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EXPERIMENTAL AND ANALITICAL STUDY OF LOAD AND SLIP CAPACITY OF HEADED STUD CONNECTORS IN COMPOSITE SLABS FOR BUILDINGS

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ABSTRACT

An extensive experimental investigation in accordance with EC4-1-1 Annex B.2, has been carried out to determine the behaviour of shear connectors in composite beam construction. Six push-out tests were reported to demonstrate the ultimate strength behaviour of the steel- concrete composite structure from the component level to the structure level. The specimens were investigated, with variation of constructive parameters, with push-out tests. Type of steel sheeting and position, longitudinal and transversal, were varied for headed stud connector $d=19\text{mm}$, $h_{sc}=100\text{mm}$. Also, number of shear connectors in cross section (1 or 2), and welding procedure, with holes and through deck welding, were varied. Concrete with grade C25/30, as common used grade, and reinforcement with minimum percentage, were adopted. Results of load capacity were compared with proposed load capacity according to EC4-1-1 (6.6.3 and 6.6.4), where significant differences in some cases were obtained.

This article presents the preparation and execution of experimental investigation for two models with three elements of push tests, with one shear connector in the cross section. The obtained load and slip capacities are also presented. The failure mode and ductility are the object of investigation to establish the analytical model for the shear connection.

The analytical solution with 3D/FM models in the “ABAQUS eksPLICIT 2024” has also been carried out to determine the accuracy of the analytical solution with the experimental one.

Keywords: Composite structure, shear connector, push test, EC-4.

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1. Introduction

The scope of use of composite structures made of steel and concrete in construction is very wide, they are used in the construction of high-rise buildings, administrative buildings and bridges all over the world. These structures offer fast, economical and environmentally friendly construction. The possibility of occupying large spaces with beams and decks with relatively small dimensions, lighter structure by 20-40% and faster construction, made these structures very popular among architects and civil engineers.

Unfortunately, aside of all worldwide positive experiences, composite steel and concrete structures are occasionally used in construction works in our country. Possible reasons are lack of experience and traditional concrete oriented construction.

Floor slabs at buildings are field where advances of composite steel and concrete structures are evident. The common concrete slab positioned on top of steel beam (usually welded or rolled I or H steel section) opens the door for composite action. The concrete slab could be casted on traditional formwork, or profiled steel sheeting could be used as formwork. Second case, mostly used, offers fast building and possibility to establish composite action in flor slab (composite slab). However, main benefit is reached with composite action of steel beam and concrete slab.

The transfer of longitudinal shear between the steel beam and the concrete slab is achieved by installing various types of mechanical devices called shear connectors. Mostly used shear connectors at composite slabs for buildings are headed studs (Fig. 1). Headed studs, in case of profiled steel sheeting, could be welded through a hole in steel sheeting, or welded through the deck (Fig. 2).



Figure 1. Headed stud shear connectors



Figure 2. Welded headed studs

Shear connectors shall have sufficient resistance to transmit the shear force, and deformation capacity to justify any inelastic redistribution of assumed shear in design. Therefore, it is necessary to determine the shear resistance and slip capacity of the headed stud connectors prior to their use in construction.

Eurocode 4 [1] prescribes the principles and rules for design of composite steel and concrete structures. Design resistance of headed stud connectors in solid slabs and concrete encasement is stated in clause 6.6.3, and clause 6.6.4 when headed studs are used with profiled steel sheeting. Also, annex B.2 gives the rules for test of shear connectors.

There are many types of profiled steel sheeting with open and re-entrant profile used in composite slabs. Design resistance and ductility of headed stud connectors depend on many parameters: type of steel sheeting, position over steel beam (transversal/longitudinal), height and number of connectors in cross section (1/2), method of welding, depth of slab, quality of concrete, reinforcement, mutual position of elements in cross section.

According to our experience, design resistance and rules for ductility proposed by EC4 not always correspond with real resistance and ductility. Values of reduction factors k_l and k_t , in some cases are under question. There is a need of experimental investigation to establish more effective compliance between design resistance and real resistance of headed stud connectors.

Commonly used profiled steel sheeting FR38/158, and headed stud connectors NELSON with diameter $d=19\text{mm}$ and total height $h_{sc}=100\text{mm}$ are adopted. Also, the corresponding solid slabs have been investigated. Concrete grade C25/30 has been adopted, as commonly used concrete quality in floor slabs.

