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Nina Gluhović[1]

PONAŠANJE SMIČUĆIH SPOJEVA IZVEDENIH MOŽDANICIMA SA EKSERIMA SA EKSPLOZIVNIM UPUCAVANJEM

Rezime:

Spregnuto dejstvo između čeličnih nosača i prefabrikovanih ili punih betonskih ploča može da se ostvari primenom različitih vrsta sredstava za sprezanje koji se međusobno razlikuju po svojim osnovnim karakteristikama, vremenu potrebnom za njihovu ugradnju i opremi koja je potrebna za sprovođenje ovog procesa. Mehanički spojena sredstva za sprezanje predstavljaju alternativu tradicionalno korištenim zavarenim moždanicima sa glavom ili zavrtnjevima kao sredstvima za sprezanje. X-HVB moždanici ugrađeni sa dva X-ENP-21 HVB eksera sa eksplozivnim upucavanjem su najznačajniji predstavnici ove grupe moždanika. Ponašanje smičićeg spoja ostvarenog pomoću X-HVB moždanika, analizirano je kroz eksperimentalno ispitivanje i razvoj numeričkih modela moždanika i eksera sa eksplozivnim upucavanjem. U ovom radu prikazani su rezultati sprovedenog ispitivanja, koji treba da doprinesu boljem razumevanju ponašanja X-HVB moždanika, ali i proširenju trenutno male baze dostupnih eksperimentalnih rezultata.

Ključne reči: prefabrikovana gradnja, mehanička spojna sredstva, mehanizmi ankerovanja

BEHAVIOUR OF SHEAR CONNECTIONS REALISED BY CONNECTORS FASTENED WITH CARTRIDGE FIRED PINS

Summary:

Composite action between steel beams and prefabricated or solid concrete slabs can be achieved with various types of shear connectors which differ considering their main properties, installation time and required equipment at the construction site. Mechanically fastened shear connectors represent an alternative solution to the traditionally used welded headed studs or bolted shear connectors. X-HVB shear connectors fastened with two X-ENP-21 HVB cartridge fired pins are their main representative. The behaviour of shear connection realised by X-HVB shear connectors is investigated through experiments and numerical analysis of both parts: shear connectors and cartridge fired pins. Main achievements of this investigation are presented in this paper and should lead to a better understanding of X-HVB shear connectors behaviour and extension of the currently small basis of available experimental results.

Keywords: prefabricated construction, mechanical fasteners, anchorage mechanisms

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1. INTRODUCTION

Mechanically fastened shear connectors represent an innovative and relatively new group of shear connectors which are fastened to the steel base material with various types of mechanical fasteners. They represent a unique system comprised of two elements, shear connector and mechanical fasteners. Therefore, understanding of behaviour and failure mechanisms of fasteners is essential for the analysis of shear connection with mechanically fastened shear connectors. Experimental and FE numerical investigation of X-HVB 110 shear connectors in prefabricated concrete slabs, as the main representative of mechanically fastened shear connectors, and behaviour of X-ENP-21 HVB cartridge fired pins through shear and tension tests is presented in this paper.

The X-HVB shear connectors are L shaped cold-formed metal connector with 2.0 to 2.5 mm thickness which are produced from DC04 steel, EN 10130:2006 [1]. They are comprised of two parts: fastening leg with holes for installation of two X-ENP-21 HVB cartridge fired pins and anchorage leg with connector head cast into the concrete to prevent separation of concrete slab from steel beam, as presented in Figure 1. The main characteristic of X-HVB shear connectors is lower installation time in comparison to the welded headed studs or bolted shear connectors without welding or predrilling of holes in the base material and profiled sheeting. The installation procedure is performed with a simple hand-held installation tool, which does not require electrical power supply at the construction site. Since installation procedure does not include welding, application of X-HVB shear connectors is also beneficial for the renovation of old buildings, where the applicability of welded studs is doubtful due to unknown weldability of old steel [2].

