Innovative composite slab system with integrated installation floor

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Summary

The paper presents a novel type of composite floor system using cellular beams. A major benefit of the novel system is the integrated installation floor, providing additional value to the floor at no extra costs. 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 and details of the construction of the novel floor system. Then the results of tests on the dynamic behaviour and the load-carrying capacity are presented and compared to common calculation models for composite slabs. Finally, the paper presents an example of a first building where the novel type of floor system will be used.

Keywords

Composite slab; Integrated installation floor; Cellular steel beams; Bending tests, Vibration tests

Introduction

A large variety of composite floor systems are widely used for buildings throughout the world. They allow fast erection and are light weight [8]. 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 buildings must satisfy high requirements with regard to structural behaviour (stiffness, strength and vibration), sound insulation and fire safety. Further, especially office buildings require flexibility for installations that need to be regularly controlled 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.

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 using cellular beams. The paper first presents the general design and details of the construction of the novel floor system. Then the results of tests on the dynamic behaviour and the load-carrying capacity of two floor elements with a span of 7.2 m are presented and compared to common calculation models for composite slabs. Finally, the paper presents an example of a first building where the novel type of floor system will be used.

Novel type of composite floor system

The novel type of composite floor system 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.

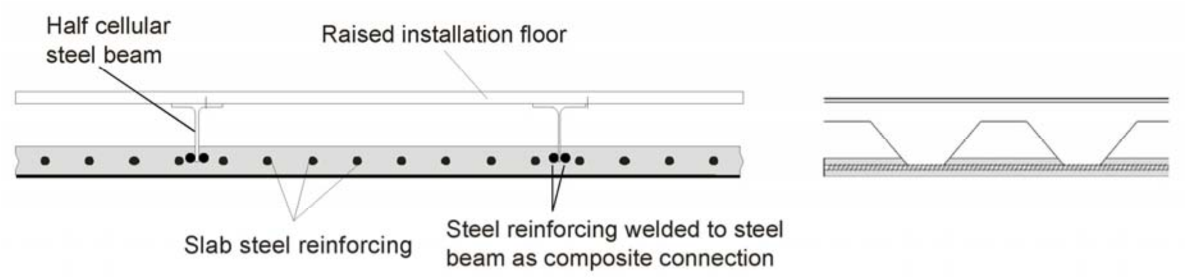


Figure 1 – Novel type of composite slab with integrated installation floor using cellular beams: the concrete slab is placed on the bottom

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: π-cross-sections with 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 novel type of 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. The composite action is provided by common reinforcing steel, welded headed studs or other kinds of shear connectors are not required. The concrete slab stabilizes the steel beams against lateral- torsional buckling.

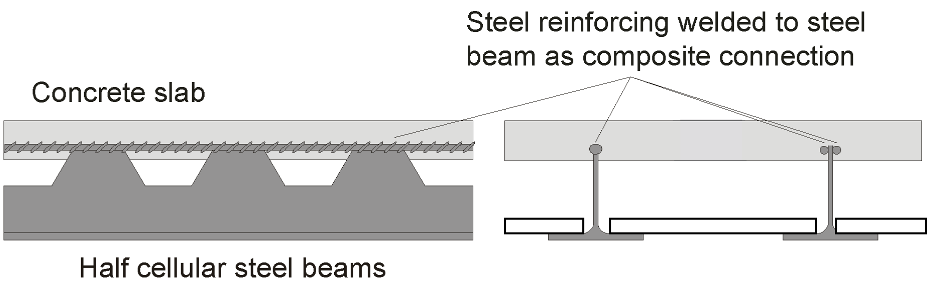


Figure 2 – Novel type of composite slab with integrated installation floor using cellular beams: the concrete slab is placed on top

When bending resistance is the dominant requirement, the novel type of 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.

Bending tests

The load-carrying behaviour of the novel composite floor system was experimentally analysed using two test specimens. 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 [6]. 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 [3] and common reinforcing steel with steel quality B500 according to the Swiss Standard SIA 262 [11] 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.

