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Mechanically fastened shear connectors in prefabricated concrete slabs – experimental analysis

Nina Gluhović[*1], Zlatko Marković[1a], Milan Spremić[1b] and Marko Pavlović[2c]

[1]*Department of Materials and Structures, Faculty of Civil Engineering University of Belgrade, B. k. Aleksandra 73, Serbia*
[2]*Department of Engineering Structures, Faculty of Civil Engineering and Geosciences, Delft University of Technology, Stevinweg 1, Delft, The Netherlands*

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Abstract. Nowadays, in prefabricated composite construction, composite action between steel beam and concrete slab is often achieved with positioning of shear connectors in envisaged openings of concrete slabs. Prefabricated concrete slabs are used for composite steel-concrete buildings and bridges, both for the construction of new structures and for renovation of existing ones, significantly reducing construction time. Development of different types of shear connectors represent alternative solution to the traditionally used headed studs, considering their shear resistance, stiffness and ductility. New types of shear connectors tend to reduce the construction time and overall construction cost. Mechanically fastened shear connectors represent a viable alternative to headed studs, considering their fast installation process and shear resistance. X-HVB shear connectors are attached to the steel beam with two cartridge fired pins. The first step towards extensive implementation of X-HVB shear connectors in composite construction is to understand their behaviour through experimental investigation. Results of the push-out tests, in accordance to Eurocode 4, with X-HVB 110 shear connectors positioned in envisaged openings of prefabricated concrete slabs are presented in this paper. The experimental investigation comprised three different specimen's layout. Group arrangement of X-HVB shear connectors in envisaged openings included specimens with minimal recommended distances and specimens with reduced distances between connectors in both directions. Influence of different installation procedures on overall behaviour of the connection is presented, as well as the orientation of shear connectors relative to the shear force direction. Influence of variations is characterized in terms of failure mechanisms, shear resistance and ductility.

Keywords: X-HVB, experiments; cartridge fired pins; push-out test; steel-concrete composite structures

1. Introduction

Construction industry is constantly facing new demands towards fast construction and optimization of construction process. In recent decades, development of different types of prefabricated concrete slabs has taken an important place in the field of composite construction, significantly reducing the construction time. Grouting of grouped welded headed studs in envisaged openings of prefabricated concrete slabs is well known technology to establish hybrid interaction by shear connection in prefabricated composite construction (Spremic *et al.* 2018, Wang *et al.* 2019). Installation of different types of shear connectors (Pavlović *et al.* 2013, Vianna *et al.* 2013, Pathirana *et al.* 2016, Le *et al.* 2017) is characterized with significant diversity in required equipment and quantity of work at construction site, preparation of base material and requested temperature and weather conditions during installation procedure. Besides, various types of shear connectors have different main properties, such as shear resistance, stiffness and ductility. In recent period, investigation of demountable shear connectors and prefabricated concrete slabs is performed by Rehman *et al.* (2016), Suwaed and Karavasilis (2017), Ataei *et al.* (2018) and Feidaki *et al.* (2019) in order to investigate possibilities for beneficial reconstruction, construction reuse and cost effective construction.

Mechanically fastened shear connectors for composite steel-concrete construction are fastened to the steel base material with cartridge fired pins. They represent a unique system comprised of two elements: shear connector and mechanical fasteners. Therefore, their overall behaviour is, among other factors, also related to the behaviour and failure mechanisms of fasteners. X-HVB shear connectors are well-known representative of mechanically fastened shear connectors. They are manufactured as L shaped cold-formed metal connector (ETA-15/0876 Assessment, 2016) made from low carbon steel DC04 (1.0338) with 2.0 or 2.5 mm thickness, according to EN 10130 (2006). X-HVB shear connector is comprised of the fastening leg fixed to the steel base material with two X-ENP-21 HVB cartridge fired pins and anchorage leg and head casted into the concrete slab to prevent separation of concrete slab from steel base material. Geometry of X-HVB 110 shear connector, which is used in own experimental investigation presented in this paper, is given in Fig. 1.

*Corresponding author, Ph.D., Assistant Professor
E-mail: nina@imk.grf.bg.ac.rs
[a]Professor
[b]Assistant Professor
[c]Assistant Professor

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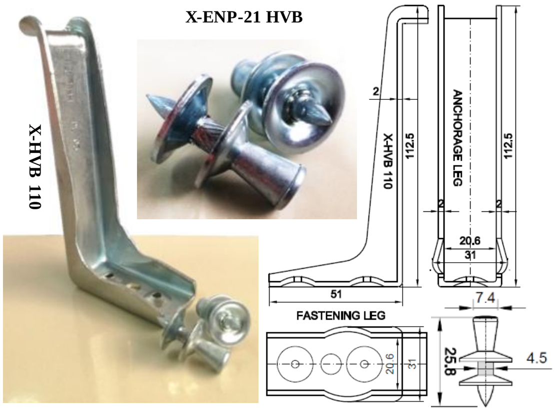