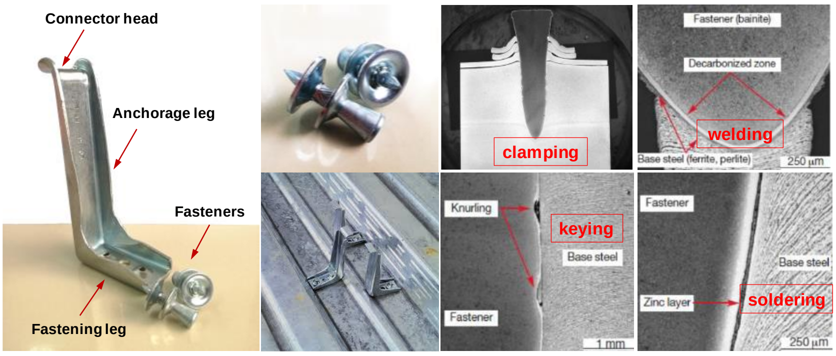


Figure 1 – X-HVB shear connectors and pins anchorage mechanisms, adapted from [3]

Nowadays, application and the main characteristic of X-HVB shear connectors in solid and composite concrete slabs with profiled sheeting are defined in ETA-15/0876 Assessment [4]. The whole range of X-HVB shear connectors with heights from 40 mm to 140 mm can be used for composite steel-concrete construction with normal-weight concrete classes C20/25-C50/60 and with light-weight concrete classes LC20/22-LC50/55 and can be fastened to the steel base material S235, S275 and S355 in qualities JR, JO, J2, K2. X-HVB shear connectors are determined as ductile shear connectors considering requirements given in EN 1994-1-1:2004 [5].

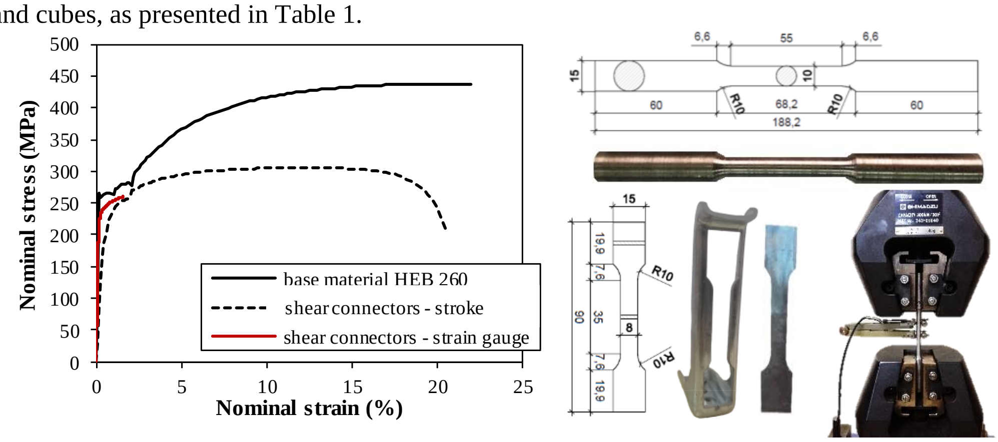
EN 1993-1-3:2009 [6] defines cartridge fired pins as mechanical fasteners which can be used for cold-formed members and sheeting. Failure mechanisms of X-HVB shear connectors are mostly related to the shear failure and pull-out failure of cartridge fired pins. Pull-out failure of cartridge fired pins is associated with the failure of anchorage mechanisms which are developed during the installation procedure. The term "anchorage" refers to the hold obtained by the fastener in the base material [2]. Metals with plastic deformation behaviour provide suitable anchorage mechanism for this type of fasteners and the most important base material is unalloyed structural steel. Anchorage mechanisms are classified as clamping, keying, welding and soldering, as given in Figure 1. Anchorage capacity should be determined through appropriate testing procedures and the contribution of each type of anchorage mechanism in overall anchorage is not constant. It is assumed that clamping obtains the most important influence on fasteners pull-out resistance which is a result of the radial dislocation of the base steel material resulting in plastic strains and residual stresses towards the body of the protruded pin. Other types of anchorage mechanisms such as keying, welding and soldering are the result of high temperatures developed during the highly dynamic installation procedure, melting of zinc layer on the surface of the pin and micro embossments of the knurled surface of the pin.

