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АНАЛИЗА НА ОДНЕСУВАЊЕТО НА МОЖДАНИЦИ КАЈ ЛОНГИРУДИНАЛНО ПОСТАВЕНИ ЛИМОВИ И ПОЛНА ПЛОЧА

РЕЗИМЕ

Испитувањето на однесувањето на мождоници кај спрегнати конструкции со подолжно поставен лим за спрегање и испитни модели со полна бетонска плоча е дел од големо и комплексно истражување кое е спроведено на Градежениот факултет во Скопје. Примероците се дел од спрегната греда со чеп мождоници во согласност со EN 1994. Во овој труд се изнесени резултатите за максималната носивост, одлепувањето на бетонската плоча од челичниот профил како и вертикалното пролизгување на примерокот, мерени во текот на испитувањето. Испитани се по 2 примероци од секој различен попречен пресек. Начинот на испитувањето, подготовката на елементите и прикажувањето на резултатите се извршени во согласност со EN 1994-1-1.

Клучни зборови: мождоници, испитување на мождоници, спрегнати конструкции

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ANALYSIS OF THE BEHAVIOUR OF SHEAR CONNECTORS WITH LONGITUDINAL SHEETING AND SOLID SLAB

SUMMARY

The experimental analysis of headed shear studs with solid concrete slab and with longitudinal sheeting, is part of a larger and complex experiment carried out at the Faculty of civil engineering in Skopje. The tests are T-cross section beams with headed shear studs according to EN 1994. The failure load of the testing sample, the transversal separation of the concrete slab from the steel beam and the vertical slip between the concrete slab and the steel beam are fully described. The results for the shear connectors are given as “P-δ“ diagrams. The tests are carried for 2 samples of each different type of cross section. The tests are carried out according to rules, preparation and evaluation of the results in accordance with EN 1994-1-1, as described in the paper.

Keywords: shear studs, push-out test, composite structures,

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INTRODUCTION

The advancement of material properties and technologies alongside creative innovations in construction industry has challenged civil engineers to overcome greater heights and spans. The need of big surfaces with great spans has rejected the steel and concrete as autonomous materials for building this type of structures and that is where the idea of composite steel-concrete structure is born. Steel-concrete composite construction being among the fastest, economical and eco-friendly building methods, has been extensively used in building high-rise buildings, administrative buildings and bridges all around the world. The possibility of mastering large spans with beams and deck with relatively small dimensions, lighter structure for 20-40% and faster building, has made this kind of construction method very popular and eye catching among the architects and civil engineers.

Steel-concrete structure is composed of steel profile (usually welded or rolled I or H steel section) as a beam and on top of it a concrete slab. There are two types of concrete slabs in the composite structure, with and without steel sheeting and in both cases they can be in-situ casted or pre-casted. The steel sheeting is used as formwork in the casting of the deck and it also replaces tensile reinforcement in the bottom face of the slab. Shear connection and transverse reinforcement shall be provided to transmit the longitudinal shear force between the concrete and the structural steel element, ignoring the effect of natural bond between the two.

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. Shear connectors have sufficient deformation capacity to justify any inelastic redistribution of shear assumed in design. Therefore, it is necessary to determine the shear strength and stiffness of the stud connector prior to their use in construction. Among the most commonly used and widely spread connectors are the headed shear studs (Fig. 1.). The shear studs are welded through the steel sheeting with specialized stud gun as shown on Fig. 2.

Fig. 1. Headed shear connectors with ceramic ferrule

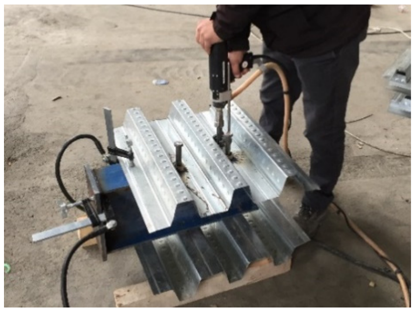

Fig. 2. Welding headed stud through steel sheeting with stud gun

As a relatively new construction method and lack of design rules, experimental analysis and testing is necessary to determine behaviour and strength of the composite structure components. The test should be carried out in a way that provides information on the properties of the shear connection required for design. The strength of the concrete needs to be determined by testing concrete cubes or cylinders under pressure, with pre-determined dimensions and age of the concrete, according to the design code. The yield strength of the steel should be determined according the design code.