Specific push test in accordance with annex B.2 of EC4-part 1.1 has been carried out on 6 specimens. Preparing of test specimens, testing procedure, measurements and results, are presented in this article.

2. Specific push test

When the shear connectors are used in T-beams with a concrete slab of uniform thickness, or with haunches, standard push test may be used. In other cases, with longitudinal or transversal sheeting, specific push test should be used. Specific push test should be carried out so that the slab and the reinforcement are suitably dimensioned in comparison to the beams, according to rules and recommendations given in EN 1994-1-1, Annex B.2.

2.1 Preparation of specimens

The length of each slab has been related to the longitudinal spacing of the connectors in the composite steel-concrete structure. The width of each slab was chosen not to exceed the effective width of the slab of the beam. The slab thickness of 100mm for FR38/158 steel sheeting was adopted.

The slabs were casted horizontally, as they are casted as part of a composite structure (Fig. 3).



Figure 3. Casting of concrete

The concrete was casted first on one side of the test sample, and with turning, on the other side. The concrete was air-cured as per practice for composite beams.

From each concrete mix four concrete specimens (cubes) were taken for determination of the strength of the concrete for each of the sides of the sample. The concrete specimens were cured alongside the push test specimen.

The yield strength, the tensile strength and the maximum elongation of a representative sample of the shear connector material, steel beam and profiled steel sheeting, were determined with the referent standard tests.

2.2 Test procedure and evaluation

As recommended in EC4-1-1 annex B.2, the load was applied in increments up to 40% of the expected failure load, and then 25 time cycled between 5% and 40% of the expected failure load. After the 25th cycle, subsequent load increments were imposed up until failure in the specimen is reached, but not in less than 15 minutes. While testing, the longitudinal slip between the concrete slab and the steel beam is measured constantly. Also, the transverse separation between the slab and the steel section was measured as close as possible to each group of connectors.

Expected failure load is obtained by multiplied design shear resistance of a headed stud, according to clause 6.6.3.1 of EC4-1.1 (1), with number of applied connectors.

$$P_{Rd} = \frac{0.8 \cdot f_u \cdot \pi \cdot d^2 / 4}{\gamma_v} \quad \text{or} \quad P_{Rd} = \frac{0.29 \cdot \alpha \cdot d^2 \sqrt{f_{ck} E_{cm}}}{\gamma_v} \quad (1)$$

whichever is smaller, with $\alpha=1$ for $h_{sc}/d=100/19 > 4$.

Partial factor γ_v is taken as 1.0, specified ultimate tensile strength of the material of the stud $f_u=500MPa$, the characteristic cylinder compressive strength of the concrete at the age of testing $f_{ck}=30MPa$, secant modulus of elasticity of concrete $E_{cm}=33000MPa$.

Shear resistance of headed stud, with above values in equation (1) is:

$$P_{Rd} = \frac{0.8 \cdot 500 \cdot \pi \cdot 19^2 / 4}{1.0} \cdot 10^{-3} = 113.35kN \quad \text{or} \quad (2.1)$$

$$P_{Rd} = \frac{0.29 \cdot 1.0 \cdot 19^2 \sqrt{30 \cdot 33000}}{1.0} \cdot 10^{-3} = 104.16kN \quad (2.2)$$

Assumed shear resistance of headed stud is 104.16kN.

When profiled steel sheeting is used with ribs parallel to the supporting beam, shear resistance should be multiplied by the reduction factor k_l (3), (Fig. 4).

$$k_l = 0.6 \frac{b_0}{h_p} \left(\frac{h_{sc}}{h_p} - 1 \right) \leq 1.0 \quad (3)$$

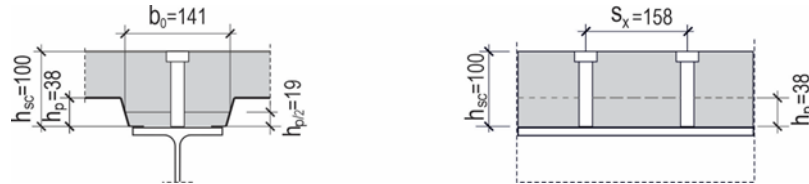


Figure 4. Beam with profiled steel sheeting parallel to the beam (cross-sectional and longitudinal sections)

Values of reduction factor k_l , for different types of steel sheeting, are calculated and presented in Part 3.

