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New concept of composite steel-reinforced concrete floor slab in the light of computational model and experimental research

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Abstract

This paper deals with a new concept of composite steel-reinforced concrete floor slab. This type of the floor slab consists of newly constructed steel and concrete composite beam mandatory connected together with cast in situ or prefabricated floor slab. The description of the nonlinear behavior of this newly designed steel and concrete composite beam with horizontal studs is a subject of a separate paper. Existing test results indicate that the loss of capacity of such structures may be linked to the loss of bonds between the composite beam and the floor slab. To prevent such behavior, special connecting elements have been designed in form of RC studs. Two types of structures, each consisting of composite beam and the prefabricated floor slabs, have been the subject of full scale tests performed in cooperation with ITB strength tests laboratory. Prefabricated prestressed hollow-core floor slabs have been supported on lower flanges of the steel part of the composite beam with reversed T cross-section to provide a flat lower surface of finished floor slab. In order to prevent the separation of composite beam and floor slabs a number of reinforced concrete studs were arranged for ensuring the adequate bond between these components. The studs have been devised as the set of horizontal rebars passing through the perforated webs of the beam and anchored in the circular openings of the hollow-core slabs. Self-compacting concrete have been used to obtain adequate filling of hollow-core slabs openings. The studs have been designed according to the provisions of Eurocode 2. The expression defining the load carrying capacity of this junction, after some rearrangements, enabled the derivation of equations for the determination of the slab width interacting effectively with composite beam. As an interconnection between composite beam and slabs, these studs have sufficient strength and stiffness to enable both components of the structure to be designed as the parts of a single structural member able to attain the ultimate limit states. During the tests no signs of splitting between beam and slabs subjected to design loads were observed. Experimental and computational results showed satisfactory consistence.

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1. Introduction

This paper deals with a new concept of composite steel-reinforced concrete floor slab. The experience of recent years in the field of prefabrication makes it possible to create a very effective and cost-efficient systems developed as the tailor-made. These include, among others, the floor systems: *slim floor* or *shallow floor* type, i.e. the flush floor slab systems with a low overall height and integrating all elements constructing the floor structures. This is achieved by using asymmetric steel-reinforced concrete composite beams with a properly wide bottom flange, which enables the slabs to be placed on the upper surface of the bottom flange with adequate bearing. The floor slab may be in the form of a precast concrete slab or a composite slab with metal decking (either shallow or deep decking may be used). The main elements of the *slim floor* system are prefabricated slabs, eg. HC type (hollow-core) or semi-prefabricated floor plates with Filigree Slabs or composite plates on trapezoidal sheets - eg. Cofra type, which are supplemented with cast concrete until after the assemble on the site. Supporting elements of the plates, ie. the beams are arranged in the same level with the plates which allows to achieve significant material savings by minimizing the necessary amount of building construction depth.

Existing test results indicate that the loss of capacity of such structures may be linked to the loss of bonds between the composite beam and the floor slabs. To prevent such a behaviour some special connecting elements have been designed in form of RC studs. Experimental and computational results showed satisfactory consistence proving that proposed analytical model provides good results.

2. Structural concept

The considered type of the floor slab - beam structural system consists of newly constructed steel and concrete composite beam mandatory connected together with cast in situ or prefabricated floor slabs. Prefabricated prestressed hollow-core floor slabs have been supported on lower flanges of the steel part of the composite beam with reversed TT cross-section to provide a flat lower surface of finished floor slab (see Figs. 1 and 2). In order to prevent the separation of composite beam and floor slabs a number of reinforced concrete studs were arranged for ensuring the adequate bond between these components. The studs have been devised as the set of horizontal rebars passing through the perforated webs of the beam and anchored in the circular openings of the hollow-core slabs (see Fig. 2). Self-compacting concrete have been used to obtain adequate filling of hollow-core slabs' openings.