2. EXPERIMENTAL INVESTIGATION

Experimental investigation of mechanically fastened shear connectors in prefabricated concrete slabs was separated into two investigation programs: push-out tests of X-HVB 110 shear connectors and shear and tension tests of X-ENP-21 HVB cartridge fired pins [7]. The experimental program was performed at the University of Belgrade, Faculty of Civil Engineering. Push-out tests of X-HVB 110 shear connectors were performed to investigate the behaviour of shear connectors positioned in envisaged openings of prefabricated concrete slabs. Complete insight into the behaviour of shear connection was possible through additional investigation of cartridge fired pins. Material properties of shear connectors, steel base material, prefabricated concrete slabs and infill concrete were determined through standard testing procedures.

2.1. INVESTIGATION OF MATERIAL PROPERTIES

Material properties of the shear connector, steel beam HEB 260 which is used for push-out tests and base material of shear and tension test of cartridge fired pins were determined through tension tests of material coupons, as shown in Figure 2. Material properties of X-ENP-21 HVB cartridge fired pins were provided by the kindness of Hilti Company and they are considered as proprietary. The geometry of the examined tensile coupons is given in Figure 2b. The testing procedure was performed according to recommendations given in EN 10002-1:2001 [8]. Round tensile coupons were equipped with digital extensometer which was not applicable for flat tensile coupons due to the specific geometry. Therefore, flat tensile coupons built from shear connector anchorage leg were equipped with two strain gauges for elongation measurements. Similar tensile coupons were built from steel base material of shear and tension tests of cartridge fired pins, which results are presented in Chapter 2.3. Nominal stress-strain curves are given in Figure 2a. Material properties of steel beam HEB 260 for push-out specimens correspond to the steel grade S235 while testing procedure of tensile coupons built from shear connectors indicates that cold-forming procedure leads to material strength-enhancement in comparison to the average material properties of steel DC04 [1]. Material properties of infill concrete and concrete of prefabricated slabs which were used in push-out tests were obtained by testing concrete cylinders and cubes, as presented in Table 1.



a) nominal stress-strain curves *b) testing specimens*

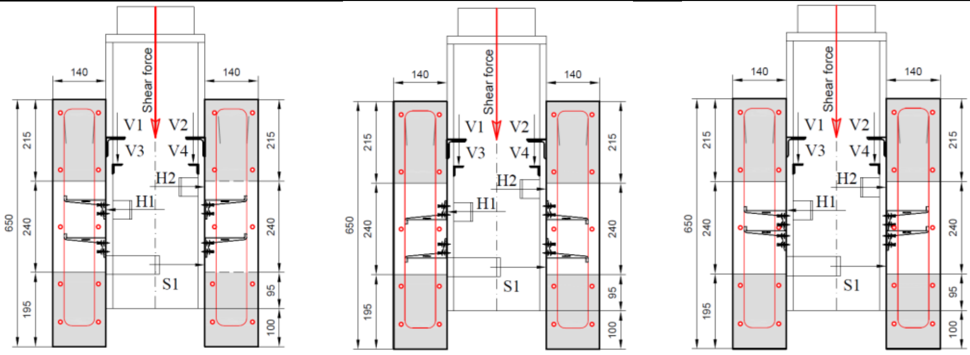
Figure 2 – Examination of steel material properties

2.2. PUSH-OUT TESTS

Push-out tests of X-HVB 110 shear connectors were performed through four test series to investigate the influence of several parameters on the behaviour of shear connection. Influence parameters which were analysed are the orientation of shear connectors relative to the shear force direction, the distance between shear connectors in longitudinal and transversal direction and installation power level which was used during the installation procedure. The geometry of tested push-out tests specimens is given in Table 1 and Figure 3. After the installation of shear connectors and positioning of prefabricated concrete slabs, envisaged openings were filled in the horizontal position with concrete which material properties are presented in Table 1. Influence of shear connector orientation relative to the shear force direction was analysed through HSF and HSB test series. The forward orientation of shear connectors adopted for HSF test series is characterized with the position of shear connector anchorage leg in front of fastening leg, relative to the shear force direction, while fastening leg precede to the anchorage leg in the backward orientation of shear connectors for HSB test series, as presented in Figure 3a and 3b. For both analysed test series shear connectors were positioned at minimal recommended distances in both directions, as presented in Table 1, according to recommendations of ETA-15/0876 Assessment [4]. The forward orientation of shear connectors was further analysed through their group arrangement in HSFg and HSFg-2 test series, without clear distance between shear connectors in both directions, as shown in Figure 3c. For HSF, HSB and HSFg-2 test series, installation power level which was set on the direct fastening tool was 3.5 (maximum 4.0), while smaller installation power level 2.0 was used for test series HSFg, as presented in Table 1. Four specimens were tested for each test series, sixteen specimens in total.