When profiled steel sheeting is used with ribs transverse to the supporting beam, shear resistance should be multiplied by the reduction factor k_t (4), (Fig. 5).

$$k_t = \frac{0.7}{\sqrt{n_r}} \frac{b_0}{h_p} \left(\frac{h_{sc}}{h_p} - 1 \right) \quad (4)$$

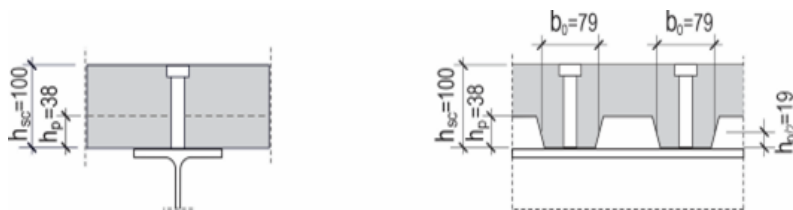


Figure 5. Beam with profiled steel sheeting transverse to the beam

Where n_r is the number of stud connectors in one rib at a beam cross section.

Upper limit $k_{t,max}$ for k_t is:

$k_{t,max} = 0.85$ for $n_r = 1$ and through deck welding

$k_{t,max} = 0.75$ for $n_r = 1$ and welding through holes

Values of reduction factor k_t , for different types of steel sheeting, are calculated and presented in Part 3.

2.3 Measuring equipment

Measuring equipment consist of measuring devices (Fig.6) and instruments for data acquisition (Fig.7).

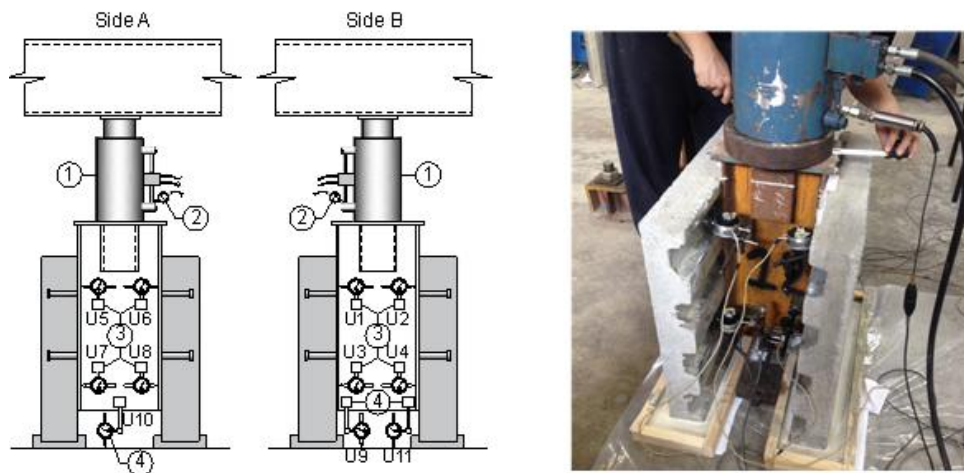


Figure 6. Test equipment – measuring devices

1) 100 tons hydraulic jack; 2) load cell; 3) displacement transducers for measuring the transverse separation between the steel beam and the slabs (U1, U2, U3, U4 on one side and U5, U6, U7, U8 on the other side); 4) displacement transducers for measuring the longitudinal (vertical) slip (U10 on one side and U9, U11 on the other)



Figure 7. Test equipment – data acquisition

The force was applied by 1000kN hydraulic jack with strain gauge pressure transducer in full bridge. Five strain gauge displacement transducers in full bridge (Kyowa) with measurement range 20mm were placed on U5, U6, U7, U8 and U10. Four inductive displacement transducers (HBM) with measurement range 10mm were placed on U1, U2, U3 and U4. Two inductive displacement transducers (HBM) with measurement range 50mm were placed on U9 and U11.

Measuring devices were connected to data processing instruments HBM Quantum and HBM Spider 8. Two personal computers and program Catman Easy (HBM) for data storage were used. Data acquisition was with frequency of 5Hz.

3. Description of specimens

Experimental investigation was performed with push test on 6 specimens. Two types with three specimens per type were prepared with FR38/158 steel sheeting.

Data regarding to description of specimens could be seen in Table 1.

3.1 FR38/158 profiled steel sheeting

FR38/158 steel sheeting is widely used in our country. This steel sheeting is without indentations or embossments, and it is not recommended for composite slabs. However, there are no limitations for the usage of this type as formwork and in composite action of steel beam and concrete slab. Experimental investigation of composite beams with concrete slab casted on FR38/158 was carried out in our laboratory.