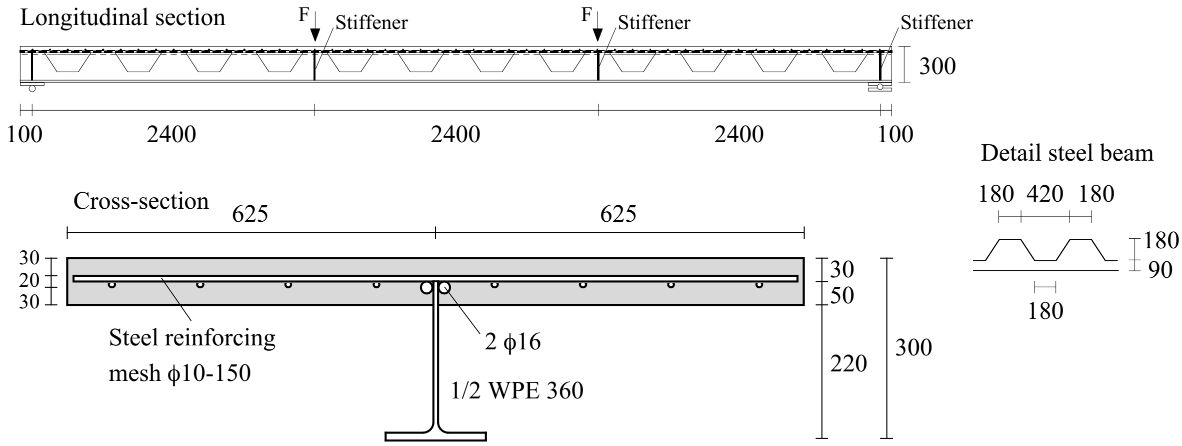


Figure 3 – Steel-concrete composite beam with concrete slab on top ("beam I")

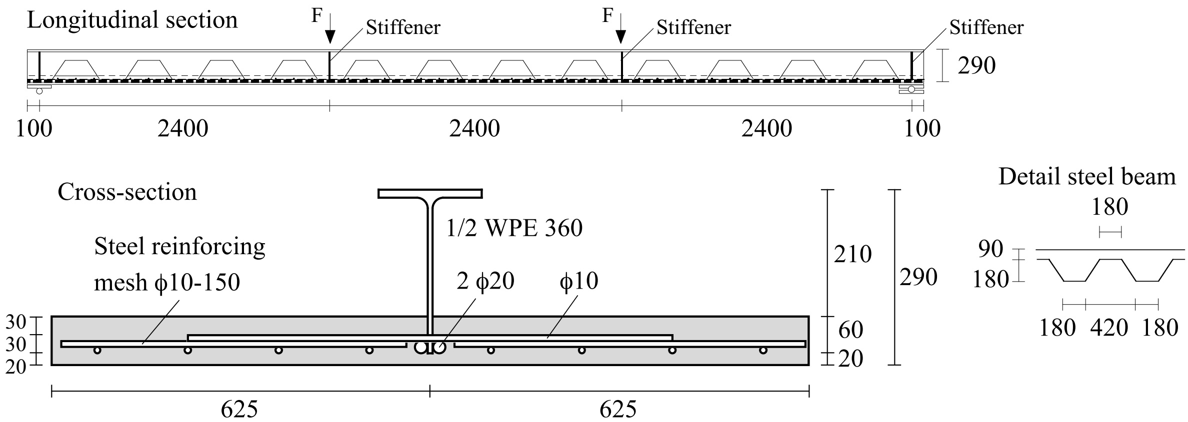


Figure 4 – Steel-concrete composite beam with concrete slab on the bottom ("beam II")

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 and tensile strength of the steel beam II and the reinforcing steel used were tested with a series of tensile tests according to EN 10002-1 [5]. Table 1 summarizes the yield and tensile strength of the steel beam II and reinforcing steel.

Table 1 – Yield strength f_y and tensile strength f_u of beam II and reinforcing steel

	Steel beam II		Reinforcing steel ø10 mm		Reinforcing steel ø20 mm	
	Test 1	Test 2	Test 1	Test 2	Test 1	Test 2
f_y [N/mm^2]	314	304	481	475	545	544
f_u [N/mm^2]	428	430	617	618	649	647

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 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.