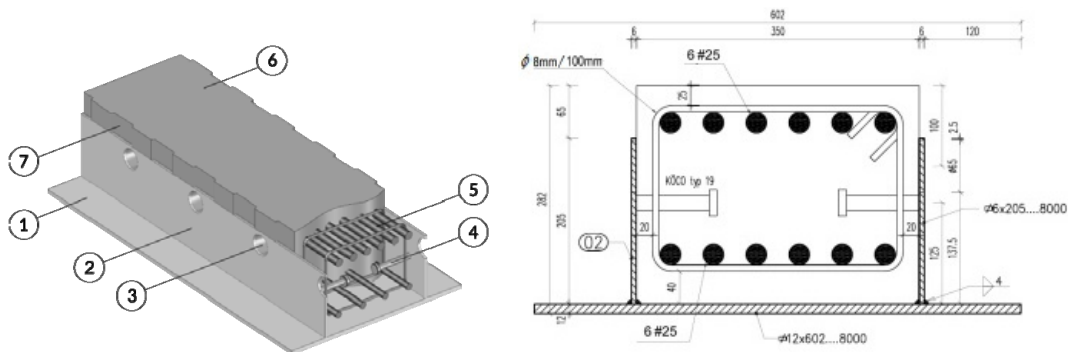


Fig. 1. The rectangular RC cross-section placed inside a reversed TT cross-section steel beam cross-section. Symbols: 1 - the lower flange, 2 - the web, 3 - opening in the beam, 4 - swollen pin, 5 - rebar, 6 - concrete of the beam, 7 - notched surface.

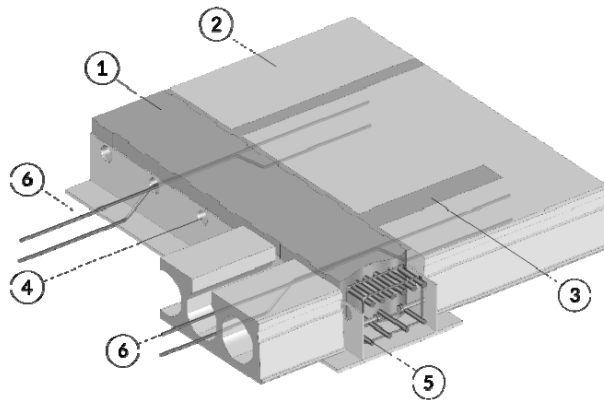


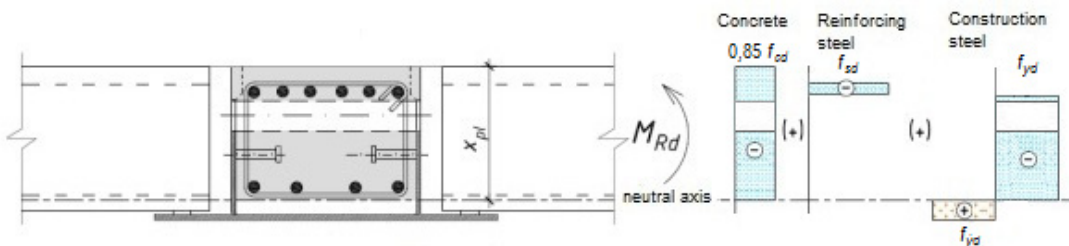
Fig. 2. The floor slab & composite beam joint structural system. Symbols: 1 – steel & reinforced concrete composite beam, 2 – the floor slab, 3 – the concrete cast in situ in channels, 4 – opening in the beam, 5 – longitudinal rebar, 6 – stitching reinforcement.

