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TESTING THE BEHAVIOR OF SHEAR CONNECTORS

SUMMARY

The testing of the behavior of shear connectors is a part of complex experimental and theoretical research of the behavior of continuous composite (steel and concrete) beams. In this report the results are given form the modified testing of the shear connectors as "P-δ" diagrams. The modified test is carried for three samples with elements of the cross section as same as the cross section of the main researched beam, but in accordance with the rules given in EN 1994. Also a short description for the rules, preparation and evaluation of the standard test procedure is given, in accordance with EN 1994-1-1, Annex B.

Keywords: composite structures, shear connectors, studs

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ИСПИТУВАЊЕ НА ОДНЕСУВАЊЕ НА МОЖДАНИЦИ

РЕЗИМЕ

Испитувањето на однесување на можадиците претставува дел од едно комплексно експериментално и теориско истражување на однесувањето на спрегнати континуирани греди. Во ова соопштение дадени се резултатите од модифицираното испитување на мождуниците во вид на "P-δ" дијаграми. Модифицираното испитување е извршено на три примероци со елементи на попречниот пресек исти како и за главната греда која е крајна цел на истражувањето, во согласност со EN 1994. Исто така даден е мал осврт на правилата за стандрадно испитување на мождуници во согалсност со EN 1994-1-1, Анекс B.

Клучни зборови: спрегнати конструкции, мождуници, чеп мождуници

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1. STANDARD TESTING OF SHEAR CONNECTORS

The rules for the standard testing on shear connectors are given in EN1994, Eurocode 4: Design of composite steel and concrete structures, Part 1-1: General rules for buildings, Annex B.

If the design rules according to EN 1994 are not applicable, the design must be based on tests according to the needs of the real structure. The tests must provide information for the properties and the behavior of the shear connectors required for the design and in accordance with the mentioned European standard.

The testing for the behavior of the shear connectors, is also recommended for more accurate designing for composite steel and concrete structures, with real behavior of the structures and the connection of the two different materials, steel and concrete.

The geometry, the mechanical properties of the slab, the shear connectors and the reinforcements are the variables that determine the results of the testing. The resistance to loading it's determined with push tests on previously made (minimum three) testing specimens.

1.1. Testing arrangements and preparation of specimens

If the shear connectors are part of T-beam with uniform concrete slab (or with haunches), standard testing is used for determination of the behavior of the shear connectors. In other cases, with use of profiled steel sheeting decks, longitudinal or transversal to the length of the beam, a modified (specific) test can be used.

For the standard test the dimensions of the test specimen are given in Figure 1, according to the rules given in EN 1994.

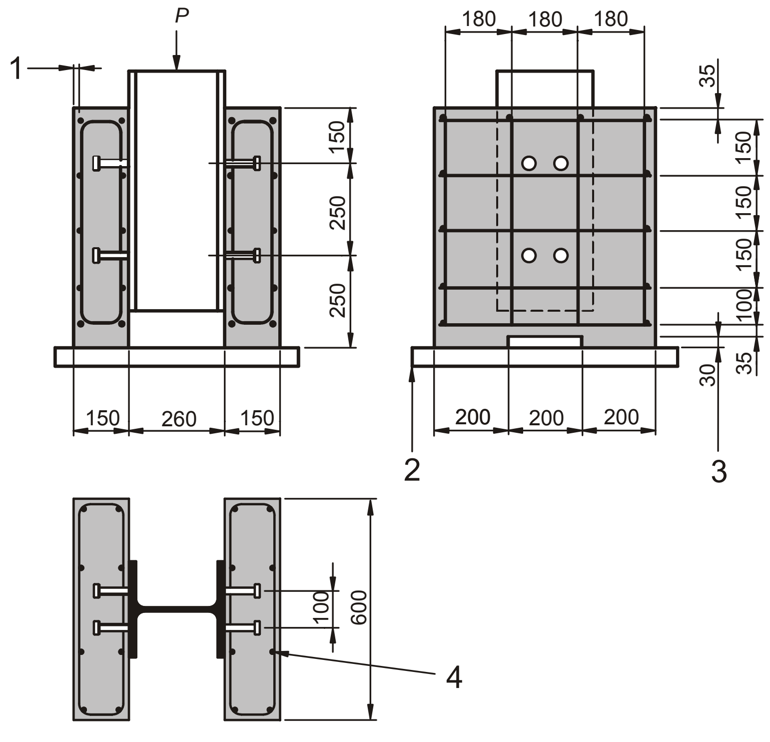

Figure 1. Test specimen for standard testing

Where:

1) cover 15mm
2) bedded in mortar or gypsum
3) recess optional
4) reinforcement ribbed bars *Ø10*, $450 \leq f_{sk} \leq 550\ N/mm^2$, steel section *HEB260* or *UC254*

For modified (specific) tests the dimensions and the arrangement of the parts that create the cross section must be as the designed, but according to the following rules:

a) the length "l" of each slab should be related to the longitudinal spacing of the connectors in the composite structure

b) the width "b" of each slab should not exceed the effective width of the slab of the beam

c) the thickness "h" of each slab should not exceed the minimum thickness of the slab in the beam

d) the slabs should have the same haunch and reinforcement as the beam

The casting of the concrete slabs are in horizontal position, as for the real composite beam, and the specimen should be air-cured. For each mix of concrete minimum three specimens of cylinders or cubes should be prepared for determination of the concrete strength "f_{cm}". The compressive strength "f_{cm}" at the time of testing must be 70% ± 10% of the specified strength of the concrete "f_{ck}" of the beams for which the test is designed.

The yield strength, the tensile strength and the maximum elongation of a representative sample of the shear connector material, steel beam and steel sheeting (if used) should be determined.

1.2. Testing procedure and evaluation

The testing procedure is the same for the standard and for the modified (specific) tests. The load is applied in increments up to 40% of the expected failure load and cycled 25 times between 5% and 40%.

After the cycled loading, subsequent load increments are imposed until failure occur in not less than 15 minutes. The longitudinal slip between the concrete and the steel section should be measured continuously until the load has dropped to 20% below the maximum load. Also, the transverse separation between the steel section and the concrete should be measured.

If the results of the three specimens does not exceed 10%, the design resistance can be determined as follows:

- the characteristic resistance "P_{Rk}" should be taken as the minimum failure load reduced by 10%
- the design resistance "P_{Rd}" should be calculated as given in (1)

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

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 from the man exceeds 10%, three more tests should be made, and the test evaluation should be carried in accordance with EN 1990, Annex D.

The slip capacity "δ_u" is 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 statistical evaluation from all the results in accordance with EN 1990, Annex D.

2. MODIFIED TESTING OF SHEAR CONNECTORS

The modified test sample is T-beam cross section with *IPE270* as main steel beam, with transversal steel sheeting deck *Bondeck 600* with stud shear connector thru deck welded with diameter $d=19mm$ and height $h_{sc}=100mm$. The concrete slab thickness is 52+58=110mm, where 52mm is the height of the steel sheeting deck, and 58mm is the continuous concrete plate, reinforced with *Q273* (*Ø6/100mm*), as showed in figure 2. The concrete strength class is *C25/30* according to EN 1992-1-1, Table 3.1.

At the top of the steel beam, detail for receiving the force is constructed from steel plate *200x300x15mm* and *UNP100* profiles as stiffeners. The bottom face of the concrete slab is bedded in mortar (Exmal) with thickness approximately of 50mm.