The modified testing for welded headed studs welded directly on the steel beam, the topic of this paper, is part of a larger experiment carried out to give relevant data for behaviour of headed studs and behaviour of composite steel-concrete structures. The experimental trials were conducted according to the newly promoted and soon to be fully implemented legislation in Macedonia, Eurocode 4 (EN1994). The large scale push-out test is conducted on two identical specimens for each type of steel sheet position (longitudinally or transversally referring to the steel beam), different number of shear studs in cross-section (single and double) and also different types of sheeting (BONDECK, HIDECK and F38-158) all of which are widely used in buildings and bridges in Macedonia. This experimental trial is the largest of its kind in the region and it has given relevant data for designing and building steel-concrete composite structures.

1. STANDARD 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 modified push test should be used.

1.1. Preparation of samples

Specific push test should be carried out such 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. The length of each slab should be related to the longitudinal spacing of the connectors in the composite steel-concrete structure. The width of each slab should not exceed the effective width of the slab of the beam. The thickness of each slab should not exceed the minimum thickness of the slab in the composite beam. The slab should have the same haunch and reinforcement as the beam.

The slabs are casted horizontally, as they would be casted if part of a composite structure. First it is casted one of the sides and then the sample is turned and the other side is casted. The concrete should be air-cured as the composite beams in practice.

From each concrete mix it should be taken minimum of four concrete specimens (cylinders or cubes with predetermined dimension according to Eurocode) for determination of the cylinder strength of the concrete for each of the sides of the sample. The concrete specimens should be 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, if used, need to be determined.

1.2. Testing procedure and evaluation

For both, the standard and the modified test, the procedure is the same. The load is 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 is finished, subsequent load increments should then be imposed up until failure in the sample 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 or at each load increment. The slip should be measured at least until the load has dropped to 20% below the maximum load that is applied. The transverse separation between the slap and the steel section should be measured as close as possible to each group of connectors.

If the results of three tests on nominally identical specimens does not exceed 10%, the design resistance may be determined as follows:

- the characteristic resistance P_{Rk} should be taken as the minimum failure load (divided by the number of connectors) reduced by 10%;
- the design resistance P_{Rd} should be calculated from:

$$P_{Rd} = \frac{f_u}{f_{ut}} \cdot \frac{P_{Rk}}{\gamma_v} \leq \frac{P_{Rk}}{\gamma_v} \tag{1}$$

Where:

- f_u is the minimum specified ultimate strength of the connector material;
- f_{ut} is the actual ultimate strength of the connector material in the specimen;
- γ_v is the partial safety factor for shear connection.

If the deviation exceeds 10%, at least three more samples of the same kind should be made. The test evaluation should then be carried out in accordance with EN 1990, Annex D.

The slip capacity of the sample δ_u should be taken as the maximum slip measured at the characteristic load level. The characteristic slip capacity δ_{uk} is the minimum test value of δ_u reduced by 10% or determined by statistical evaluation from all the results, according to EN 1990, Annex D.

2. MODIFIED TEST

There are two types of samples that are tested and part of this paper. Sample 1 is with longitudinal sheeting as shown on Fig. 3 and sample 2 is with concrete slabs without steel sheeting as shown on Fig. 4. Both of the testing samples are constructed with IPE270 steel profile, 600mm in length, as main steel beam, made of steel S275JR, with yield strength f_y=275N/mm^2. The slab thickness is 120mm and the concrete strength class for one side is C35/45 and the other side is C25/30 according to EN 1992-1-1, Table 3-1. The reinforcement is Q188 (Ø6/15cm) and meets the requirements for reinforcement according to the Eurocode. The cover of the reinforcement is 20mm and meets the minimum cover thickness of 15mm. At the top of the beam, steel plate with dimensions 170x300mm and thickness d=15mm is welded for receiving the force and underneath, welded to the web of the profile, there are two UPN120 profiles, 150mm in length, one at each side, for increasing the rigidity of the detail. The steel sheeting for one type of the test sample is BONDECK 600 with thickness t=1.0mm. The shear studs are NELSON with diameter d=19mm and total height h_{SC}=100mm and are welded directly to the steel beam in both cases. The sample without steel sheeting is reinforced in two zones, while the other one is only reinforced near the outside face of the slab.