Two types with total of 6 specimens were prepared using FR38/158 steel sheeting ($d=1.0\text{mm}$).

One type (1.1, 1.2 and 1.3) is with longitudinal position of ribs, one shear connector in cross section, and welded through holes (Fig. 12).

Reducing factor k_l (3), for $b_o=79$, $h_p=38$ and $h_{sc}=100$ is $2.035 > 1$, so that $k_l=1$

Expected failure load (2) for type 11 is $104.16 \times 1 \times 6 = 625.0\text{kN}$

The steel beam is IPE240 (S275JR), and reinforcement is Q188 ($\varnothing 6/15\text{cm}$).

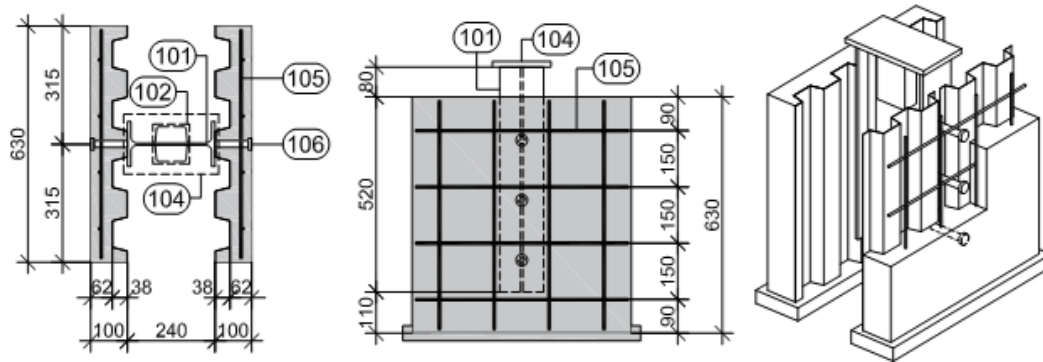


Figure 12. FR38/158 – longitudinal position

One type (2.1, 2.2 and 2.3) is with transversal position of ribs, one shear connector in cross section, and welded through deck (Fig. 13).

Reducing factor k_t (4), for $b_o=79$, $h_p=38$, $h_{sc}=100$ and $n_r=1$ is $2.374 > k_{t,max}=0.85$.

Expected failure load (2) for type 10 is $104.16 \times 0.85 \times 6 = 531.2\text{kN}$

The steel beam is IPE240 (S275JR), and reinforcement is Q188 ($\varnothing 6/15\text{cm}$).

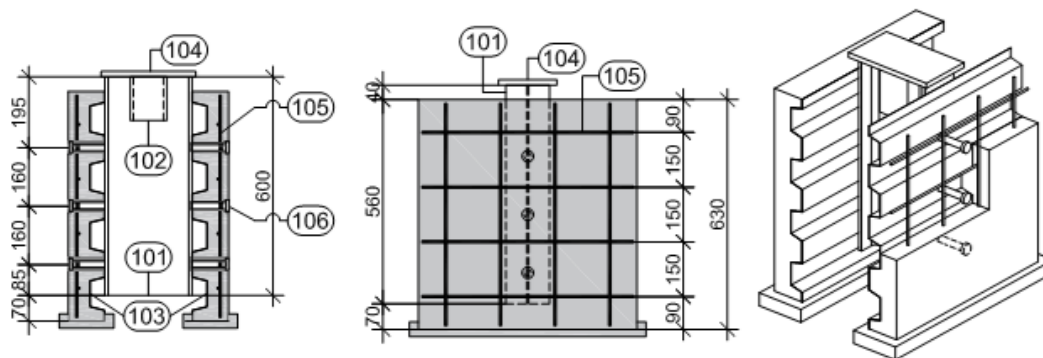


Figure 13. FR38/158 – transversal position

4. Results of testing

General description of specimens and data for measured and expected load capacity are presented in Table 1.