Fig. 1 Geometry of X-HVB 110 shear connector

The main characteristics of X-HVB shear connectors are significantly lower installation time, simple installation procedure with hand tool, which does not require electrical power supply, without welding or any other technological process. The quality of installation procedure is not affected with special atmospheric or temperature conditions at construction site, resulting in less work interruptions. Therefore, the construction costs with use of X-HVB shear connectors are expected to be lower when compared to traditional headed studs. Moreover, their installation does not require predrilling of holes in the base material and profiled decks, significantly optimizing fabrication tolerances of prefabricated elements.

X-HVB shear connectors are beneficial for renovation of old buildings, where applicability of welded studs is doubtful due to unknown weldability of old steel (ETA-15/0876 Assessment, 2016). Beside the main usage of this type of shear connectors for composite steel-concrete floor beams, they are often used for lateral bracing of steel beams and end anchorage of profiled steel decks in composite floor construction (Beck *et al.* 2011).

Several research programs of X-HVB shear connectors were performed during the 1980s and 1990s in order to obtain data for system evaluation and were followed with gathering of international technical assessments for construction applications. However, there are still only a few published research information and experimental data in this field. The results of experimental research are mostly presented in technical reports of manufacturer, which are considered proprietary.

Results of the first experimental works of X-HVB shear connectors were presented by Crisinel (1990). The experimentally gained findings were compared with similar investigations of headed studs in order to compare overall behaviour, such as shear resistance, stiffness and ductility. Also, characteristic shear resistance of newly developed X-HVB shear connectors was compared with former analytical expressions for shear resistance reduction factors developed for headed studs in composite slabs, given by Johnson and Molenstra (1991). Using the experimental data from the aforementioned investigations, Crisinel (1990) presented in his work that reduction factors for shear resistance of headed studs in composite slabs with profiled decks can be used for determination of shear resistance of X-HVB shear connectors. Moreover, results of three beam tests with X-HVB 100 shear connectors with different degrees of partial shear connection were presented by Crisinel (1990). The experimental data of beam tests indicated that behaviour of shear connectors remains ductile even with low degrees of partial shear connection. The results were compared with design procedure for partial shear connection which was given in former draft version of Eurocode 4 and presented by Crisinel (1990). Moreover, usage of partial-interaction analysis and reduction of partial shear connection degree up to 25% was suggested for X-HVB shear connectors (Crisinel 1990).

Nowadays, wide range of X-HVB shear connectors with different heights are applicable in composite construction, such as X-HVB 40, 50, 80, 95, 110, 125, 140 shear connectors with designation of connectors height in their label. Current ETA-15/0876 Assessment (2016) defines characteristic shear resistance of X-HVB shear connectors in solid slabs and composite slabs with profiled decks and their range of application. They 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 raw density higher than 1750 kg/m^3 (ETA-15/0876 Assessment, 2016). These connectors may be used for connection to the structural steel base material S235, S275 and S355 in qualities JR, JO, J2, K2 according to EN 10025-2 (2004) and minimal base material thickness for composite steel-concrete beams of 8.0 mm. Moreover, according to ETA-15/0876 Assessment (2016), X-HVB shear connectors are determined as ductile shear connectors considering requirements given in Eurocode 4 (2004) and therefore, can be used for plastic analysis of design moment resistance of composite cross-section. The partial safety factor for shear connection γ_V=1.25 (ETA-15/0876 Assessment, 2016) should be used for calculation of design resistance, according to recommendations given in Eurocode 4 (2004).

In recent period, new types of mechanically fastened shear connectors, Rib connectors and Strip connectors were examined by Fontana and Bärtschi (2002). For both types of connectors, shear connection is achieved with cartridge fired pins X-ENP-21 HVB. Rib connectors are developed as cold formed steel angle with perforated edge on anchorage leg of connector (angle leg which is in connection with surrounding concrete slab) performing a similar behaviour as for perforated shear connectors. Rib shear connectors were examined through push-out tests with solid and composite concrete slabs. Experimentally obtained failure mechanisms of angle Rib connectors in solid concrete slabs, depending on the connectors orientation relative to the shear force direction, are pull-out and shear failure of fasteners, local bearing of connectors and washer pull-over. Achieved resistance per one cartridge fired pin is approximately from 21.03 kN to 25.69 kN for Rib connectors (Fontana and Bärtschi 2002). Strip connectors are made from profiled metal sheet with more complex geometry in comparison to the Rib connectors and were examined through push-out tests in composite concrete slabs. Considering their geometry, various failure mechanisms were achieved, mostly related to the fracture of the shear connector. Therefore, achieved resistance per one fastener is significantly lower and amounts from 14.08 kN to 22.10 kN (Fontana and Bärtschi, 2002). Another type of mechanically fastened shear connector, which is recently developed, is CFT shear connector comprising the geometry and behaviour of headed stud and X-HVB shear connectors. Tahir *et al.* (2009) examined their behaviour through push-out tests. Ultimate shear resistance per one shear connector in solid concrete slabs is between 42.0 kN and 55.8 kN and obtained failure mechanism is fracture and pull-out of fasteners. Experimental data obtained from seven push-out test specimens (Tahir *et al.* 2009), indicated that slip corresponding to the ultimate shear resistance is less than 3.1 mm and ductile behaviour of CFT shear connectors is not achieved, according to requirements given in Eurocode 4 (2004).