The slabs are casted horizontally, as it would be casted the composite beam in reality. First one side is casted and after 14 days the samples are turned to the other side and concrete is poured once again. The samples are air-cured as the real composite beam will be in practice. After 14 days from the concreting of the second side, they are put in vertical position, ready for testing. The bottom face of the samples is bedded in exmal (mortar) with approximately 40mm thickness for leveling while testing and eliminating any eccentricity due to uneven casting of the concrete. All the dimensions and technical data for the samples are presented in Fig. 3 and Fig. 4.

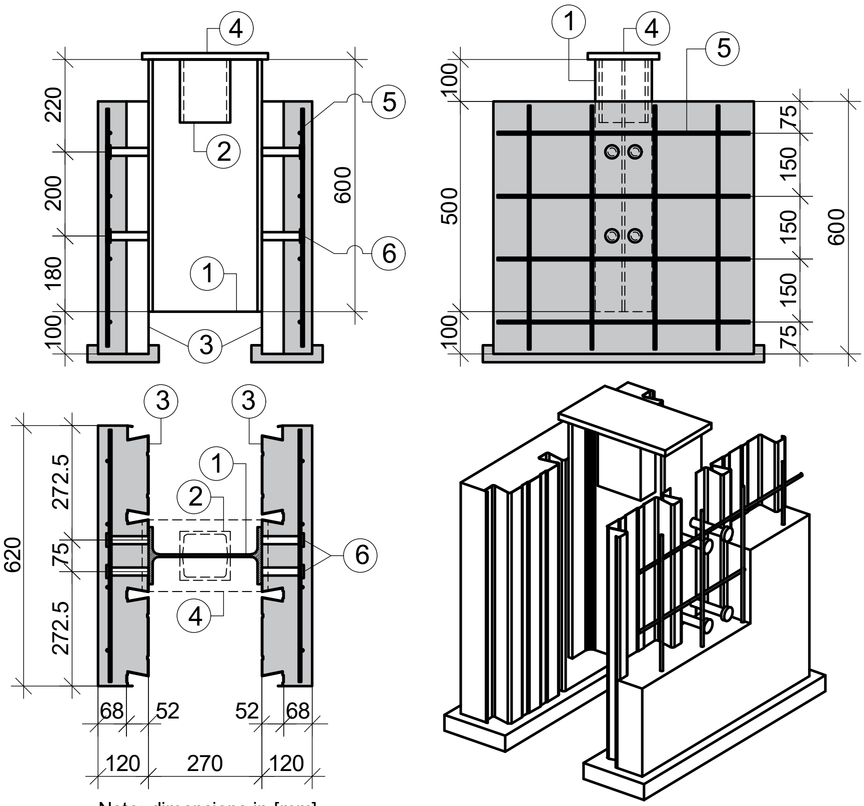

Fig. 3. Details of modified test with longitudinal sheeting

Where, 1) IPE270; 2) UPN120; 3) BONDECK 600; 4) Steel plate; 5) Reinforcement Q188; 6) Headed shear studs NELSON.