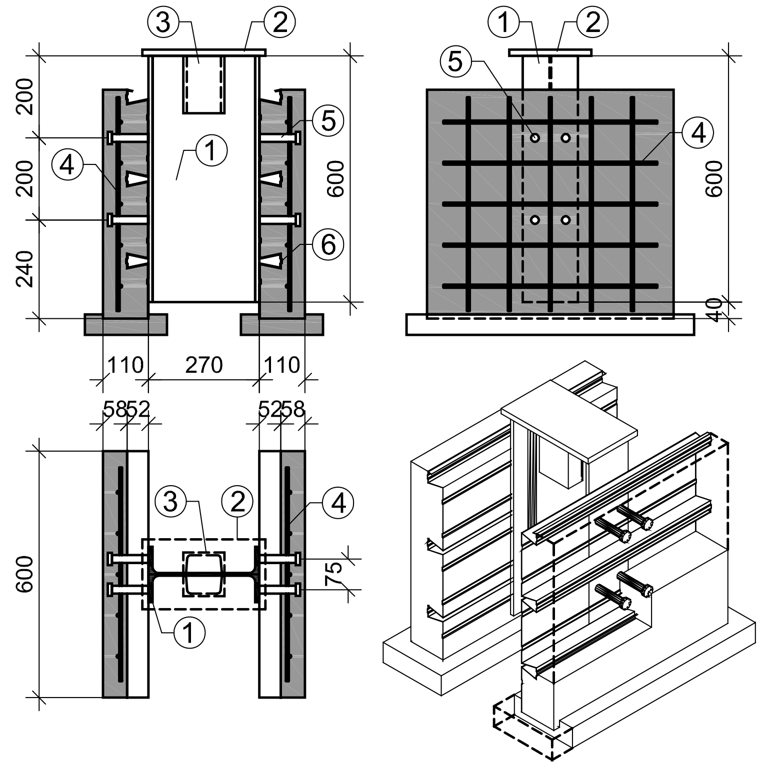

Figure 2. Test specimen for modified (specific) testing

Where:

1) steel beam *IPE200*
2) steel plate *200x300x15mm*
3) *UNP100* as stiffener
4) reinforcement *Q283* (*Ø6/100mm*)
5) headed stud (*Nelson*) $d=19mm$, $h_{sc}=100mm$
6) steel sheeting deck *Bondeck 600*

The casting of the concrete slabs was made in horizontal position, as the casting of the main continuous beam. After seven days the samples were rotated for 180 degrees and the second composite slab was casted in horizontal position with concrete of same strength class.

Figure 3. Casting of the concrete for the modified testing specimens

2.1. Testing the strength of the concrete

After every casting of the concrete a sample was taken for testing the strength of cubes with dimensions 150x150x150mm. The testing of the cubes for the strength of the concrete was carried out on the 29th day form the casting of every concrete slab. For concrete strength class C25/30, according to EN 1992, the strength of cylinder is $f_{ck}=25N/mm^2$, and the strength of cube is $f_{ck,cube}=30N/mm^2$.

Cast	Cubes	age of conc. [days]	density [kg/m^3]	force [kN]	strength [MPa]	σ [stan.dev.]	$f_{ck,cube}$ [N/mm^2]	difference [%]
Casting 1	K 1	29	2416	775.2	34.5	1.95	31.71	+5.7
	K 2	29	2405	736.4	32.7			
	K 3	29	2405	824.3	36.6			
Casting 2	K 4	29	2416	775.2	30.6	0.46	30.19	+0.6
	K 5	29	2405	736.4	30.6			
	K 6	29	2405	824.3	31.4			

Table 1. Concrete characteristics

For the time needed for the application of the measuring and loading equipment, the test specimens were tested on the 34th, 35th and 38th day from the casting of the concrete slab, or 5th, 6th and 9th day from the testing of the concrete samples.

2.2. Testing the strength of the steel

The yield strength, the tensile strength and the maximum elongation of a representative sample of the shear connector material, steel beam, reinforcement and steel sheeting is 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 $\varepsilon_{uk}=9.9\%$.

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 $\delta_5=18.5\%$.

The steel for the steel sheeting deck is class S550GD Z275, in accordance with EN 10147, with yield strength $f_y=675N/mm^2$, tensile strength $f_u=770N/mm^2$, with $k=f_u/f_y=1.14$ and $\delta=24.6\%$.

The steel for the beam is 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 $\varepsilon_u=18.9\%$.

The results from the testing of the steel (reinforcement, headed suds, steel sheeting and steel beam) meet the requirements from EN 1992 and EN 1993.

2.3. Testing process

The three samples for the modified (specific) testing of the behavior of the shear connectors are tested in the same environment, with the same testing equipment and testing conditions.