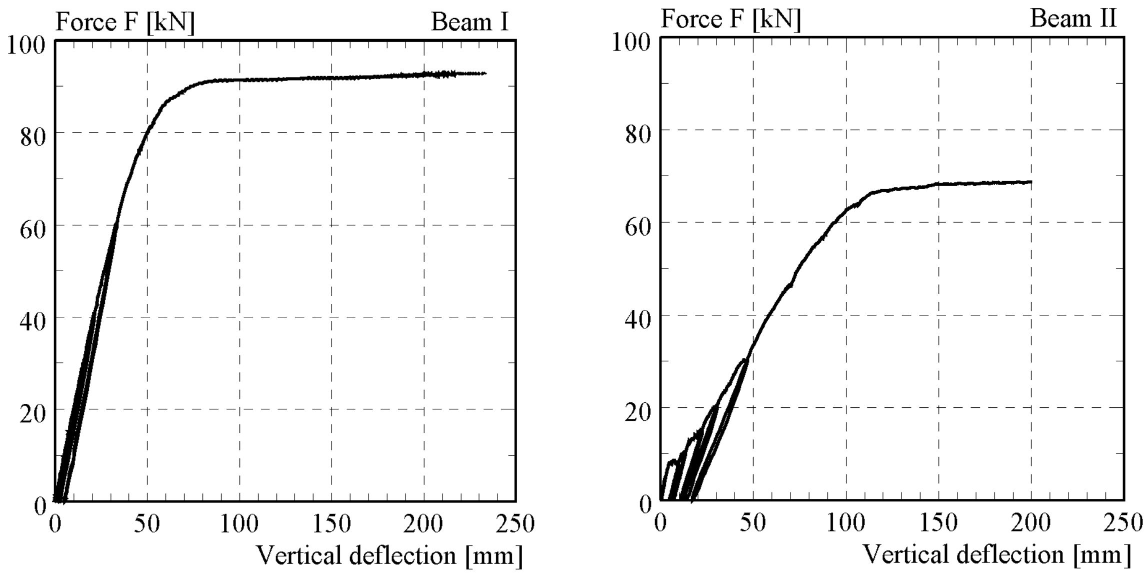
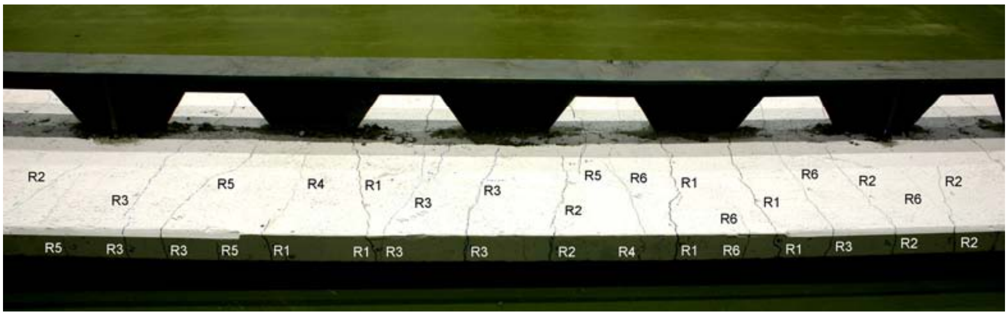


Figure 5 – Measured load per jack vs. vertical deflection at mid-span curves for the bending test with beam I (left) and beam II (right)

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 150 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 7 shows the cracks observed on the concrete slab in the middle part of the beam between the hydraulic jacks. Further Figure 7 shows the cracks occurred at the different load levels marked with R1 to R6 during the bending test.

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



Load level
R1: 8 kN
R2: 10 kN
R3: 15 kN
R4: 20 kN
R5: 30 kN
R6: 45 kN

Figure 7 – Observed cracks on the concrete slab

Comparison to calculation model

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 [4] and [9]). The plastic resistance moment M_{pl} of the composite beams was calculated based on the rigid-plastic theory.

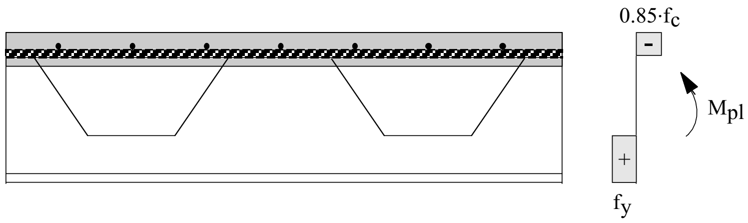


Figure 8 – Model for the calculation of the plastic resistance moment M_{pl} of the composite beam I with concrete slab on top

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 (see Figure 8). For the calculation of M_{pl} the effective measured values of yield strength f_y and compressive strength f_c were considered. Further, the reinforcement in the concrete slab was neglected. The elastic behaviour of the composite beam was calculated assuming the uncracked flexural stiffness, i.e. assuming that the whole thickness of the concrete slab was uncracked. The following moduli of elasticity were assumed for the calculation: E_a = 210 kN/m^2 for steel and E_c = 35 kN/m^2 for concrete. Figure 9 left compares the calculated load-carrying behaviour of the composite beam I with the measured load-deflection curve. The simple analytical model led to adequate results for the stiffness and the ultimate resistance compared to the test results.