Table 1. Specimens characteristics, measured and expected forces

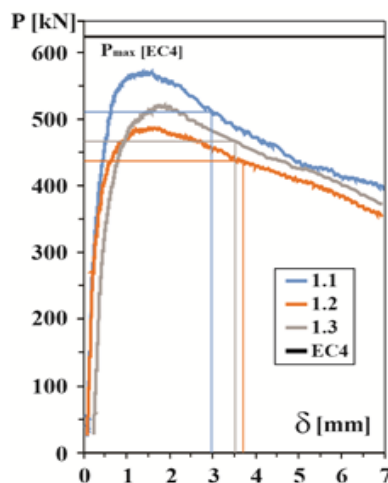
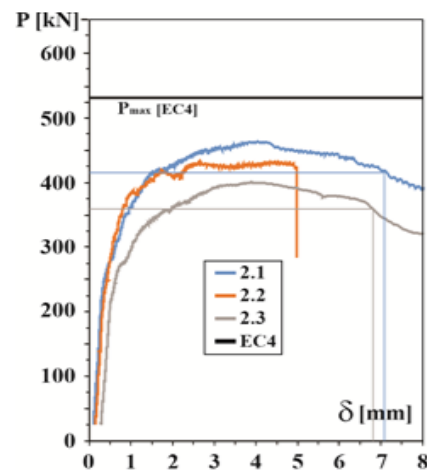
Spec. No.	Type of prof. steel sheeting	Position L long. T trans.	Number of shear connect.	Welding TD thro. deck H with holes	P_{max} exp. [kN]	P_{max} EC4 [kN]
1.1	FR38/158	L	1	H	570.3	625.0
1.2	FR38/158	L	1	H	486.5	625.0
1.3	FR38/158	L	1	H	520.3	625.0
2.1	FR38/158	T	1	TD	462.9	531.2
2.2	FR38/158	T	1	TD	431.8	531.2
2.3	FR38/158	T	1	TD	399.9	531.2

In the following graphics are presented the measured maximum force for each specimen and P- δ behavior. Horizontal line shows the expected maximum force. Ductile behavior of shear connector, according to EC4, requests at least 6mm slip capacity in push test at characteristic load level ($0.9P_{max}$).

For steel sheeting with higher ribs (h_p), there is evident underestimation of headed stud shear resistance proposed by EC4. The values of reduction factors (k_l , k_t) mostly depend on value of rib height (h_p). Entire height of concrete, or height of concrete above ribs, is not taken in consideration.

Measured maximum forces for **type 1** (Fig. 14) are approximately 16% lower than EC4 analytical prediction. Request for ductility is not satisfied. Failure occurred in concrete.

Measured maximum forces for **type 2** (Fig. 15) are approximately 19% lower than EC4 analytical prediction. Specimens 2.1 and 2.3 satisfied the request for ductility, and failure occurred in concrete. Failure by shear of connectors occurred on specimen 2.2.

**Fig 14.** Load-slip curves Specim. 1.1, 1.2 and 1.3**Fig 15.** Specim. 2.1, 2.2 and 2.3

Following pictures illustrate the failure state of two specimens.



Figure 16. Specimen 1.2



Figure 17. Specimen 2.1

4. ANALYTICAL MODELS

General FE code ABAQUS was used for the FE modelling of the push-out tests specimens with elastic concrete [9]. Considering the material and geometric nonlinearities in the FE simulation, *ABAQUS/Explicit 2024* type of solver was used in the FE analysis to overcome the convergence problem. 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.

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).

An elastic-plastic stress (σ)–strain (ϵ) model with strain hardening for structural steel, which is used in the present study for steel beams has been developed by Tao et al.[10]. It should be noted that mild steel is very ductile to accommodate large deflection of the steel beam, and no fracture of the steel beam has ever been reported in the literature. Thus, steel fracture is not considered in the material model of steel beams

The steel material used for shear studs generally has good ductility. 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 ($\epsilon_u=25\epsilon_y$, $\epsilon_{u2}=90\epsilon_y$) [11].

In proces of loading the element, it is very common for part of the concrete slab to be under tension, while the remaining part is under compression. That is why a concrete damaged plasticity (CDP) module is used [12]. With this module, tension cracks and possible compressive crushing of concrete can be covered.

Following pictures illustrate the failure state of two specimens (analytical mode).

