensions of 150 mm according to EN 12390-3 [7]. The mean value of the concrete compressive strength of beam I was 39.5 N/mm^2, for beam II 38.0 N/mm^2. The yield strength f_y and tensile strength f_u of the steel beam II and the reinforcing steel used were tested with a series of tensile tests according to EN 10002-1 [8]. The mean values were as following:

- Steel beam II: f_y = 309 N/mm^2; f_u = 429 N/mm^2
- Reinforcing steel ø10 mm: f_y = 478 N/mm^2; f_u = 617 N/mm^2
- Reinforcing steel ø20 mm: f_y = 544 N/mm^2; f_u = 648 N/mm^2

The bending tests were performed in the IBK testing laboratory of ETH Zurich as four point tests with a span between the supports of 7.2 m. The distance from the support to the point load was 2.4 m (see Figures 3 and 4). The beams were braced in order to prevent lateral-torsional buckling. Beam I with the concrete slab on top (see Figure 3) was first subjected to seven loading cycles with the maximum value of 5, 10, 15, 20, 30, 40 and 60 kN. Beam II with the concrete slab on the bottom (see Figure 4) was first subjected to six loading cycles with the maximum value of 5, 8, 10, 15, 20 and 30 kN. Then, both beams were loaded to failure at a rate of approximately 10 kN per minute.

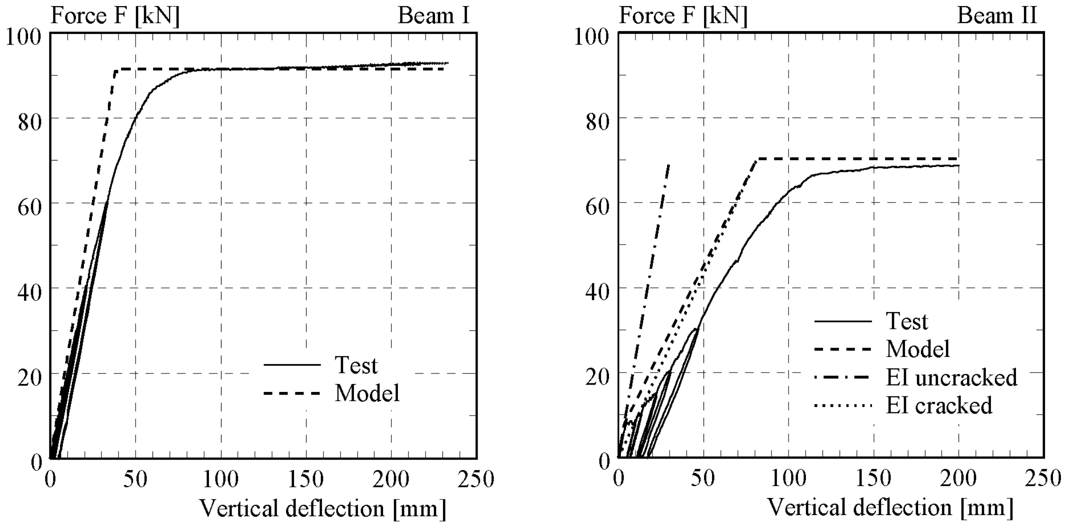

Figure 5 – Measured load per jack vs. vertical deflection at mid-span curves for the bending test with beam I (left) and beam II (right);

Figure 5 shows the measured load-deflection (vertical deflection at mid-span) curves for the bending tests. Beam I showed linear-elastic behaviour until approximately 70 kN. At higher load levels a non-linear plastic behaviour was observed. The steel beam started yielding at about 92 kN leading to a large increase of the vertical deflections. The load level remained constant during yielding of the steel beam until the test was stopped when the deflection at mid-span reached about 230 mm (see Figure 6 left). During the test neither slip between concrete slab and steel beam as well as nor significant cracks in the concrete slab were observed, except a longitudinal crack on the top of the concrete slab observed during yielding of the steel beam.

Beam II showed linear-elastic behaviour until about 8 kN per jack, when the first cracks occurred in the concrete slab. When the load was increased additional cracks were observed that successively reduced the stiffness of the composite beam and thus led to a non-linear increase of the vertical deflections. The development of the last cracks was observed at about 45 kN. No slip deformation between concrete slab and steel beam was measured. The reinforcing steel started yielding at about 66 kN leading to a large increase of the vertical deflections. The load level remained fairly constant during yielding until the test was stopped when the deflection at mid-span reached about 200 mm (see figure 6 right). Based on visual observations after the bending test it can be assumed that the upper flange of the steel beam reached the yield strength during yielding of the reinforcing steel.