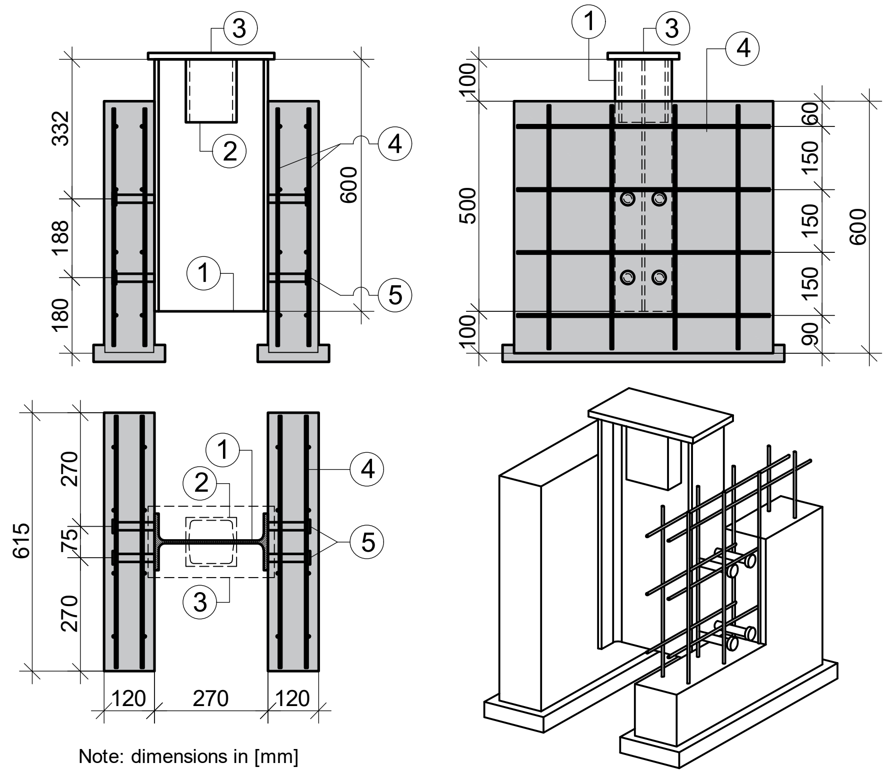

Fig. 4. Details of modified test without steel sheeting

Where, 1) IPE270; 2) UPN120; 3) Steel plate; 4) Reinforcement Q188; 5) Headed shear studs NELSON.

Where: 1) 100 tons press; 2) electronic dynamometer; 3) electronic comparators 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) electronic comparator for measuring the longitudinal (vertical) slip (U10 on one side and U9, U11 on the other).

Fig. 5. Casting of the concrete

2.1. Testing the strength of the concrete

For each mix of concrete, for casting both of the sides of the samples, six cubes are taken for testing the strength of the concrete. The cubes are with standard predetermined dimensions of 15/15/15cm according to EN 12390-1, filled and cured according to EN 12390-2 The minimum characteristic compressive strength for C25/30 is 21N/mm^2 for cylinder and 26N/mm^2 for cube and for concrete C35/45 the minimum characteristic strength is 30N/mm^2 for cylinder and 38N/mm^2 for cube. The testing results are assessed according to EN 13791:2007 (Testing of concrete). The estimated characteristic strength of the test is the lower value of:

$$f_{ck} = f_m - 1.48 \cdot \sigma \qquad (2)$$

Where:

- f_{ck} is characteristic compressive strength of standard specimen;
- f_m is mean compressive strength of the test results;
- σ is standard deviation.

According to EN 1992, for concrete C25/30, the strength of cylinder is $f_{ck,cyl}$=25N/mm^2 and the strength of cube is $f_{ck,cube}$=30N/mm^2. For concrete C35/45, the strength of cylinder is $f_{ck,cyl}$=35N/mm^2 and the strength of cube is $f_{ck,cube}$=45N/mm^2.

For each concrete mix, three of the samples are tested on the 28th day after casting the push-out test samples. Due to the size of the test for behavior of shear studs, which included 29 samples with different variations of the number of shear studs and the position of the steel sheeting, the other three samples are tested on two occasions, throughout the testing of the modified test samples, or on the 62nd day from the casting of the first side of the test sample or 83rd day from the casting of the second side.

The test results from the compressive test for the first three cubes of the first cast, are with standard deviation of 0.55 and the compressive strength of the cubes is $f_{ck,cube}$=46.8N/mm^2. The other three cubes from the first cast resulted with compressive strength of is $f_{ck,cube}$=54.1N/mm^2 and standard deviation for this results is 1.23. For the casting of the other side of the push-out test sample, the results are with standard deviation of 0.60 and the compressive strength of the cubes is $f_{ck,cube}$=30.8N/mm^2. For the second testing of the cubes from the second cast, the compressive strength of the cubes is $f_{ck,cube}$=35.2N/mm^2 ad standard deviation of 0.70. All the results are in accordance with EN 1992.

2.2. Testing the strength of the steel

The characteristic tensile strength, yield strength of the steel beam, the steel sheeting, reinforcement and shear studs, elements that are part of the push-out test samples, are determined.

The reinforcement steel is class B, in accordance with EN 1992-1-1, Annex C, table C.1 and C.3N, with yield strength of f_{yk}=597N/mm^2, tensile strength f_{uk}=662N/mm^2, with $k=f_{uk}/f_{yk}$=1.11 and ε_{uk}=9.9%.

