EXPERIMENTAL AND ANALITICAL STUDY OF COMPOSITE BEAMS WITH PROFILED STEEL SHEETING

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The paper presents the results of experimental and analytical research on steel-concrete composite beams of floor structures with the application of steel profiled sheet. The parallel and transversal position of the ribs of the profiled sheet in relation to the axis of the steel beam is considered.

A test of the resistance and ductility of the headed stud connectors for parallel and transversal position of profiled sheet was carried out according to a standardized test procedure [4],[5] (EC 4, part 1-1, annex B2).

The main part of the research was carried out with a full-scale testing of two models of a simple beam with a span of 5750 mm, with longitudinal and transversal ribs of the profiled sheet.

For comparison with the experimentally obtained results, an elastic-plastic analysis was applied, carried out with 3D/FM models in the "Abaqus 6.14" software package, using material nonlinearity modeled on the basis of the previously determined behavior of the constituent materials.

Keywords: composite beams, headed stud connectors, steel profiled sheet

1. INTRODUCTION

In the modern construction of multi-story buildings, everywhere in the world, the application of steel structures is frequent. In combination with them, a concrete slab cast on a steel profiled sheet is used as a floor slab.

The slab composed of concrete and steel profiled sheet has several advantages over the classic reinforced concrete slab: the sheet in the concreting phase serves as a formwork for the fresh concrete, the steel sheet can be bonded to the concrete and replaces a good part, or entire required reinforcements in the lower zone of the slab. The profiled sheet can be placed with ribs parallel to the beam, or with ribs transversal to the span of the beam.

The supporting beams from the floor structure, on which the profiled sheet is directly placed, are usually bonded to the floor slab with headed stud connectors. The headed stud connectors are welded to the steel girder with specialized equipment [7]. There are two general approaches in welding them, directly to the steel beam with holes in the sheet, and welding through the sheet.

A composite simple beam, with a span of 5,75m, made of IPE240 with a concrete slab (d=100mm) cast on a steel profiled sheet (FR38/158 d=1,0mm) placed in the first case parallel to the span of the beam, and in the second case perpendicular to the span of the beam, was considered. For both alternatives, a full-scale model was tested. The testing was carried out in the laboratory for testing of constructions at the Faculty of Civil Engineering from the University "St. Cyril and Methodius" in Skopje.

Headed stud connectors (d=19mm, hc=100mm) type Nelson, without a protective layer of concrete above the head of the connector, were used as means of connection. The resistant of the connectors, which depends on many factors, was examined with a "push" standardized test according to the procedure of EC 4: Part 1-1: Annex B2.

In both tests, modern equipment was used to register the parameters of the structural behaviour under the influence of the test load (force, deformations, strains), as well as for the acquisition of the measured values.

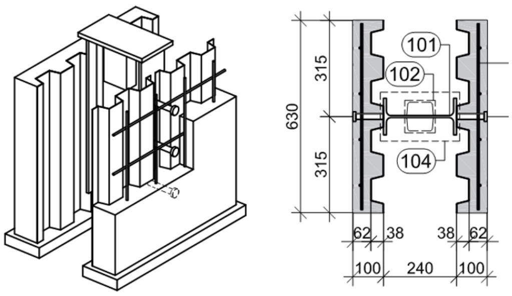
In addition to the experimental investigation of the composite effects, an analytical investigation was also carried out with computer modelling of the test beams in the Abaqus software package. The values obtained from the examination of the constitutive materials (steel and concrete), i.e. the declared values from the attestation documentation (connectors, reinforcement and profiled sheet) were used in the modelling.

The obtained experimental and analytical results in terms of ultimate limit resistance and deformability are compared for the two test models and presented in the form of diagrams, graphs and tables.

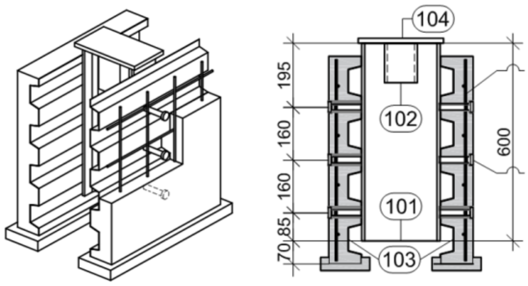
The load-bearing capacity of composite beams, using profiled sheet as a formwork for the fresh concrete, depends on a number of factors and is the subject of analytical and experimental investigations. Eurocode 4, part 1-1, provides principles and rules for the design of the ultimate bearing capacity, that is, the plastic bending moment in a characteristic section [4]. The stiffness of the coupled beams is of essential importance for serviceability. Using of elastic shear connectors leads to relevant displacements in the contact plane even for relatively low values of the load [6]. This phenomenon can be determined by experimental investigation, or through complex computer models in which the calibration of parameters are based on experimental results.