Figure 6 – Bending test with composite beam I (left) and beam II (right)

The results of the bending tests were compared to results based on simple analytical models. The bending tests showed that the reinforcing steel welded to the steel beam was able to guarantee a rigid full composite action between steel beam and concrete slab. Thus, the load-carrying behaviour of the tested beams was calculated using rigid connection between steel and concrete for the structural analysis of the steel-concrete composite beams (see for example [9] and [10]). The plastic resistance moment M_{pl} of the composite beams was calculated based on the rigid-plastic theory using the effective measured values of yield strength f_y and compressive strength f_c. For beam I with the concrete slab subjected to compression and the steel beam mainly subjected to tension it was assumed that the flange and the lower part of the web of the steel beam was stressed to its yield strength f_y and the concrete slab resisted a compressive stress of $0.85*f_c$, constant over the whole depth between the plastic neutral axis and the most compressed fibre of the concrete. Further, the reinforcement in the concrete slab was neglected. For beam II with the concrete slab subjected to tension and the steel beam mainly subjected to compression it was assumed that the reinforcing steel (2ø20 + 8ø10, see Figure 4) were stressed to their yield strength fy, while the flange of the steel beam partially reached its yield strength f_y. Figure 5 compares the calculated load-carrying behaviour of the composite beams with the measured load-deflection curves. It can be seen that the simple analytical model led to adequate results for the stiffness and the ultimate resistance compared to the test results.

4 STATIC ANALYSIS AND DEATAILNG

4.1 Local instabilities

For steel-concrete composite elements with concrete slab on the bottom local buckling can occur only in the web of the half cellular beams. Based on the assumption that the web between the openings acts as internal compression part while the web at the openings acts as outstand flange it can be seen that no local buckling is expected for steel grade S235 for common steel cross-sections according to the width-to-thickness ratios given in EN 1993-1-1, Table 5-2 [11]. For steel grade S355 and higher local buckling should be considered.

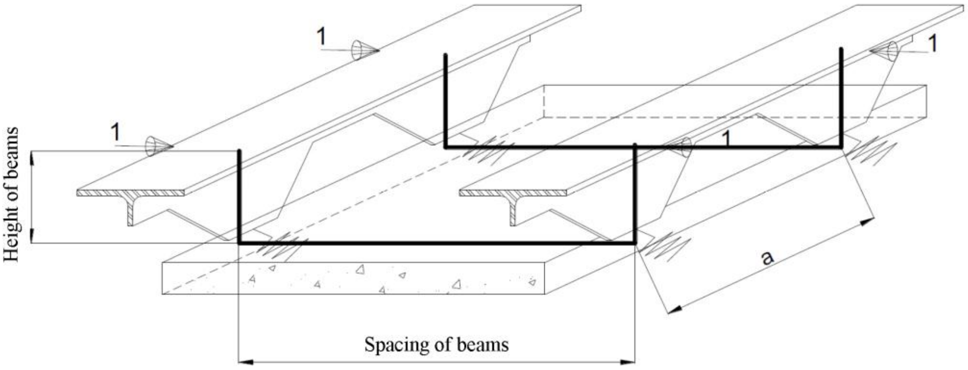

Figure 7 – Static model for calculating the buckling length of the upper flange under compression

The lateral-torsional buckling of the upper flange of the steel beams can be studied considering an elastic embedded beam (see Figure 7) and taking into account the stiffness of the web of the steel beam and the concrete slab. The results of a parametric study show that without bracings against lateral-torsional buckling the load-carrying capacity of common cross-sections varied in the range of 70 to 85% of the full load-carrying capacity.

4.2 Local bending due to shear forces

The interaction between stresses caused by global bending and stresses caused by local bending due to shear forces can be taken into account with the simple model shown in Figure 8. This model can be used for the optimization of the size of the web openings as well as the stiffness and the load-bearing capacity of the steel beams.