The testing is carried out according to EN 1994, with cycled loading with first step of loading from 0% to 40%, then 25 cycles of loading from 5% to 40%. After the cycled load, the samples were loaded until failure in time not less than 15 minutes.

For the need of the testing, measuring and loading equipment is used. The load is applied through 100 ton press where the force is regulated with electronic dynamometer. The longitudinal slip between the steel and the concrete is measured with 3 electronic comparators. The transverse separation between the concrete slab and the steel section is measured with 4 electronic and 4 dial comparators. The accuracy of the testing equipment is in the range of ±3%.

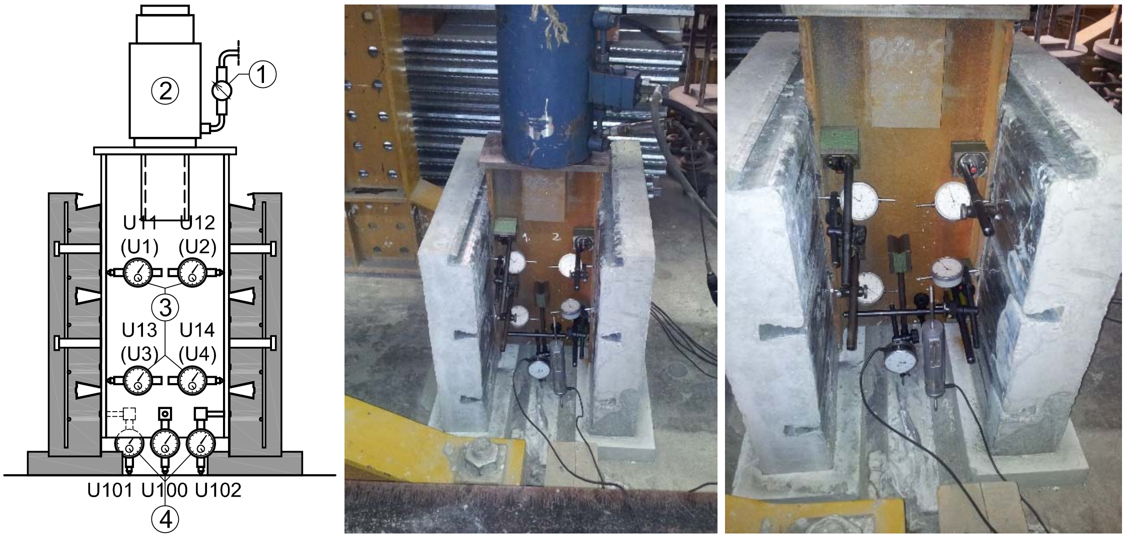

Figure 4. Disposition of the loading and measuring equipment

Where:

1) dynamometer for load measuring
2) 100 ton press for load application
3) dial (U11-U14) and electronic (U1-U4) comparators for transverse separation
4) electronic comparators (U101 left, U100 middle, U102 right) for longitudinal slip

The electronic equipment is connected to HBM Quantum data acquisition system amplifier with direct connection to computer. The measuring of the electronic equipment is carried out through the whole testing in real time.

2.4. Analysis of the design resistance and expected results

The analysis of the design resistance of the shear connectors is made in accordance with EN 1994-1-1 (6.6.3.1), for headed stud type Nelson with $d=19mm$ and $h_{sc}=100mm$. The headed studs are thru deck welded to the beam. The steel sheeting is type *Bondeck 600* with thickness of $t=1.0mm$.