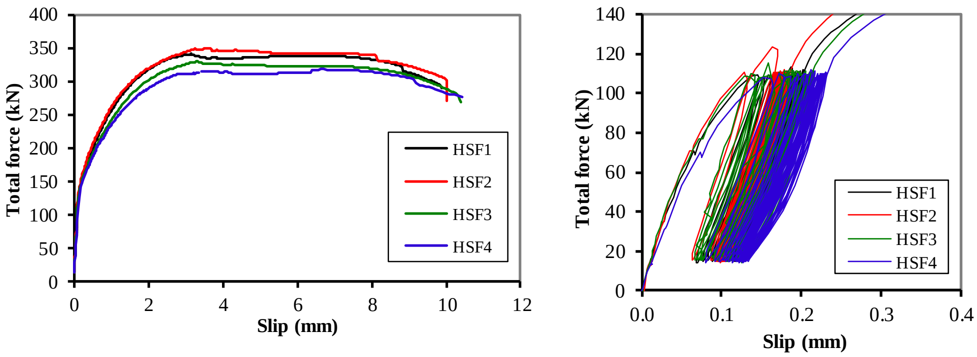
Table 1 – Geometry of push-out test specimens

Specimens series	Connectors spacing (mm)		Installation power level (-)	Properties of infill concrete	
	longitudinal	transversal		compressive strength f_{cm} [MPa]	elastic modulus E_{cm} [GPa]
HSF, HSB	48	23.6	3.5	28.51	27.61
HSFg	0	0	2	33.68	33.05
HSFg-2	0	0	3.5	37.15	35.34



a) HSF series *b) HSB series* *c) HSFg and HSFg-2 series*

Figure 3 – Push-out specimens' layout



a) failure loading *b) cyclic loading*

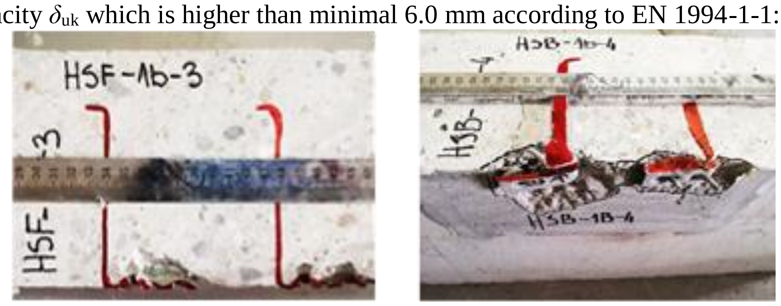
Figure 4 – Force-slip curve for HSF test series

Each specimen was equipped with seven inductive displacement transducers to measure the slip and separation between the concrete slab and steel profile, as presented in Figure 3. The loading regime was adopted as force-controlled cycling loading applied in 25 cycles ranging from 5% and 40% of assumed shear resistance, according to EN 1994-1-1:2004 [5]. After the cyclic loading, failure loading was applied in one step. Results of the push-out testing of HSF test series as force-slip curves for failure loading is presented in Figure 4a, while cyclic loading is presented in Figure 4b. Mean value of ultimate shear force P_{ult} for each test series is presented in Table 2. Also, this table presents the average value of longitudinal slip measured between concrete slabs and steel profile (sensors V1-V4, Figure 3), for each test series. Longitudinal slip is separated in two parts, initial slip δ_{init} accumulated during cyclic loading and characteristic value of slip capacity δ_{uk} which is obtained for 90% of ultimate shear force on descending branch of the load-slip curve and used as the main property of shear connectors, concerning ductility.