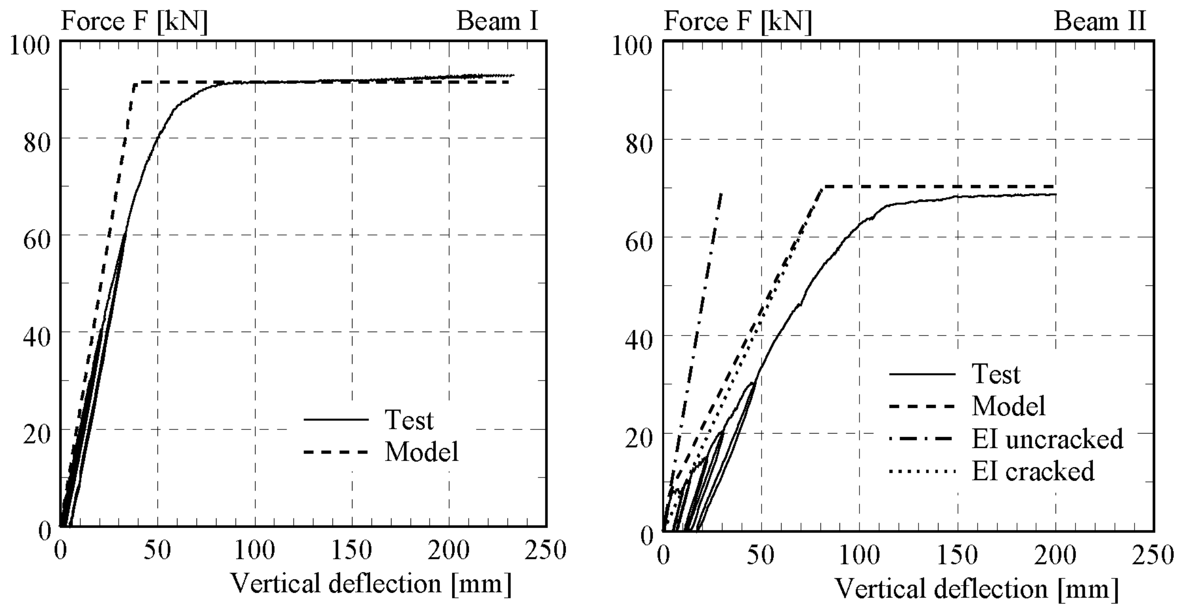


Figure 9 – Comparison between test results and simple calculation models

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 f_y, while the flange of the steel beam partially reached its yield strength f_y (see Figure 10). The elastic behaviour of the composite beam was calculated assuming the uncracked flexural stiffness as well as the cracked flexural stiffness. The uncracked flexural stiffness was calculated assuming that the concrete slab in tension was uncracked. The cracked flexural stiffness was calculated neglecting the concrete slab in tension but including the reinforcing steel. The cracking moment of the concrete slab was calculated assuming a concrete tensile strength of 3.0 MPa based on the compressive strength measured. For the moduli of elasticity of concrete and steel the same values as for beam I were assumed. Figure 9 right compares the calculated load-carrying behaviour of the composite beam II with the measured load-deflection curve. Table 2 shows the calculated and measured values for the composite beam II. It can be seen that the calculated cracking moment $M_{cracking}$ and the plastic resistance moment M_{pl} agreed well with the measured values. The uncracked and cracked flexural stiffness of the composite beam was slightly overestimated by the calculation model in comparison with the measured values. For the calculation of the cracked flexural stiffness all reinforcing steel (2ø20 + 8ø10, see Figure 4) was considered. However, it may be possible that some rebars diameter 10mm were not fully activated due to the effects of shear lag.