The design resistance of the headed stud, automatically welded thru deck in accordance with EN 14555, is determined according to EN 1994-1-1, (6.18), (6.19) and (6.21)

$$P_{Rd}^{(1)} = \frac{0.8 \cdot f_u \cdot \pi \cdot d^2 / 4}{\gamma_V} = 90.68kN \tag{2}$$

$$P_{Rd}^{(2)} = \frac{0.29 \cdot \alpha \cdot d^2 \cdot \sqrt{f_{ck} \cdot E_{cm}}}{\gamma_V} = 73.73kN \tag{3}$$

$$\text{where } \alpha = 1 \text{ for } h_{sc} / d = 5.26 > 4 \tag{4}$$

$$min\left(P_{Rd}^{(1)}, P_{Rd}^{(2)}\right) = P_{Rd}^{(2)} = 73.73kN \tag{5}$$

Where:

f_u is specified ultimate tensile strength of the stud, not greater than 500N/mm^2

f_{ck} is characteristic cylinder compressive strength at the age considered

γ_v is the partial safety factor for shear connection, recommended value 1.25

h_{sc} is the overall nominal height of the stud

d is the diameter of the stud

For steel sheeting with ribs transverse to the length of the beam, reduction factor is calculated according to EN 1994-1-1, (6.23)

$$k_t = \frac{0.7}{\sqrt{n_r}} \cdot \frac{b_o}{h_p} \cdot \left(\frac{h_{sc}}{h_p} - 1 \right) = 1.47 > 1 \tag{6}$$

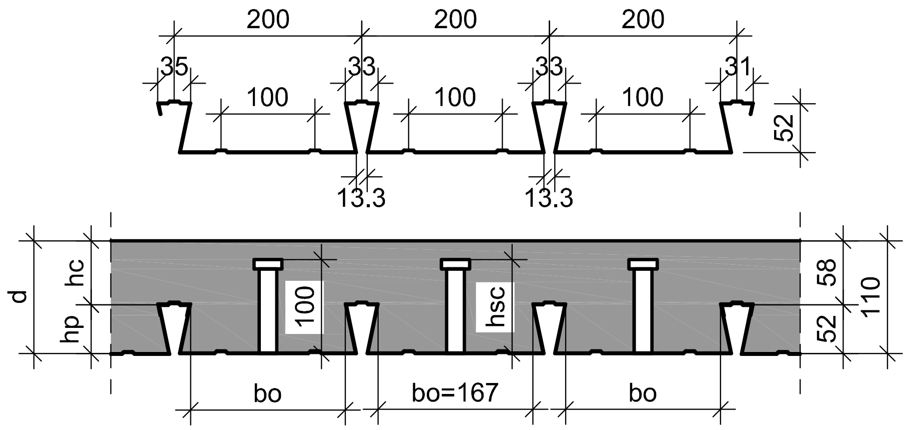

Figure 5. Sheeted steel *Bondeck 600* with thickness $t=1.0mm$, headed studs and concrete slab

For value of the reduction factor $k_t>1$, table 6.2 form EN 1994-1-1 is used, where the upper limit for the reduction factor is $k_{t,max}$= 0.70.

$$P_{Rd} = k_t \cdot P_{Rd}^{(2)} = 51.61kN \tag{7}$$

The expected results, including the partial safety factor $\gamma_v=1.25$, for 4 studs per side is:

$$P_{Rd,U,\gamma v} = 2 \cdot 4 \cdot 51.61 = 412.88kN \tag{8}$$

The expected real result of the resistance of the studs, without the partial safety factor, for 4 studs per side is:

$$P_{Rd,U} = 1.25 \cdot 412.88 = 516.10kN \tag{9}$$

2.5. Results from the testing

In table 2 the results from the testing of the three specimens are given with the measured strength of the force of failure ($P_{Rk,U}$), and the analyzed values of the strength of one headed stud.

Specimen	P_{Rd} [kN]	$P_{Rd,U}$ [kN]	age of conc [days]	$P_{Rk,U}$ [kN]	P_{Rk} [kN]	f_u/f_{ut}	$P_{Rd,(1)}$ [kN]	difference [%]	$P_{Rd,D}$ [kN]
П 1	51.61	516.10	34	602.86	542.57	0.996	54.04	+4.71	51.84
П 2			35	561.82	505.64		50.36	-2.42	
П 3			38	578.02	520.22		51.81	+0.39	

Table 2. Results from the testing

Where:

P_{Rd} is design resistance of one stud including the partial safety factor

$P_{Rd,U}$ is ultimate design resistance of eight studs, without the partial safety factor

$P_{Rk,U}$ is ultimate design resistance of eight studs from the testing

P_{Rk} is reduced ultimate design resistance of eight studs from the testing, according to EN 1994-1-1, B.2.5, $P_{Rk}=0.9 \cdot P_{Rk,U}$

$P_{Rd,(1)}$ is design resistance of one stud including the partial safety factor from the testing

$P_{Rd,D}$ is design resistance for the stud from the three specimens, statistical evaluated from all the results in accordance with EN 1990, Annex D.