2. TESTS ON SHEAR CONNECTORS

When shear connectors are used in T-beams with a constant-thickness concrete slab, or with haunches, the standard push test may be used [2], [8]. In other cases, with longitudinal or transverse placement of profiled steel sheet, a specific push test should be used. In this case, an ordinary sheet was used without indentations or embossments that are used to connect the slab to the sheet [9], [11], [13].



a) parallel ribs



b) transversal ribs

Figure 1. Test specimens for standard push test

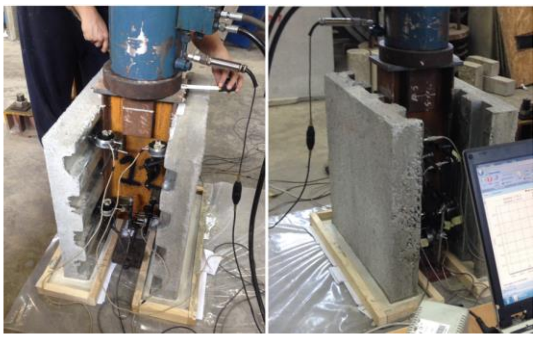


Figure 2. Test equipment

During the test, the applied force and the longitudinal slip between each concrete slab and the steel section are measured, as well as the transverse separation between the steel section and each slab (Fig. 1).

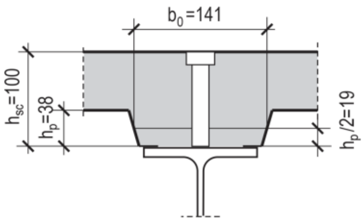
The expected breaking load is obtained by multiplying the design load capacity of the headed stud connector, according to paragraph 6.6.3.1 of EC4-1.1 (1), by the number of applied connectors.

$$P_{Rk} = \frac{0{,}8 \cdot f_u \cdot (\pi \cdot d^2/4)}{\gamma_v} \quad \text{or}$$

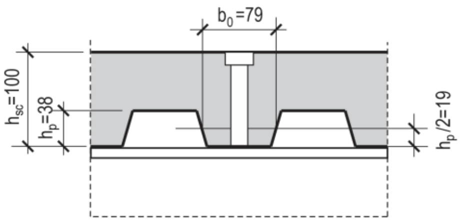
$$P_{Rk} = \frac{0{,}29 \cdot \alpha \cdot d^2 \cdot \sqrt{f_{ck} \cdot E_{cm}}}{\gamma_v} \qquad (1)$$

which is smaller, with α=1 for h_{sc}/d=100/19 > 4.

The partial safety factor γ_v is taken equal to 1,0, the specified ultimate tensile strength of the connector material f_u=500MPa, the characteristic cylinder compressive strength of the aged concrete f_{ck}=30MPa, the secant modulus of elasticity of concrete E_{cm}=33000MPa.



a) parallel ribs



b) transversal ribs

Figure 3. Characteristic geometric values

The shear resistance of the headed stud connector, with the values given in expression (1), is:

$$P_{Rk} = \frac{0{,}8 \cdot 500 \cdot (\pi \cdot 19^2/4)}{1{,}0} = 113{,}35\text{kN} \quad \text{or} \qquad (2)$$

$$P_{Rk} = \frac{0{,}29 \cdot 1{,}0 \cdot 19^2 \sqrt{30 \cdot 33000}}{1{,}0} = 104{,}16\text{kN} \qquad (3)$$

When using a profiled steel sheet with ribs parallel to the beam, the shear resistance should be multiplied by the reduction factor k_l (4), (Fig. 3a).

$$k_\ell = 0{,}6 \cdot \frac{b_0}{h_p} \cdot \left(\frac{h_{sc}}{h_p} - 1\right) \le 1{,}0 \qquad (4)$$

When using a profiled steel sheet with ribs transversal to the beam, the shear resistance should be multiplied by the reduction factor k_t (5), (Fig. 3b).