Table 2 – Results of push-out test specimens

Specimens series	Mean value of ultimate shear force P_{ult} [kN]	Average slip	
		initial δ_{init} [mm]	characteristic δ_{uk} [mm]
HSF	335.4	0.12	9.63
HSB	300.3	0.15	8.71
HSFg	284.6	0.11	6.14
HSFg-2	323.8	0.11	7.60

Results presented in Table 2 indicate that the forward orientation of shear connectors (HSF) is more favourable, with approximately 12% higher shear resistance in comparison to the backward orientation (HSB). Group arrangement of shear connectors in HSFg-2 test series with the same installation power level in comparison to the HSF test series does not result in a significant reduction of shear resistance, approximately 4%. Lowering of installation power level for group arrangement of shear connectors of HSFg test series resulted in approximately 14 % lower shear resistance in comparison to the HSFg-2 test series. For all analysed test series, X-HVB 110 shear connector presented ductile behaviour considering obtained characteristic value of slip capacity δ_{uk} which is higher than minimal 6.0 mm according to EN 1994-1-1:2004 [5].



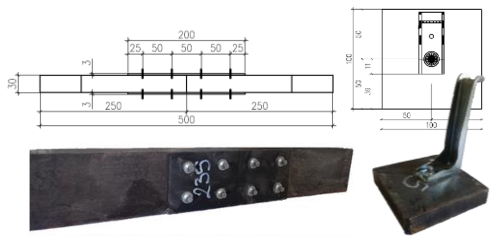
a) HSF test series *a) HSB test series*

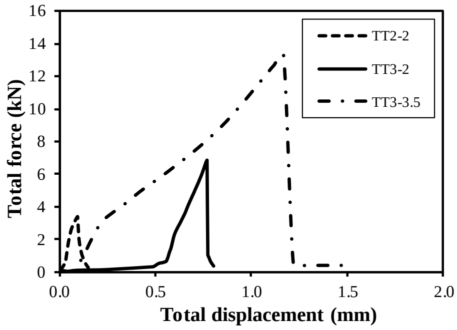
Figure 5 – Failure mechanisms of push-out specimens

Failure mechanisms of HSF and HSB test series are given in Figure 5, presenting prefabricated concrete slabs cut through shear connectors after testing procedure. For all analysed test series with the forward orientation of shear connector, characteristic failure mechanism is the pull-out failure of most cartridge fired pins and shear failure of few pins with small deformation of surrounding concrete and deformation of the shear connector. The backward orientation of shear connectors in HSB test series is characterized with pull-out and shear failure of cartridge fired pins with significant deformation of the fastening leg of shear connectors and surrounding concrete of prefabricated concrete slabs. Global cracks in prefabricated concrete slabs were not observed for any analysed tests series.

2.3. SHEAR AND TENSION TESTS OF CARTRIDGE FIRED PINS

X-ENP-21 HVB cartridge fired pins were examined through double-lap shear specimens and tension specimens, as shown in Figure 6. The testing procedure was adopted according to recommendations given in ECCS publication [9]. Cover plates of double-lap shear specimens were adopted with 3 mm thickness while, steel base plate was with the thickness of 30 mm. Number of cartridge fired pins per one cover plate was eight, and total number per specimen was sixteen, as shown in Figure 6a. Installation of cartridge fired pins was performed with installation power level 3.5. Achieved steel grade for the base plate of shear test specimens is S355, according to measurements of tensile test coupons. Tensile test specimens were built with the installation of one cartridge fired pin over fastening leg of X-HVB shear connector into 20 mm thick steel base plate, as shown in Figure 6a. Tensile test specimens were built with the variation of base plate steel grade and pins installation power level.