3. Computational model

3.1. Checking of the composite beam in the assembly and the operation state

The composite beam at first has to be checked in the assembly state. Pre-tensioned prefabricated hollow-core floor slabs supported on lower flanges of the steel part of the composite beam with reversed T cross-section also provide a supplementary compression zone of upper parts of finished floor structures.

a



b

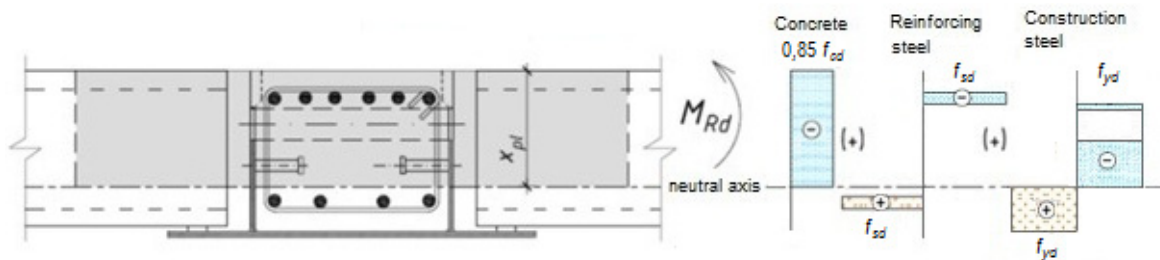


Fig. 3. Computational models of the composite beam in the (a) assembly and the (b) operation state.

Load-bearing capacity of the composite beams in the assembly state is determined for the weakened cross-section without mounting holes filled with cast concrete. The torsional stiffness of the beam is calculated in accordance with

EN 1992-1-1 [1] and EN 1993-1-1 [2]. As the composite beam acts with the adjacent reinforced concrete floor slabs the bearing capacity of composite beam is enhanced by expanding of the compressive zone of concrete area (see Fig. 3(b)). Ultimate capacity of the composite beams in the service state can be calculated for the two cases: for the full composite cross-section of the beam and for described above slab-beam floor system due to the limit state conditions determined according to EN 1994-1-1 [3]. Selection of the proper approach was dependent on the results of full scale tests of slab-beam floor systems (see below).

3.2. Computational model of composite beam with horizontal studs

The interconnection between the concrete and steel components of a composite beam should have sufficient strength and stiffness to enable the two components to be designed as parts of a single structural member. The examined type of the composite beam can be described as the structural member subjected mainly to bending with components of concrete and structural steel, interconnected by horizontal shear connections so as to limit the longitudinal slip between both materials and the separation of one component from the other. Widely spread experimental research conducted in Building Research Institute - ITB in Warsaw indicates that the loss of capacity of such structures is essentially linked with the loss of bonds between steel and concrete (see e.g. [4]). Three basic parameters: strength, stiffness and ductility are regarded to be the most important for static behavior of stud shear connectors [5, 6]. The main parameters describing the behavior of shear connectors include the height, diameter and tensile strength of headed studs, compressive and tensile strength of concrete, its modulus of elasticity and the direction of casting of concrete [7, 8]. Important test research in scope of strength, stiffness and ductility of headed studs as shear connectors were conducted in Universität Stuttgart [9–17] and in Universität Leipzig [18]. Lewiński and Więch presented the analytical model and the numerical study of composite beams (of I-type steel section) with horizontal studs at AMCM 2014 conference [19]. Reinforcement against separation of concrete and steel has been devised by the sets of horizontal studs connected at the centres of the two perforated webs. The considered shear connections were checked analytically as an interconnection between concrete and steel components being the parts of sufficiently resistant and stiff composite beam. The design strength of stud shear connectors which are welded automatically, is specified by Eurocode EC4 [3], by the equation (6.18) and (6.19) given in the p. 6.6.3.1 of this standard. However, the considered shear connections were checked analytically making the allowance for the model of load resistance for horizontally lying studs presented in the cited reference book [15]. The load-bearing capacity of this special type of connections between steel and concrete in the composite beam provided by horizontal studs is defined by the subsequent equations for the case of:

- load resistance for longitudinal shear:

$$P_{Rd,L} = \frac{1,4k_v(f_{ck} \cdot d \cdot a'_r)^{0,4}(a/s)^{0,3}}{\gamma_v} \quad (1)$$

- load resistance for vertical shear:

$$P_{Rd,V} = \frac{0,012(f_{ck} \cdot \phi_l)^{0,5}(d \cdot a/s)^{0,4}(\phi_s)^{0,3}(a'_{r,o})^{0,7}k_v}{\gamma_v} \quad (2)$$

- interaction:

$$(F_{d,L}/P_{Rd,L})^{1,2} + (F_{d,V}/P_{Rd,V})^{1,2} \leq 1, \quad (3)$$

where:

a - spacing of studs,
 a'_r - effective edge distance,

k_v - factor for position of shear connection; $k_v = 1$ for edge position, $k_v = 1.4$ - middle position,

d - diameter of the stud shank,

h - overall height of the stud, where $h/d \geq 4$,

s - spacing of stirrups, where $a/2 \leq s \leq a$ and $s/a_r \leq 3$,

ϕ_l and ϕ_s - diameters of longitudinal reinforcement and stirrups, respectively,

γ - partial factor equal to γ_{M2} ,

$F_{d,L}$ - design longitudinal shearing force per one stud, due to the transmission of the compressive force in compressive zone of RC cross-section to the steel cross-section via the studs.

$F_{d,V}$ - design vertical shearing force per one stud.

The edge position is encountered in case of external steel web with horizontally fixed shear studs, while the middle position - in case of internal web with studs on both sides of the web. There is the edge position for the case under consideration. Both for the longitudinal shear due to beam bending and for the vertical shear due to transversal forces, we can observe the phenomenon of horizontal splitting failure of concrete in the composite beam.

3.3. The bonds between the composite beam and the floor slab

Existing test results indicate that the loss of capacity of such structures may be linked to the loss of bonds between the composite beam and the floor slab. The expression defining the load carrying capacity of this junction, after some rearrangements, enabled the derivation of equations for the determination of the slab width interacting effectively with composite beam. As an interconnection between composite beam and slabs, the RC studs have sufficient strength and stiffness to enable both components of the structure to be designed as the parts of a single structural member able to attain the ultimate limit states. The studs have been designed according to the provisions of Eurocode 2 [1]. In order to take into account in the design calculations that the part of reinforced concrete floor slabs act with the composite beam and they form the slab-beam floor system, it is assumed that the maximum shear force carried by reinforced shear pin assembly at the junctions of composite beams to the floor slabs, determined using the principles given in the EN 1992-1-1 [1], it is equal to the force transmitted by an effective cross-section of floor slabs based on the lower flanges of the composite beams and acting together with this beams.

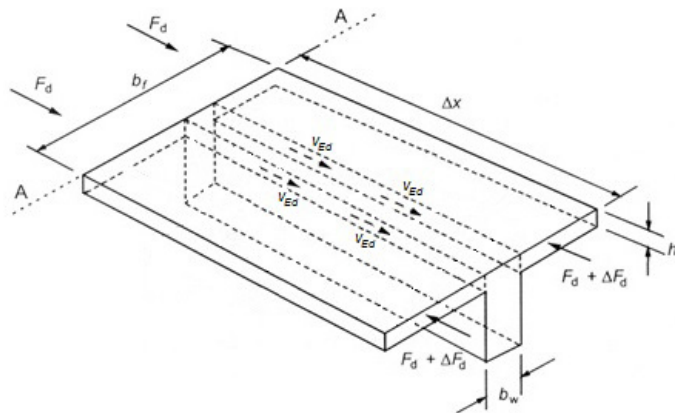


Fig. 4. Notations for the connection between flange and web (composite beam); b_f - effective flange width, b_w - composite beam width.