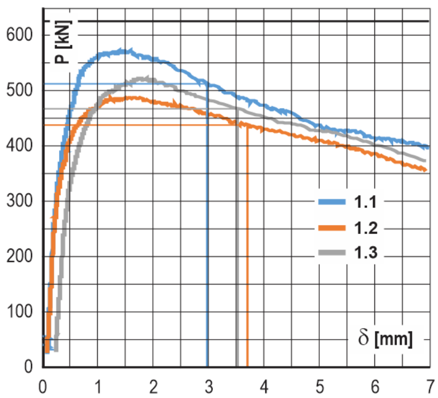
$$k_t = \frac{0{,}7}{\sqrt{n_r}} \cdot \frac{b_0}{h_p} \cdot \left(\frac{h_{sc}}{h_p} - 1\right) \qquad (5)$$

Where n_r is the number of connectors in one rib of the cross section of the beam. Upper limit $k_{t,max}$ for k_t is: $k_{t,max}$=0,85, for n_r=1 and welding through the sheet. The values obtained with the standardized test are given in tab. 1.

Table 1. Measured and calculated forces

Samp. Nb.	Disposition L parallel T transver.	Welding TD through deck H through holes	P_{max} (measured) [kN]	P_{Rk} EC4 [kN]
1.1	L	H	570,3	625,0
1.2	L	H	486,5	625,0
1.3	L	H	520,3	625,0
2.1	T	TD	462,9	531,2
2.2	T	TD	431,8	531,2
2.3	T	TD	399,9	531,2

The following graphs present the measured maximum force for each sample and the P-δ relation.



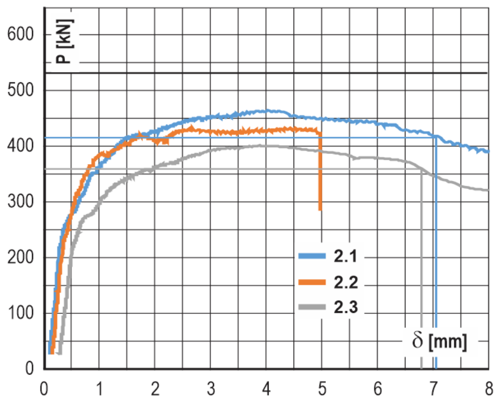


Figure 4. P-δ diagrams of the tested samples

The horizontal line shows the expected maximum force. The ductile behaviour of the headed stud connectors, according to EC4, requires a sliding capacity of at least 6mm in a push test at a characteristic load level (0,9Pmax).

The measured maximum forces for type 1 specimens are approximately 16% lower than the corresponding value according to EC4. The required ductility is not satisfied. The failure appeared in the concrete.

The measured maximum forces for type 2 specimens are approximately 19% lower than the corresponding value according to EC4. The required ductility is met in samples 2.1 and 2.3 by the occurrence of failure through the concrete. A shear failure of the connectors occurred in specimen 2.2.

3. TESTS ON COMPOSITE BEAMS

The experimental research is based on a full-scale testing of two test beams which, according to the static system, represent simple beams with a length of 6,00m and span of 5,75m (Fig. 5).

Figure 5. Test beams and load application equipment

The cross-section of the two beams is steel profile IPE240 with a reinforced concrete slab 100mm thick and 1200mm wide. In the first beam, the reinforced concrete slab is cast on the formwork of profiled steel sheet FR38/158 d=1mm placed parallel to the beam, and in the second beam the sheet is placed transversal.

The connection between the steel beam and the reinforced concrete slab is made by headed stud connectors with d=19mm, Nelson type. The studs are placed at a distance of 158mm between each rib in the transversal position. The same raster is adopted for beam 1, for comparative reasons.

The loading is applied by four concentrated forces placed at a distance of L/4 (1450mm). Two by two of the concentrated forces are applied through two secondary traverses, and the aggregate force (P=4*P1) is applied with a hydraulic jack of 1000kN through the primary traverse. The concentrated forces (P1) are applied as a linear load along the width of the reinforced concrete slab of the test beam (1200mm). For this purpose, U120...1200 profiles are welded to the secondary traverses, which rest on wooden beams 10/12cm.

The deflections were measured at 3 points at L/4 of the beam with displacement transducers; the strains were measured in the middle of the beam with strain gauges (3 on the concrete, 3 on the reinforcement, 5 on the steel section and 6 on the headed studs); the slips in the contact plane were measured in 6 points with two mechanical comparators and four inductive displacements transducers. The force is registered with a dynamometer built in the hydraulic jack.