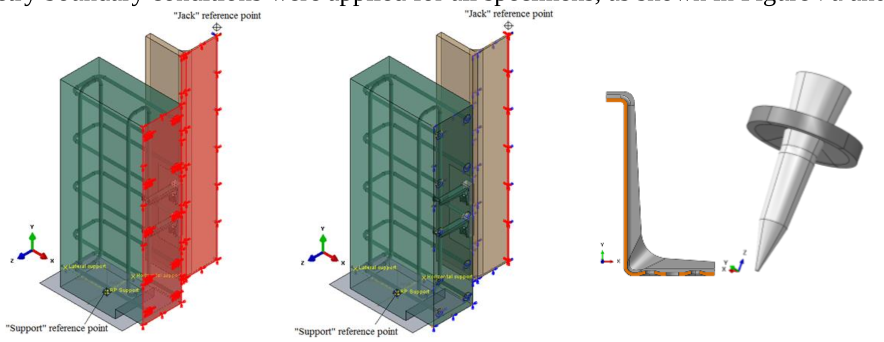
a) shear and tension test specimens *b) pull-out resistance of tension specimens*

Figure 6 – Experimental investigation of X-ENP-21 HVB cartridge fired pins

Obtained failure mechanism of all shear test and tension tests specimens was the pull-out failure of all pins. Mean value of shear resistance per one cartridge fired pin of four examined shear test specimens is 14.11 kN which is approximately 20 % to 30 % lower shear resistance in comparison to the shear resistance per one cartridge fired pin in push-out tests specimens, which results are given in Table 2. Pull-out resistance of tension test specimens is given in Figure 6b. The first number in the designation of the test specimen is the designation of steel grade, i.e. 2 for S275 and 3 for S355, while the second number represents installation power level, 2.0 or 3.5. Lower installation power level 2.0 applied for specimens with different steel grades, resulted in approximately 50 % lower pull-out resistance (TT2-2 vs. TT3-2 specimen). Variation of installation power levels from 2.0 to 3.5 for specimens with the same material properties of base plate increased pull-out resistance for approximately 52 % (TT3-2 vs. TT3-3.5 specimen). Results obtained from the examination of X-ENP-21 HVB cartridge fired pins indicate the influence of steel material properties on pull-out resistance. Also, it can be expected that driving force introduced during installation procedure through installation power levels influence the developed clamping, as main anchorage mechanism, between pin surface and surrounding base material and therefore defines the overall pull-out resistance of cartridge fired pins.

3. NUMERICAL ANALYSIS

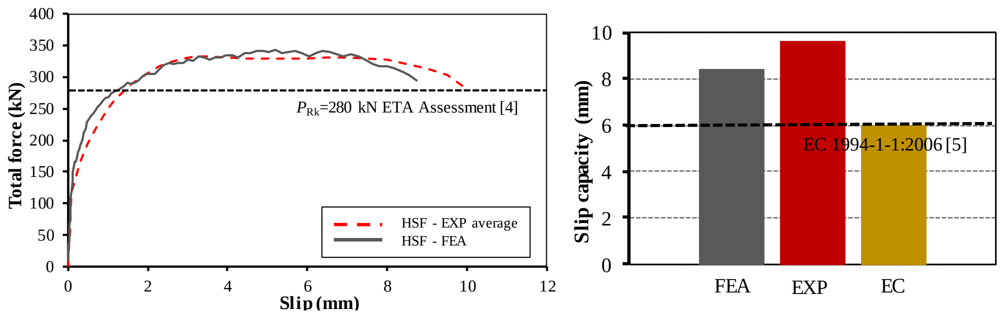
Extensive finite element analysis was conducted to develop and calibrate FE models based on the results of presented experimental research. FE analysis was conducted using Abaqus/Explicit code, version 6.12-3 [10]. FE models matching the push-out tests of four test series were built with all specimens' components: prefabricated concrete slabs, reinforcement bars, steel beam, X-HVB 110 shear connectors and X-ENP-21 HVB cartridge fired pins, with parameters which were varied through experimental analysis, shown in Table 1. Double vertical symmetry boundary conditions were applied for all specimens, as shown in Figure 7a and b.