The steel for the headed studs is class S235J2+C450, in accordance with EN 13918, with yield strength f_y=502N/mm^2, tensile strength f_u=552N/mm^2, with $k=f_u/f_y$=1.10 and δ=18.5%.

The steel for the steel sheeting deck is class S550GD Z275, in accordance with EN 10147, with yield strength fy=675MPa, tensile strength fu=770MPa, with k=fu/fy=1.14 and δ=24.6%.

The steel for the beam is class S275JR, in accordance with EN 1993, with yield strength f_y=275N/mm^2, tensile strength f_u=424N/mm^2, with $k=f_u/f_y$=1.54 and ε_u=18.9%.

2.3. Test description

The testing procedure is carried out according to rules and recommendations in EN 1994, Annex B. All of the samples are tested with the same equipment and the same testing conditions. First the load is applied until it reaches 5% of the expected failure load without partial safety coefficient. Then the load is cycled 25 times between 5% and 40% of the expected failure load. After the 25th cycle, from 5%, the load is increased until failure is achieved in one or more of the elements of the test sample, but it is important that failure does not occur in less than 15 minutes. The load is applied with 100-ton press and the force is regulated with electronic dynamometer.

The electronic comparators and the electronic dynamometer are connected to HBM Quantum and HBM Spider 8, data acquisition system amplifiers, directly connected to personal computer. The measurement is conducted with a frequency of 5 readings per second and it is carried out in real time through the whole testing period. The accuracy of the testing equipment is in range of ±1.5%.

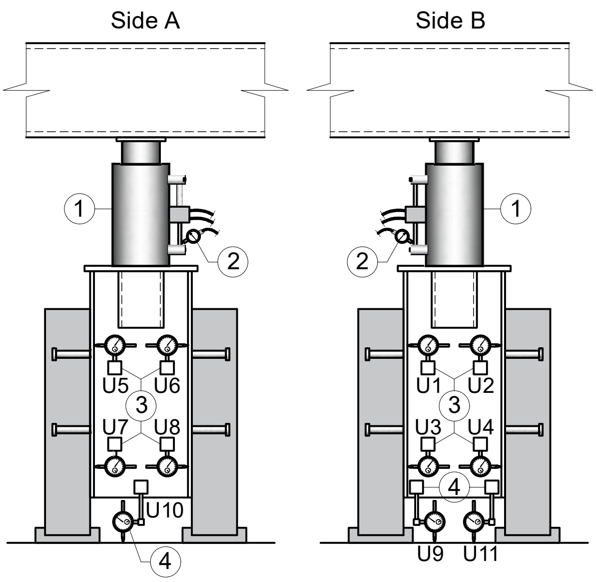

Fig. 6. Placement of the equipment

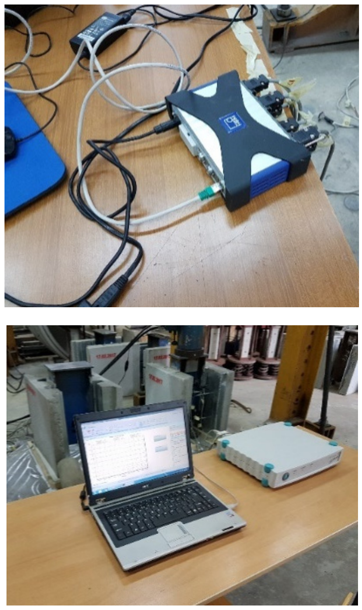
Fig. 7. Testing equipment (HBM Quantum and HBM Spider 8)

Where: 1) 100 tons press; 2) electronic dynamometer; 3) electronic comparators 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) electronic comparator for measuring the longitudinal (vertical) slip (U10 on one side and U9, U11 on the other).


Fig. 8. Sample with longitudinal sheeting


Fig. 9. Sample with solid concrete slab

2.4. Analysis of the design resistance and expected results

The analysis of the design resistance of the shear connectors in a composite beam is made according to EN 1994-1-1 (6.6.3.1), for headed studs, type Nelson with diameter d=19mm and length of the stud h_{sc}=100mm (h_{sc}/d=5.26). The headed studs are welded directly on the steel beam with specialized stud gun in both cases. The sheeting for sample 1 is BONDECK 600 with t=1.0mm thickness.