The longitudinal shear force, ΔF_d , i.e. the change of the normal force in the flange over the length Δx at the junction between one side of the flange and the web can be determined by the longitudinal shear stress in the considered part of the flange, according to the reversed equation (6.20) of EN 1992-1-1 [1]:

$$\Delta F_d = v_{Ed} \cdot h_f \cdot \Delta x, \quad (4)$$

where:

v_{Ed} - is the longitudinal shear stress,

h_f - is the flange thickness at the junctions,

Δx - is the length under consideration, see Fig. 4.

The maximum value that may be assumed for Δx is half the distance between the section in which the moment is zero and the section in which it attains the maximum value. The effective cross-section of slabs acting with the composite beam is determined as follows. The longitudinal shear stress, v_{Ed} , should not exceed the limit value of shear stress, v_{Rd} , at the interface between concrete cast at different times (see EN 1992-1-1 [1], p. 6.2.5). The depth of compression zone of slab-beam floor system x_{pl} (see Fig. 3b), is determined according to EN 1994-1-1 [3] basing on the equilibrium equation of the forces in the cross-section of the composite beam taking into account the additional forces carried out by the compression zone of the effective cross-section of the floor slabs acting together with the beam (Fig. 3b). The effective flange width, b_f (see Fig. 4), is defined by the equilibrium equation of the shear forces resulting from the longitudinal shear stress, v_{Ed} and compressive forces carried out by the compression zone of the effective cross-section of the floor slabs acting with the beam, depending on the degree of stitching reinforcement and the class of cast concrete, according to the equation:

$$\Delta F_d = 0,5 \cdot (b_f - b_w) \cdot 0,85 x_{pl} \cdot f_{cd,s}, \quad (5)$$

where:

$f_{cd,s}$ - is the design compressive strength of the cast concrete.

3.4. Serviceability Limit State

Serviceability Limit State of composite beams is calculated for the full cross-section of RC slabs-composite beam floor system (effective cross-section of the floor slabs acting with the beam), including, among others, the impact of rheological phenomena (shrinkage and creep).

4. Experimental study

Two types of structures, each consisting of composite beam and the prefabricated floor slabs, have been the subject of full scale tests performed in cooperation with ITB strength tests laboratory. One composite beam of the theoretical span 5.80 m, the depth 200 mm and the width 300 mm of its RC part as well as the second beam of the theoretical span 7.80 m, the depth 270 mm and the width 350 mm of its RC part were prepared for this study. The view of such type of the beams is shown in Fig.1. As a static scheme there was adopted a simply supported beam loaded symmetrically by pre-tensioned HC type floor slabs with a span of 6 m (see Fig. 5). Before starting the test the slabs were covered with leveling layer of sand. Before the test the force gauge load cell was introduced between each end of the beam and the support. This enabled the determination of support reactions and thus the summary load acting on the beam. This was followed by reading the initial value of the load (from the weight of the beam, floor slabs and leveling layer of sand) and was cleared to indicate the force gauge load cell. In the first phase the applied load was in the form of the road RC slabs laid on a leveling layer of sand with a crane. The scheme of arrangement and the order of stacking plates is shown in Fig. 5. In the second phase of the study, on the pre-arranged road RC slabs there were placed the tanks filled then with water. Arrangement of tanks is shown in Fig. 5 for the case of composite beam of the theoretical span 7.80 m. In the course of the study the registration of deflection of the beam in the middle of the span was carried out with LDVT sensor. Such arranged measurement eliminated the impact of subsidence of the beams on supports equipped with elastomeric bearings. Together with the deflections, the support reactions and the strains in selected areas of the longitudinal reinforcement and the beam surface were recorded by the strain gauges. During the tests no signs of splitting between beam and HC slabs subjected to design loads were observed. The deflection of the composite beam of the theoretical span 7.80 m, in the middle of the span in relation to the total external loading according to test results is shown in Fig. 6 (the curve 1).



Fig. 5. Tanks filled with water on the road slabs aggravating the floor slabs and composite beam.