a) X symmetry *b) Z symmetry* *c) connector and pin model*

Figure 7 – Numerical analysis of push-out specimens – HSF test series

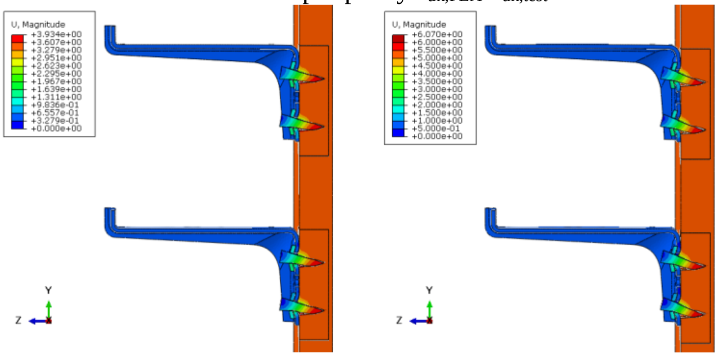
Concrete damage material properties were introduced according to recommendations of Pavlović et al. [11]. Material models of steel base material and the shear connector were applied using a quad-linear material model which includes an elastic response up to the yield point, yield plateau and strain hardening up to the ultimate tensile stress [12]. FE modelling introduced two loading steps: preloading of cartridge fired pins which simulate the installation procedure was introduced as a first step and failure loading applied as a second step. Comparison of experimental results with results of FE analysis for HSF test series is given in Figure 8.



a) force-slip curves *b) slip capacity δ_{uk}*

Figure 8 – Comparison of experimental results with FE analysis – HSF test series

The main achievement of the performed numerical analysis is the definition of the appropriate numerical model which simulates the installation procedure and which was calibrated according to the results of push-out tests and shear and tension test of cartridge fired pins with various base material properties and installation power levels. A developed numerical approach for simulation of the installation procedure is characterised with prestressing of cartridge fired pins in level which amounts approximately 5 kN per one cartridge fired pin in overall shear resistance of push-out specimen. Good agreement of FE results with experimental results is achieved, considering shear resistance, initial stiffness and failure mechanisms, as shown in Figure 8. Obtained ultimate shear force P_{ult} through experimental and numerical analysis is higher than characteristic shear resistance of X-HVB 110 shear connector, which amounts 280 kN according to ETA-15/0876 Assessment [4]. The obtained ratio between results of FE analysis and experimental results for two analysed parameters, shear resistance $P_{\mathrm{ult,FEA}}/P_{\mathrm{ult,exp}}$ and characteristic value of slip capacity $\delta_{\mathrm{uk,FEA}}/\delta_{\mathrm{uk,test}}$ is 1.02 and 0.87, respectively.



a) 96 % of ultimate shear force *b) total slip of 6.0 mm*

Figure 9 – Deformation of shear connector – HSF FE model

Connectors deformation capacity can be obtained through the difference between shear connector displacement at the connector root (displacement at contact with steel profile) and top of the shear connector embedded in concrete, in the direction of the shear force. Deformation of X-HVB 110 shear connectors for HSF test series is presented in Figure 9 for two loading levels. Displacement of X-HVB 110 shear connector is uniform over its height, which was obtained through experimental and FE analysis considering achieved failure mechanisms, which is given in Figure 5a and 9. The deformation of anchorage leg of the shear connector for HSF test series contributes by 8 % to the total displacement of the connector. The remaining, main, part of the total deformation is contributed to deformation of cartridge fired pins in the holes, emphasizing the influence of the cartridge fired pins and developed anchorage mechanisms on the overall behaviour of shear connection.

4. CONCLUSIONS

Mechanically fastened shear connectors represent an innovation in the achievement of shear connection between steel beams and concrete slabs. Despite undoubted advantages of this type of shear connectors, there is a lack of easily available experimental and numerical results in this field, which are mostly considered as proprietary. Experimental and numerical analysis of X-HVB 110 shear connectors and X-ENP-21 HVB cartridge presented in this paper should lead to better insight into the behaviour of shear connection achieved with mechanically fastened shear connectors. Following conclusions can be drawn from the presented analysis:

- forward orientation of shear connectors can be considered as more favourable in comparison to the backward orientation considering shear resistance and failure mechanisms;

- reduction of distance between shear connectors and their group arrangement in envisaged openings of prefabricated concrete slabs does not influence the reduction of shear resistance and does not compromise their ductility which is significant feature considering required tolerances and dimension of envisaged openings in concrete slabs of prefabricated constructions;

- shear resistance, ductility and failure mechanisms of X-HVB shear connectors are mostly related to the behaviour, deformation capacity and failure mechanisms of cartridge fired pins;

- pull-out resistance of cartridge fired pins is influenced by developed anchorage mechanisms during dynamic installation procedure and properties of the steel base material.

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