The difference in negative resistance of -2.42% is in the range of the accuracy of the testing equipment of ±3%. The deviation of the results from the three specimens is not bigger than 10%, and with the design value of $P_{Rd,D}=51.84kN>P_{Rd}=51.61kN$, can be concluded that the headed studs meet the requirements given in EN 1994.

In figure 6.a, 6.b and 6.c are given the "P-δ" diagrams from the cyclic loading of every specimen separately.

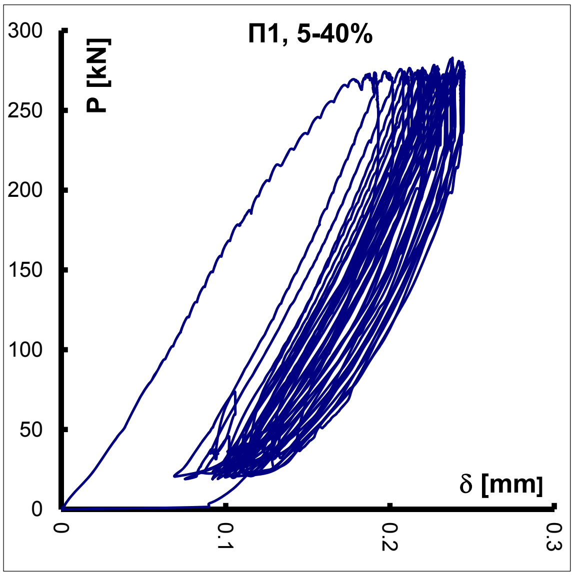

Figure 6.a. "P-δ" diagram, specimen П1

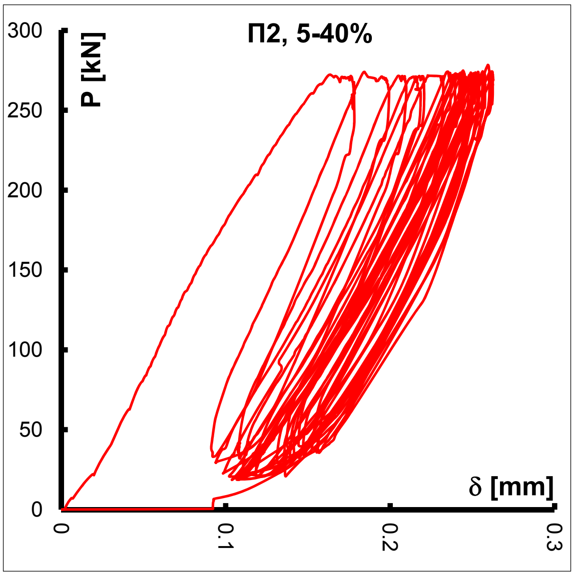

Figure 6.b. "P-δ" diagram, specimen П2

In figure 6.d is given the determination of the slip capacity "δ_u" in accordance with EN 1994.