The design shear resistance for headed studs automatically welded in accordance with EN 14555 and $h_{sc}/d>4$, is determined according to EN 1994-1-1, (6.18). (6.19) and (6.21).

$$P_{Rd}^{(1)} = \frac{0.8 \cdot f_u \cdot \pi \cdot d^2 / 4}{\gamma_V} = \frac{0.8 \cdot 500 \cdot \pi \cdot 19^2 / 4}{1.25} \cdot 10^{-3} = 90.68\,\text{kN} \quad (3)$$

$$P_{Rd}^{(2)} = \frac{0.29 \cdot \alpha \cdot d^2 \cdot \sqrt{f_{ck} \cdot E_{cm}}}{\gamma_V} = \frac{0.29 \cdot 1 \cdot 19^2 \cdot \sqrt{25 \cdot 31 \cdot 10^3}}{1.25} \cdot 10^{-3} = 73.73\,kN \quad (4)$$

Where:

- f_{ck} is characteristic compressive strength of standard specimen;
- f_u is specified ultimate strength of the stud connector;
- γ_v is partial safety coefficient, recommended value is 1.25;
- h_{sc} is overall height of the shear stud;
- d is the diameter of the headed shear stud.
- α=1 for $h_{sc}/d>4$ ($h_{sc}/d=5.26$).

The design resistance of one headed stud is the smaller value from the previous two equations.

$$P_{Rd} = \min\left(P_{Rd}^{(1)}, P_{Rd}^{(1)}\right) = 73.73\,kN \quad (5)$$

For sample 2, the expected results, without the partial safety coefficient, for 4 shear studs per side is:

$$P_{Rd} = 4 \cdot 2 \cdot 1.25 \cdot 73.73 = 737.3\,kN \quad (6)$$

For sample 1, the expected results, without the partial safety coefficient, for 4 shear studs per side it is calculated with the same principals as the sample 2, only this time the shear resistance is multiplied by the reduction coefficient k_l given in EN 1994-1-1 (6.22) or a maximum value of 1.0.

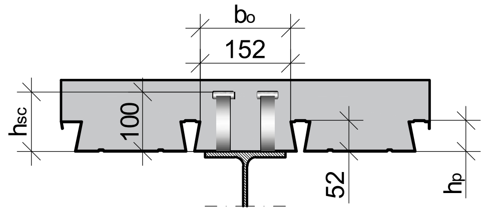

Fig. 10. Steel sheeting, headed studs and concrete slab

$$k_l = 0.6 \cdot \frac{b_o}{h_p} \cdot \left(\frac{h_{sc}}{h_p} - 1\right) = 0.6 \cdot \frac{165}{52} \cdot \left(\frac{100}{52} - 1\right) = 1.75 \Rightarrow k_l = 1.0 \quad (7)$$

From the previously highlighted, the shear resistance for sample 1 is:

$$P_{Rd} = 4 \cdot 2 \cdot 1.25 \cdot 73.73 \cdot 1.0 = 737.3\,kN \quad (8)$$

3. RESULTS FROM THE TESTING

The results from the testing are summed up in Table 1, where the measured strength of the force of failure (P_{Rd}) for all of the test subjects for eight shear studs, and also the analyzed values of the strength of one headed stud are given.

Sample	P_{Rd} [kN]	$P_{Rd,U}$ [kN]	$P_{Rk,U}$ [kN]	P_{Rk} [kN]	f_u/f_{ut}	$P_{Rd,(1)}$ [kN]	difference [%]	$P_{Rd,D}$ [kN]
1-1	73.73	737.3	830.60	747.54	0.996	74.45	0.98	**74.63**
1-2		737.3	834.45	751.00		74.80	1.45	
2-1	73.73	737.3	944.54	850.09	0.996	84.67	14.84	**79.97**
2-2		737.3	839.71	755.74		75.27	2.09	

Table 1. Results from the testing

Where: P_{Rd} is designed resistance for one headed stud including safety coefficient factor in accordance to EN 1994-1-1, $P_{Rd,U}$ is ultimate design resistance of eight shear studs, without the partial safety coefficient, $P_{Rk,U}$ is ultimate design resistance measured from the testing, PRk is reduced ultimate resistance of eight shear studs from the testing, according to EN 1994-1-1, B2.5 ($P_{Rk}=0.9 \cdot P_{Rk,U}$), $P_{Rd,(1)}$ is design resistance of one headed stud including the partial safety factor, according to equation (1) and $P_{Rd,D}$ is average value of the design resistance of one headed shear stud.