The measurement signals are registered and processed by two data loggers, Quantum and Controls, with a measurement frequency of 2Hz, and the measured values are stored and transferred to a personal computer.

4. ANALYTICAL MODELS

3D FE models have been developed by using software ABAQUS explicit 2024. The models fully correspond with the previously described test models, both in terms of geometry and in terms of loading method. An elastic-plastic analysis with material nonlinearity was carried out [10], [12].

The FE model consists of five constituent materials: steel, concrete, reinforcement, connectors and profiled sheet. 3D solid elements with eight nodes (C3D8R) are used to model the steel beam, connectors and concrete slab. The profiled sheet is modelled with surface (shell) elements with 4 nodes (S4R), and the reinforcement is modelled with two-node lattice elements (T3D2).

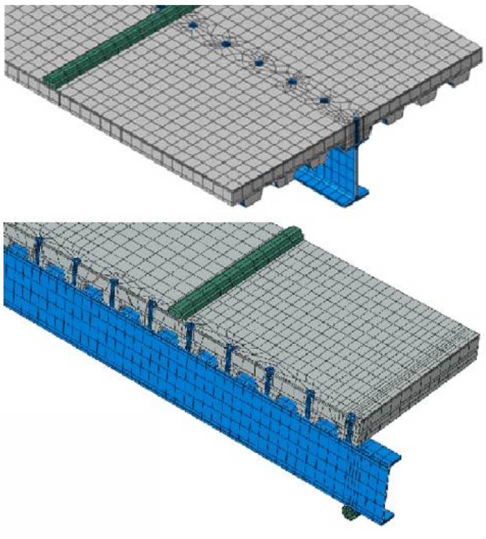


Figure 6. Finite element mesh

An elastoplastic relation σ-ε with a hardening zone for structural steel was used in the modelling of the beam steel. For the profiled sheet, considering the cold forming, an elastic ideally plastic σ-ε diagram was used.

Failure of the connectors exposed to shear and bending are very common. On the basis of this, a σ−ε relation in full range was used for the connectors, where the failure phase is also defined ($\varepsilon_u=25\varepsilon_y$, $\varepsilon_{u2}=90\varepsilon_y$).

During the loading phase, it is common part of the concrete slab to be exposed to tension, and the other part to pressure. That is why a concrete damaged plasticity (CDP) module is used. With this module, tension cracks and possible compressive crushing of concrete can be covered.

5. ANALYSIS OF THE RESULTS

Obtained results of the relation force-deflection in the middle of the beam in the Figure 7 are presented. The designation AM refers to an analytical model, and the designation EM to an experimental model.

A high degree of coincidence of the obtained results can be observed, especially for beam 2. The black line represents the relationship for assumed ideal elastic behavior through the idealized parameters of the cross section. It is evident that, even for relatively low load values, there is a deviation from the idealized line. Main reason is application of elastic shear connectors, in which relevant deformation occurs at an early stage of loadings [1], [3].