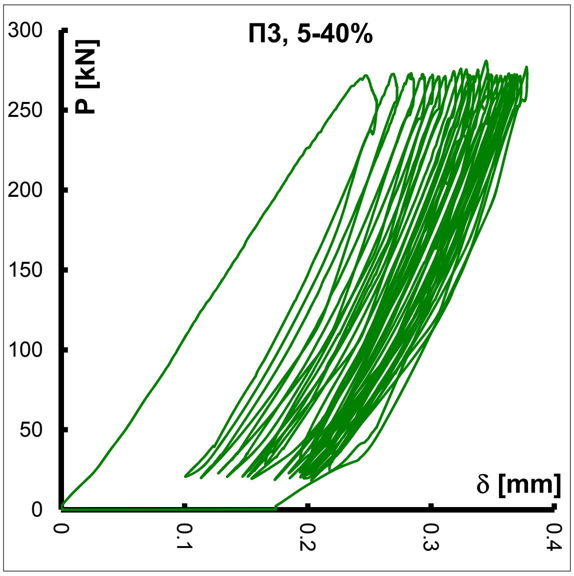

Figure 6.c. "P-δ" diagram, specimen П3

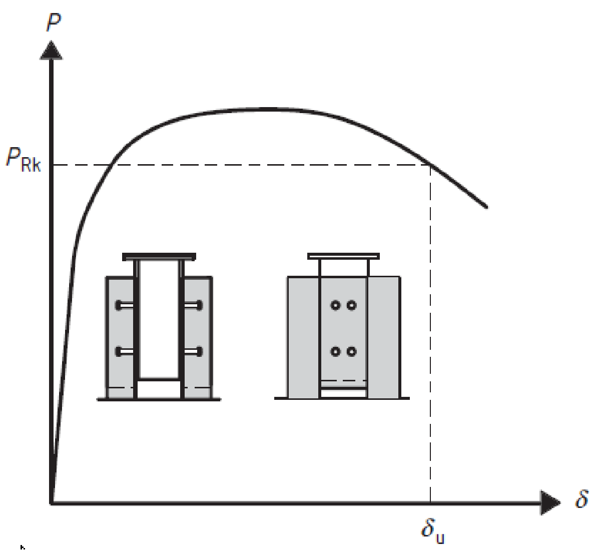

Figure 6.d. "P-δ" diagram, slip capacity

In figure 6.a, 6.b and 6.c. are given the determination of the slip capacity from the “*P-δ*” diagram for one headed stud, where $P_{Rk,(1)}=0.9\cdot P_{Rk,U,(1)}$ is reduced ultimate design resistance from the testing for one headed stud. From the value of $P_{Rk,(1)}$ and the “*P-δ*” diagram from the testing, the value of the slip capacity “δ_u” can be determined as given in figure 7.

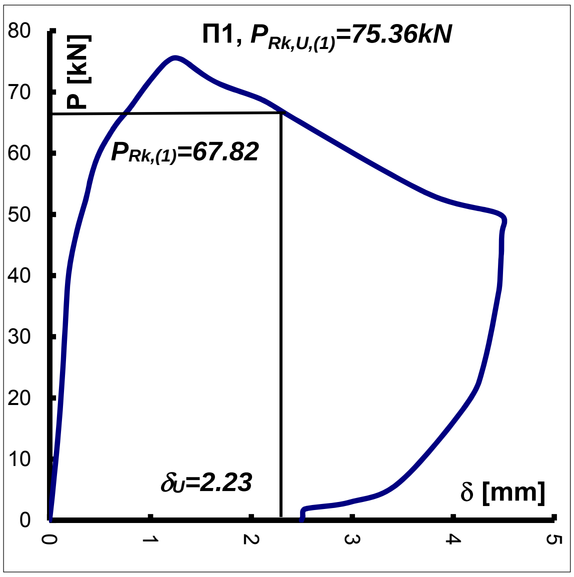

Figure 7.a. “*P-d*” diagram, specimen П1, slip capacity determination

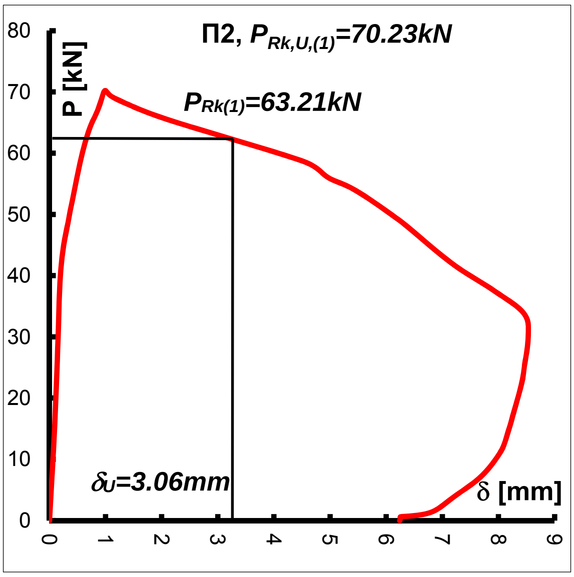

Figure 7.a. “*P-d*” diagram, specimen П2, slip capacity determination

In figure 6.d. the diagrams of all specimens are given, including the diagram for the analytical model (AM) obtained from the diagrams of the specimens but in accordance with EN 1994.