Sample 1 resulted with slightly greater design resistance, 0.98% for the first sample and 1.45% for the second sample. From the obtained results, the design resistance for one headed stud, in composite steel-concrete beam with longitudinal sheeting, is $P_{Rd,D}$=74.63kN>P_{Rd}=73.73kN. Sample 2 also resulted with greater design resistance of the shear studs, 14.84% for the first sample and 2.09% for the second sample. The design resistance for one headed stud in a solid slab is $P_{Rd,D}$=74.63kN>P_{Rd}=73.73kN. From the previously stated, the headed shear studs part of this experiment, both with steel sheeting and the solid slab, meet the requirements given in EN 1994.

On Fig. 11 it is given the force vs. slip (P-δ) diagram for cyclic loading of every specimen separately. All of the samples were loaded 25 times from 5% of the mathematically predicted design resistance until 40% of the predicted design resistance for eight headed studs. First two diagrams are for the Sample 1 (up left and right) and the second two diagrams are for sample 2 (down left and down right).

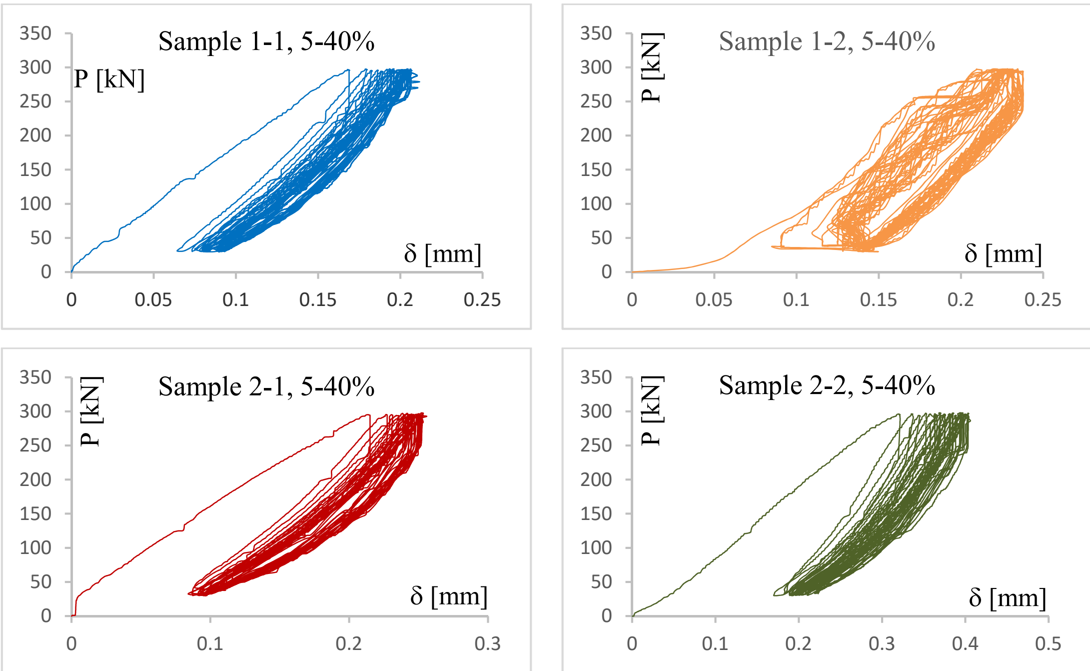

Fig. 11. Force vs. slip (P-δ) diagrams

On Fig. 12 it is given the determination of the slip capacity from force vs. slip (P-δ) diagrams for one headed stud. The upper two diagrams are for sample 1 and the lower two diagrams are for sample 2. The readings of P=93.44kN for sample 1-1, P=93.88kN for sample 1-2, P=106.26kN for sample 2-1 and P=94.47kN for sample 2-2, are reduced ultimate design resistance $P_{Rk,(1)}=0.9 \cdot P_{Rk,U}$ for one shear stud. From there it is determined the value of the slip capacity, where for sample 1-1 it is δ_U=7.61mm, for sample 1-2 it is δ_U=8.19mm, for sample 2-1 it is δ_{U2-1}=7.79mm and for sample 2-2 it is δ_{U2-2}=10.21mm. According to EN 1994, Annex B, the slip capacity for sample 1 (1-1 and 1-2) is δ_U=8.19mm and the characteristic slip capacity for sample 1 (1-1 and 1-2) $\delta_{uk}=0.9 \cdot \min(\delta_U)=0.9 \cdot 7.61$=6.85mm. For sample 2 (2-1 and 2-2) the slip capacity is δ_U=10.21mm and the characteristic slip capacity is $\delta_{uk}=0.9 \cdot 7.79$=7.01mm.