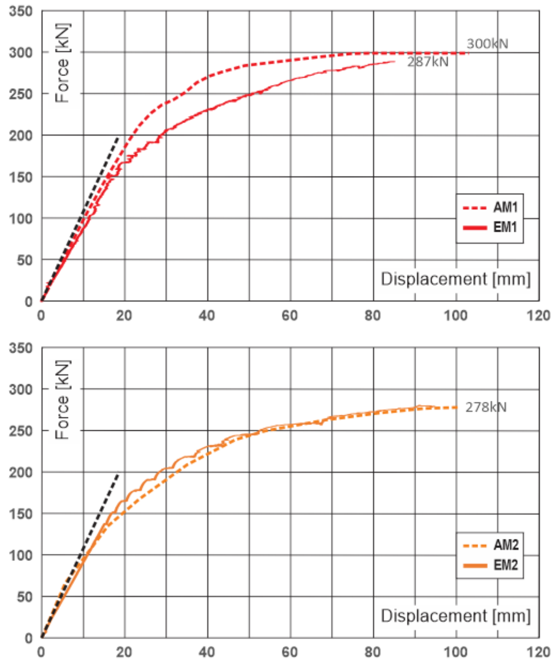


Figure 7. Relation force-maximum displacement

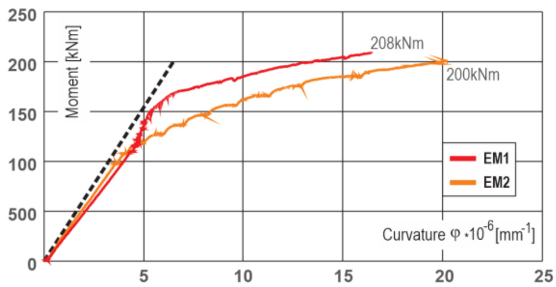


Figure 8. Experimentally determined relation M-φ

The experimentally determined relation M-φ given in Figure. 8 leads to the same conclusion. The actual stiffness of the composite beam is lower than the expected value obtained by applying elastic behavior to an idealized section.

6. CONCLUSION

Based on the conducted experimental determination of the resistance of the headed stud connectors with the standard test, it can be concluded that their resistance is lower than the recommended value in EC4. For the studs welded directly to the steel flange, in the case of longitudinal ribs of the profiled sheet, the difference is about 16%. For studs welded through the sheet, in the case of transversal ribs of the profiled sheet, the difference is about 19%.

The resistance of headed stud connectors without a protective layer of concrete above the stud head is not specifically regulated. The test results show that there is no significant resistance decrease. Also, the decrease in resistance might be addressed to other factors.

Based on the experimental and analytical study of the composite beam with a profiled sheet with ribs placed longitudinally and transversally, it can be concluded that the stiffness of the composite beam is lower than the designed stiffness for an ideal section. This should be taken into consideration during serviceability control, both in terms of maximum deformation and in terms of dynamic behaviour (period of oscillation).

In general, composite beam with transversal position of profiled sheet ribs has a lower load-bearing capacity. In terms of stiffness, there are no significant differences related to the disposition of the profiled sheet in the zone of linear elastic behaviour.

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REFERENCES

[1] Amanyire Barozi Victoire, John Nyiro Mwero, Naftary Gathimba, Experimental study on the effect of partial shear studs layout on flexural behavior of steel-concrete composite beams. Results in Engineering Volume 21, March 2024.

[2] Cvetanovski P., Popovski D., Partikov M., Dmjanovski V., “Experimental investigation of load and slip capacity of headed stud connectors in composite slabs for buildings”, Annual of the university of architecture, civil engineering and geodesy, Sofia, Volume 46, 2018.

[3] Couchman, G., Minimum Degree of Share Connection Rules for UK Construction to Eurocode 4, SCI P405, 2015.

[4] European Standard EN 1994, Eurocode 4: Design of composite steel and concrete structures, Part 1-1: General rules and rules for buildings, 12.2004, +AC 04.2009, European Committee for Standardization.

[5] European Standard EN 1994, Eurocode 4: Design of composite steel and concrete structures, Part 1-1: General rules and rules for buildings, Draft prEN 1944 1-1 March 2024, European Committee for Standardization.

[6] Faella, C., Martinelli, E. & Nigro, E., Steel and concrete composite beams with flexible shear connection: "exact" analytical expression of the stiffness matrix and applications. Computers and Structures 80 (2002) 11, pp.1001-1009.

[7] Hicks, S.J.: Strength and ductility of headed stud connectors welded in modern profiled steel sheeting, The Structural Engineer, 85, No. 10, 2007, pp 32-38.

[8] Horita Y., Tagawa Y., Asada H., Push-out test of headed stud in composite girder using steel deck -An effect of stud length of projecting part from steel deck on shear strength, 15 WCEE, Lisboa 2012.

[9] Konrad, M., Kuhlmann, U., Headed Studs Used in Trapezoidal Steel Sheeting According to Eurocode 4, SEI, Volume 19, Nr.4, 2009.

[10] Lam D., El-Lobody E., Bahaviour of headed stud shear connections in composite beam. Journal of Structural Engineering, 2005.

[11] Qureshi J., Lam D., Ye J., Behavior of headed shear studs in a push test using profiled steel sheeting, Research gate, July 2009.

[12] Spacone Enrico, Nonlinear Analysis of Steel-Concrete Composite Structures: State of the Art, A.M.ASCE, Jurnal of Structural Engineering, Vol. 130, No. 2, February 2004.

[13] Stephen J. Hicks, Andrew L. Smith, Stud Shear Connectors in Composite Beams that Support Slabs with Profiled Steel Sheeting, Structural Engineering International, 2014.