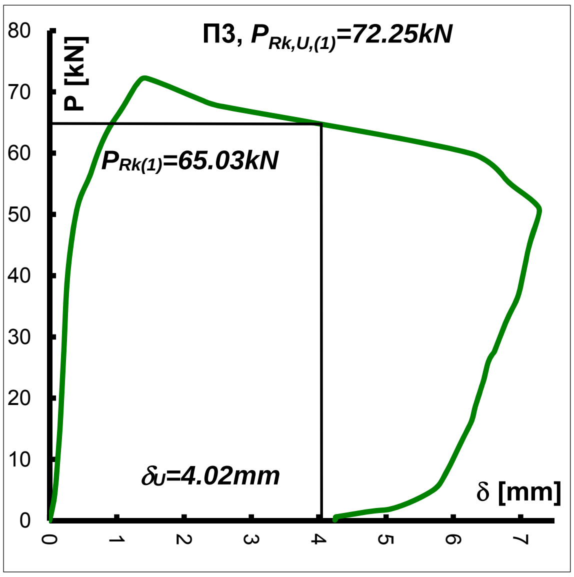

Figure 7.a. “*P-d*” diagram, specimen П3, slip capacity determination

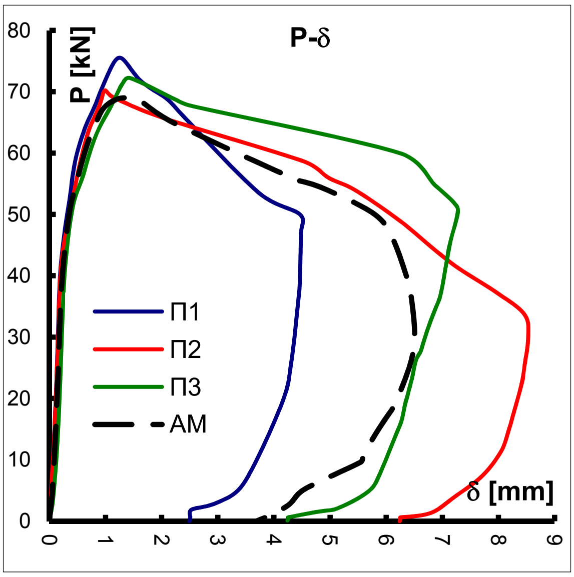

Figure 7.d. “*P-d*” diagram, all specimens

The values of the determined slip capacity for each specimen are 2.23mm for П1, 3.06mm for П2 and 4.02mm for П3, where according to EN 1994-1-1, Annex B, the value from all three specimens is:

$$\delta_{uk} = 0.9 \cdot \delta_{u,min} = 2.01mm \tag{10}$$

Or, the value of the slip capacity from all specimens can be determined with statistical evaluation from the results in accordance with EN 1990, Annex D, in which case the value is $\delta_{uk}=3.17mm$.

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

Figure 8. All three specimens after the testing

3. CONCLUSION

The design resistance in dependence of the concrete slab, with all dimensions and concrete strength class, determine the main resistance of the headed stud shear connectors. If the design resistance is needed to be determined not form the concrete slab but from the headed stud, then a lower quality steel for the stud or greater concrete strength class is required.

The value of the slip capacity is $\delta_{uk}<6mm$ which means that the shear connectors for this testing case are not ductile, and that they can be applied for achievement of full plastic capacity of the designed cross section. If a more ductile behavior for the structure is needed, a smaller diameter or lesser strength quality for the headed stud shear connector is required.

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