There are no significant measured values of transverse separation between the steel beam and the concrete slab.

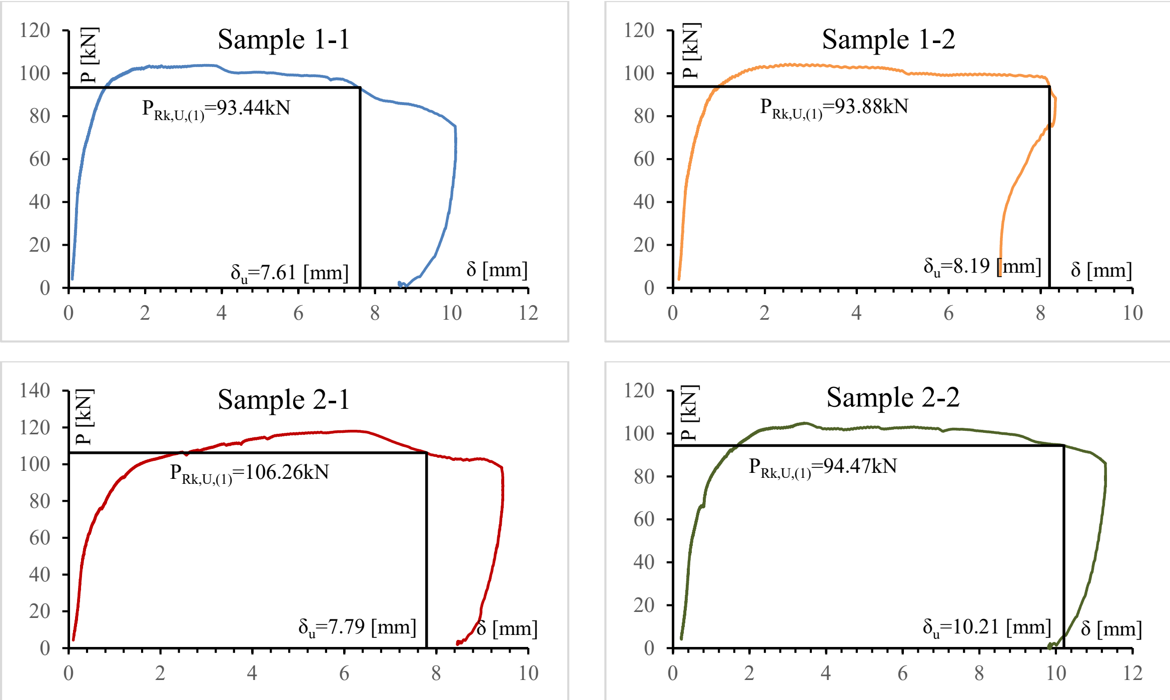

Fig. 12 Slip capacity determination for sample 2 (2-1 and 2-2), force vs. slip (P-δ) diagram

4. CONCLUSION

The measured design resistance for T-cross section with longitudinal sheeting Bondeck 600 is $P_{Rd,D}$=74.63kN and it is greater than the analytically determined design resistance P_{Rd}=73.73kN. For T-cross section with solid concrete slab, the measured design resistance is $P_{Rd,D}$=79.97kN and is also greater than the expected value of P_{Rd}=73.73kN. Previous studies at the faculty, with transversal Bondeck 600 sheeting, also show measured design resistance greater than the expected.

The characteristic slip capacity, in all of the samples that are elaborated in this paper, is greater than the minimum δ_{uk}=6mm, according to EN 1994-1-1 and that means that the shear connectors are ductile. This is not the case with transversal sheeting, where the characteristic slip capacity is smaller than the minimum value in EN 1994-1-1, as stated in previous tests and studies carried out at the Faculty.

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