5. Comparative analysis

The test results were compared with the outputs of the rigid-plastic solutions for load-bearing capacities of the considered composite beams and the solution for slab-beam floor system. These analytical models are described in 3.1. It should be mentioned that the loading procedure was ended before attaining the limit load of slab-beam floor system. The deflection and ULS of the beam of the theoretical span 7.80 m is considered below (Fig. 6).

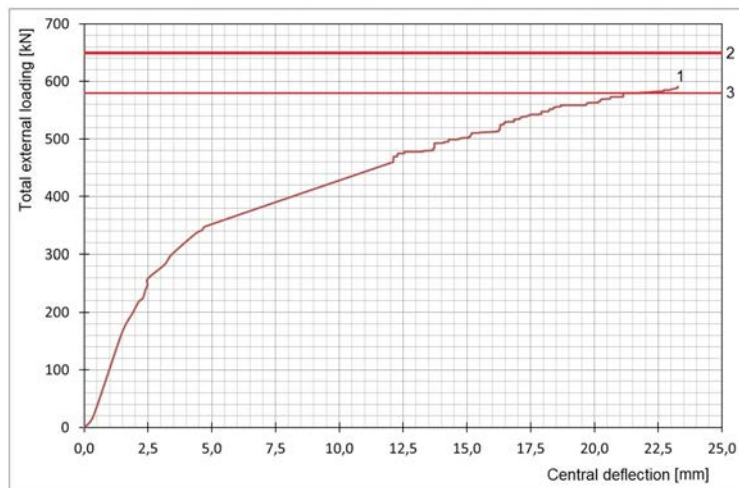


Fig. 6. Deflection of the beam of the theoretical span 7.80 m in the midpoint, in relation to the total external loading due to test results (curve 1). Rigid-plastic solutions for load-bearing capacities: 2 – limit load of slab-beam floor system, 3 – limit load of separated composite beam.

The bending moment due to the self weight of slab-beam floor system was 206.7 kNm. Ultimate bending moments due to external loads were calculated as the difference between the ultimate bending moment for slab-beam floor system as well as for separated composite beam and the bending moment due to the self weight of the structure. In the first case the ultimate moment is equal to 566.8 kNm and in a second case is equal to 633.3 kNm. On this basis, the limit load of slab-beam floor system was determined as 649.5 kN (line 2), while the limit load of separated

composite beam - as 581.4 kN (line 3, Fig. 6). According to the hitherto experimental results, the selection of the proper estimation of load-bearing capacity of the composite beams in the service state was based on ULS of separated composite beam. The comparison between analytical results (the midspan deflection of 35.7 mm) and test results (the deflection of 22.5 mm) obtained for the service load of the composite beam shows a difference resulting from the underestimation of additional stiffness obtained by means of the floor slabs acting with the beam.

6. Conclusions

A new concept of composite steel-reinforced concrete floor slab is presented in the paper. Implementation of the above mentioned combined analytical and experimental method of the analysis of composite beam with horizontal studs acting together with HC floor slabs. A considerable advantage of the proposed concept of supporting elements of the plates is that the composite beams are arranged in the same level with the plates which allows to obtain a flat bottom surface of the floor slabs. Such assumptions enabled the creation of the computational approach for the analysis of such structural systems mainly subjected to the bending (and possibly to the torsion) and the recognition of the failure mechanism, with respect to the layout and ratio of horizontal studs. This analytical model is generally supported on Eurocodes EC2 [1], EC3 [2] and EC4 [3], however it has been updated to take into account the latest experimental results of research works conducted in German and Swiss universities. Experimental and computational results showed satisfactory consistence proving that proposed analytical model provides good results. Such obtained results are on the safe side, so that assumed models were accepted by authors due to their simplicity and the safe estimation of load bearing capacity. Further studies will be linked with other types of floor slabs and non-linear finite element analysis of composite beam - floor slab systems.

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