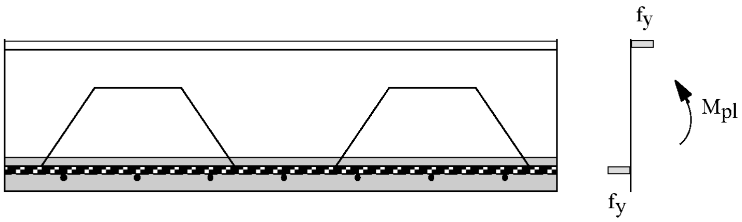


Figure 10 – Model for the calculation of the plastic resistance moment M_{pl} of the composite beam II with concrete slab on the bottom

Table 2 – Comparison between calculated and measured values for the composite beam II

	$EI_{uncracked}$ [kN/mm^2]	$EI_{cracked}$ [kN/mm^2]	$M_{Cracking}$ [kNm]	M_{pl} [kNm]
Test	$2.823 \cdot 10^{10}$	$1.004 \cdot 10^{10}$	19.2	158
Model	$3.097 \cdot 10^{10}$	$1.145 \cdot 10^{10}$	20.1	168
Test/Model	0.91	0.88	0.95	0.94

Vibration tests

Before the bending test was carried out the dynamic behaviour of both beams was experimentally studied with a series of vibration tests. Sandbag and heel drop tests were used to measure the vibration response to a sudden impact. The sandbag test was performed using a sandbag of 25 kg that was dropped from about 1 m height at mid-span of the beam. The heel drop test was performed by a person of average weight (75 kg), standing at mid-span of the beam, rising onto the balls of his feet and then dropping down on his heels. For both tests the resulting acceleration as well the vertical deformation were measured by accelerometers and LVDTs placed at mid-span of the beam. The analysis of the response spectrum permitted the evaluation of the frequency of the beams. The tests were performed first with sliding supports on both sides and then with the same supports as for the bending test (i.e. fixed on one side and sliding on the other side). For beam II the vibration tests were repeated after the composite beam was loaded up to 20 kN, i.e. after the concrete slab was completely cracked. This allowed the analysis of the influence of concrete cracking on the natural frequency of the composite beam.

The measured natural frequency of beam I was about 9.5 Hz for both tests (sandbag and heel drop) and both type of supports tested. For beam II with the uncracked concrete slab the measured natural frequency varied between 9.1 and 9.3 Hz for both tests (sandbag and heel drop) and both supports tested and was fairly the same as for beam I. For beam II with the cracked concrete slab the measured natural frequency varied between 7.2 and 7.4 Hz. The observed reduction of the natural frequency for beam II was due to the reduction of the stiffness of the composite beam after cracking of the concrete slab.

The requirements on building floor systems with regard to vibration depend on the expected use of the building [2]. For example the Swiss Standard SIA 260 [10] recommends for dance and concert halls that the natural frequency should be higher than 7.0 Hz, for gymnasiums and sport halls higher than 8.0 Hz. Office buildings are less subjected to man-induced vibrations and the natural frequency should be higher than 5.0 Hz [1]. Thus, the natural frequency measured for beam I can be evaluated as not critical with regard to vibrations. The vibration tests with beam II with the cracked concrete slab showed that this beam may be susceptible to vibration problems for some type of use.

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 11). 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. Additional measurements with regard to vibrations and deformations are planned in the future.

Figure 11 – New platform built using the novel type of composite slab system for a work space located in the ETH testing laboratory

The construction of the first building using the new floor system is planned for autumn 2009. The 42 m long and 10.5 m wide building is a six 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). 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 (see figure 12).