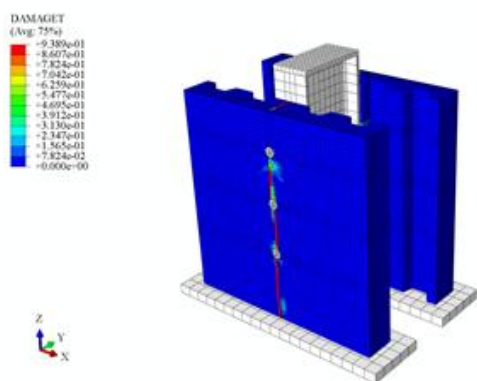


Figure 18. Specimens A 1 Parallel ribs

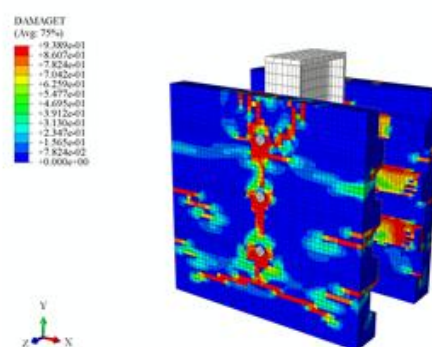


Figure 19. Specimens A 2 Transversal ribs

5. ANALYSIS OF RESULTS

The obtained results of the load-slip relationship for the test specimens and analitic mode are prezentet in fig 20-21. The designation “A.i” refers to an analytical model, and the designation “numerical 1.1 ...” to an experimental mode. A satisfactory degree of compliance of the obtained results can be observed for the two presentet models. From Fig. 20 we can conclude that the analytical calculation curve A.1 lies approximately between the experimental curves 1.3 and 1.2. While from Fig. 21 we find that the curve of the analytical calculation A.2 lies approximately between the experimental curves 2.2 and 2.3. The compliance of the failyre state for analitik and experimental mode is evident, according to Fig. 16-18 and Fig. 17-19.

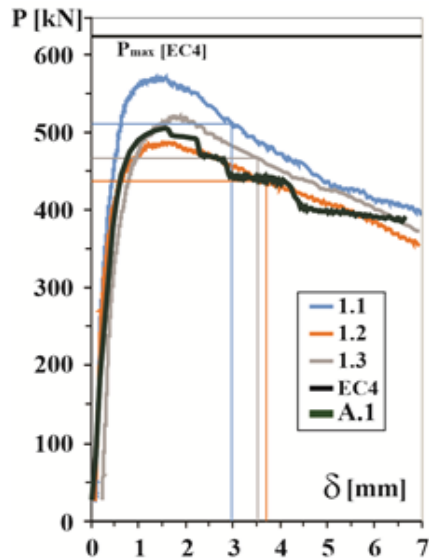


Fig. 20. Load-slip curves, eks. modes (1.1,1.2,and1.3) and analytical mode A.1

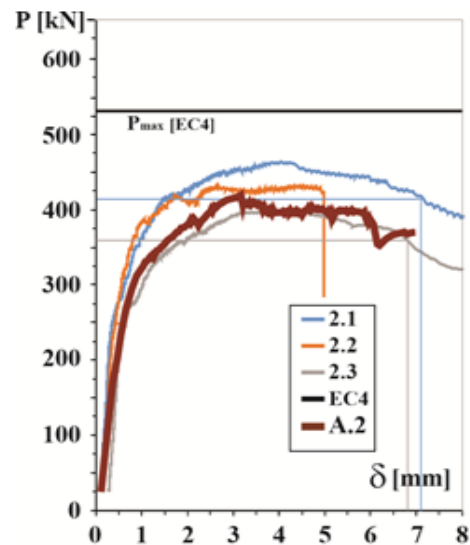


Fig. 21. Load-slip curves, eks. modes (2.1,2.2,and 2.3) and analytical mode A. 2

6. Conclusions

From the experimental investigation of the load and slip capacity of headed stud shear connectors in composite slabs for buildings, presented in this article, might be concluded:

- Based on the conducted experimental determination of the resistance of the headed stud connectors with the standard test, 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 shear resistance of through deck welded headed studs, for longitudinal position of steel sheeting, is higher than those welded through holes. There is no additional correction, or limitation, for reduction factor k_l in EC4 regarding to method of welding.
- For steel sheeting with low ratio h_c/h_p , additional experimental investigations are recommended.
- 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.

- The developed **FE** model demonstrates very good accuracy in simulating the behavior of component of push out specimens respectively composite beams. It provides valuable insights into the mechanical behavior of components that are challenging to measure through experimental tests, due to the space required to conduct the tests and the duration of the test, and the equipment needed to conduct these tests.

- The **FE** method allows for parametric analysis of the elements, enabling comprehensive results that could be used to propose an analytical design procedure consistent with Eurocode's component method design approach.

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