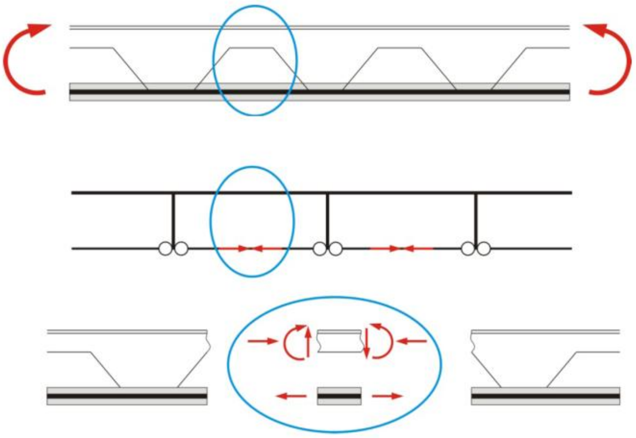

Figure 8 – Calculation model for local bending of the steel section caused by shear forces

4.3 Support conditions

Common steel angles can be used for the support of the steel elements of the composite floor system to the main structure. In the case of the composite floor system with concrete slab on top continuous steel angles can be used as shown in Figure 9 left. The steel angles reduce sound propagation and can be used as support for moisture barrier if required in the facade as shown in Figure 9 right. Further the steel angles guarantee that the composite floor works as horizontal diaphragm.

Figure 9 – Steel beams with angles as supports before concreting (left) and detail of the facade at the residential building “Residenza Villa Lugano” under construction (right)

4.4 Preliminary design

Table 1 gives basic information for a preliminary design of Topfloor integral slabs for office buildings for additional permanent load of 1.5 kN/m^2, live load of 3.0 kN/m^2 and a spacing of the steel beams of 1250 mm.

Table 1. Preliminary design of Topfloor integral slabs for office buildings

Span	½-beam (S 235)	Height of the composite floor
6.0 m	IPE 300	290 mm
7.5 m	IPE 360	350 mm
9.0 m	IPE 450	440 mm
10.0 m	IPE 500	490 mm
12.0 m	IPE 600	590 mm

Topfloor integral slabs allow an efficient and economic use of the material. An estimation of required material for topfloor integral slabs with 10m span can be performed using following basic values:

- Steel: about 40 kg/m^2
- Reinforcing steel: 12-20 kg/m^2
- Concrete: 0,1 m^3/m^2

5 CASE STUDIES

The novel type of floor system was used for the construction of a platform with the dimensions of 10.0x6.7m for a work space located in the ETH testing laboratory. The floor system with a span of about 6.6m was used in both configurations, i.e. with the concrete slab placed on the bottom as well as on the top (see Figure 10). Timber plates (Kerto Q) were placed on top of the floor system with the concrete slab on the bottom. The vibration behaviour of the floor elements was experimentally studied with a series of sandbag tests. The measured natural frequency of the floor elements with the concrete slab on top was 11.4 Hz. For the floor elements with the concrete slab on the bottom the natural frequency measured before and after the installation of the timber plates was about the same. Thus, the natural frequencies measured can be considered as not critical with regard to vibrations [12, 13].

Figure 10 – New platform built using the novel type of composite slab system for a work space located in the ETH testing laboratory

Figure 11 – Slab elements used for the enlargement of a store in Kanton Aargau (Switzerland) (left) and CAD-modell of a residential building under construction in Lugano (Switzerland) with 7 floors using the novel type of composite slab system (right)

In summer 2009 the new floor system with the concrete slab placed on the top was used for the enlargement of a store of garden furnitures in Kanton Aargau, Switzerland (see figure 12 left). The construction of the first building using the new floor system with the concrete slab placed on the top is planned for spring 2010. The 42 m long and 10.5 m wide building is a 7 storeys residential building located in the city of Lugano, Switzerland. The first four storeys are divided into two parts, which are connected with small steel bridges with common composite slabs (see figure 12 right). The new composite slabs span without support over the width of the building of approximately 10.5m, leading to high flexibility for the users of the building. In the two upper storeys in the area over the bridges the composite slabs span in the longitudinal direction. This allows a slender construction of the bridging of the two upper storeys and a better distribution of the vertical loads to the columns. All columns are made of hollow square sections with dimensions of 180x180mm. Only the section thickness of the columns changes depending on the acting vertical loads. The steel structure is braced by using diagonal compression members and the concrete core. All edge beams consist of IPE 360. In this way, the necessary number of details for construction of steelwork, facade and interior walls will be minimized.

6 CONCLUSIONS

The paper presented a novel type of composite floor system with integrated installation floor, providing additional value to the floor. The system is based on half cellular beams made of hot-rolled sections with the web of the steel beam cast into the concrete. The openings in the cellular beams allow placing installations in all directions, thus providing excellent flexibility during use when maintaining or changing installations. Further, the concrete slab improves the fire resistance of the composite floor. The composite action between cellular beam and concrete slab is provided by common reinforcing steel welded to the cellular beams. Welded headed studs or other kinds of shear connectors are not required.

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