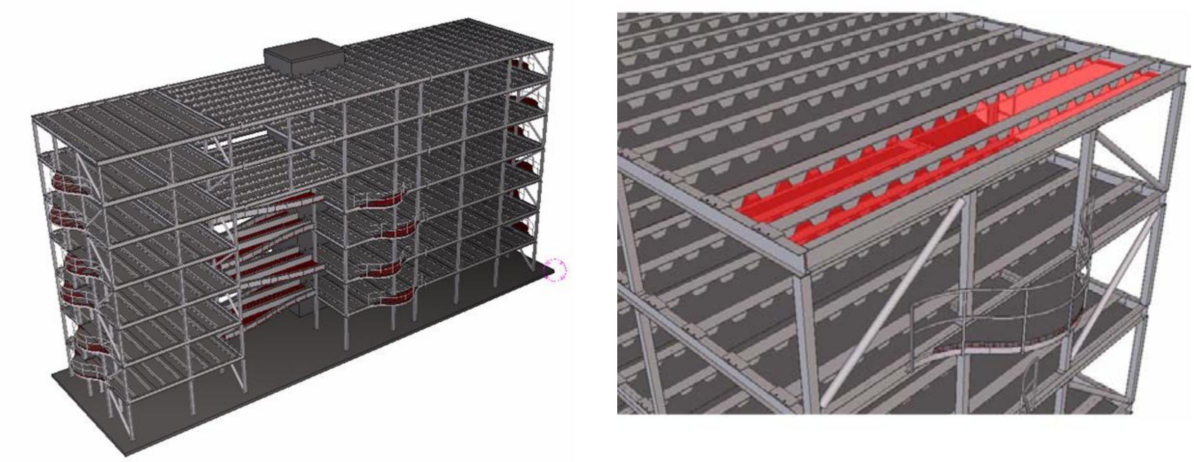


Figure 12 – Steel-structure of the planned residential building in Lugano, Switzerland using the novel type of composite slab system

For the design of the composite slabs additional structural analysis regarding ultimate limit state and serviceability limit state were performed. A simple model was developed in order to take into account the interaction between stresses caused by global bending and stresses caused by local bending due to shear forces (see figure 13). This model permitted the optimization of the size of the web openings as well as the stiffness and the load-bearing capacity of the steel beams. The lateral-torsional buckling of the upper flange of the steel beams was studied considering an elastic embedded beam and taking into account the stiffness of the web of the steel beam and the concrete slab. The results of the calculation model showed that the buckling length varied between 0.25 and 0.33 of the beam length, leading to an economic use of the material.

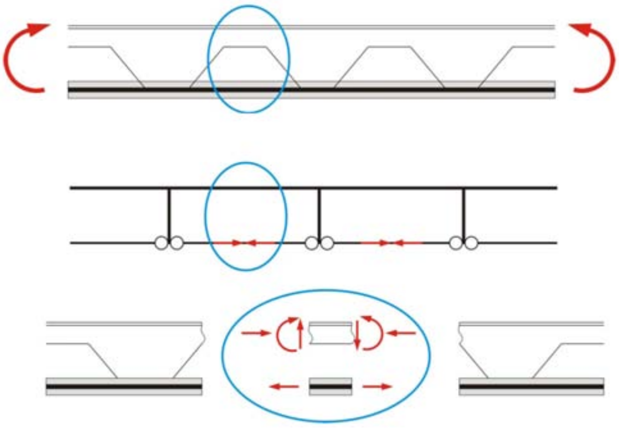


Figure 13 Calculation model for local bending of the steel section caused by shear forces

Nevertheless, the design and optimization of the composite slab system is strongly influenced by the dynamic behavior of the floor. This can be positively influenced by increasing the height of the floor-system and thus improving the possibility for the installation of building equipment. However, often the height of the floor-system is limited by architectural purposes like in the case of the building planned in Lugano. Therefore, particular attention should be given to the analysis of the dynamic behavior of the floor system.

Conclusions

The paper presented a novel type of composite floor system with integrated installation floor, providing additional value to the floor at no extra costs. 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.

Two bending tests were performed with composite beams with a span of 7.2 m, one with the concrete slab on top subjected to compression, the other one with the concrete slab on the bottom. For both tests, the reinforcing steel welded to the steel beam was able to guarantee a rigid full composite action between steel beam and concrete slab. The composite beam with the concrete slab on top showed typical elasto-plastic behaviour. For the composite beam with the concrete slab on the bottom a non-linear behaviour was observed due to cracking of the concrete slab. For both tests high ductility was observed due to yielding of the steel beam and steel reinforcing. The load-carrying behaviour of the composite beams was calculated with simple analytical model considering plastic bending moment distribution and cracking of concrete. For both tests, the simple model led to adequate results for the stiffness and the ultimate resistance compared to the test results. The measured natural frequency of the composite beam with the concrete slab on top was about 9.5 Hz, for the composite beam with the concrete slab on the bottom the measured natural frequency varied between 9.1 and 9.3 Hz before and 7.2 and 7.4 Hz after cracking of the concrete. Further research and investigations are planned to study in detail the dynamic behaviour of the composite floors with the concrete slab on the bottom.

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