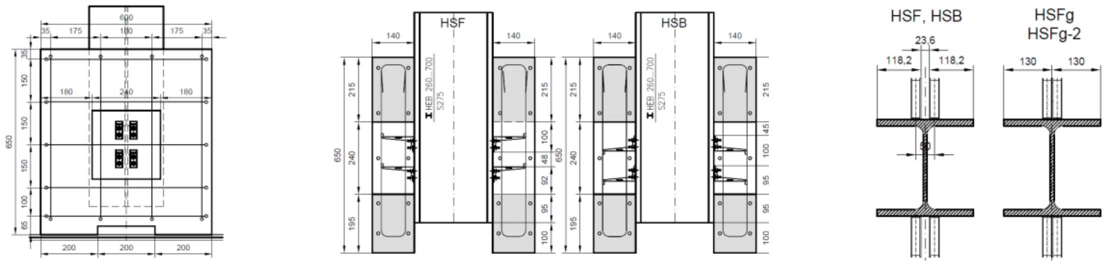
The experimental findings gained on different types of mechanically fastened shear connectors, indicated that overall behaviour of this type of shear connectors is mostly related to behaviour and failure mechanisms of cartridge fired pins. Pull-out failure of cartridge fired pin is associated to failure of anchorage mechanisms that are developed during installation process. The term anchorage refers to the hold obtained by the fastener in the base material. Metals with plastic deformation behaviour provide suitable anchorage mechanism for cartridge fired pins (Beck *et al.* 2011) and the most important base material is unalloyed structural steel according to EN 10025-2 (2004). Several anchorage mechanisms and principles are designated considering cartridge fired pins, such as clamping, keying, welding and soldering (Beck *et al.* 2011) and are developed during the installation procedure. Installation of cartridge fired pins is a highly dynamic process which has a significant influence on stress-state of fastened and base material. Goldspiegel *et al.* (2019) proposed a numerical model for high-speed nailing process for connection of dissimilar materials with different mechanical properties. Nailing simulations have shown that final installation depth of cartridge fired pins is mainly governed by damage parameters of fastened materials (Goldspiegel *et al.* 2019).

X-ENP 21 HVB cartridge fired pins, which are used for installation of X-HVB shear connectors are made from zinc plated carbon steel and their geometry is shown in Fig. 1. The strength and hardness of the cartridge fired pins have to be approximately 4 to 5 times higher than of steel base material, in order to accomplish the driving process. A hardness of the cartridge fired pins is between 49 and 58 HRc, which amounts approximately 1850 N/mm^2 to 2200 N/mm^2 of ultimate strength (Beck *et al.* 2011). The basic material which is used for manufacturing of cartridge fired pins is heat treatable carbon steel with 0.65% of carbon and ultimate tensile strength of approximately 600 N/mm^2 (Beck *et al.* 2011). The required hardness and ductility of cartridge fired pins are achieved through heat treatment, which should be applied carefully in order to avoid brittle behaviour of the fastener. The quality of the installation process is determined by fastener stand-off after installation, with clearly visible piston mark on the top of the pin washer (ETA-15/0876 Assessment, 2016). For appropriate installation when they are used for X-HVB shear connectors, cartridge fired pin stand-off amounts from 8.2 mm to 9.8 mm.

Different types of mechanical fasteners are also used for achievement of shear transfer and composite action in various types of structures. McComb and Tehrani (2015) examined a shear transfer encasement in composite concrete slabs with profiled decks through the use of steel metal screws.

Behaviour of X-HVB shear connectors in composite shear connections is expected to be different from behaviour of headed studs. Experimental and numerical analysis of mechanically fastened shear connectors can lead towards wider application in composite construction and to extend currently available recommendations for their application, obtained only through technical assessments. Also, current design recommendations for composite structures (Eurocode 4, 2004; ANSI/AISC 360-05, 2005 and JSCE, 2009) do not define design resistance for mechanically fastened shear connectors.

The aim of this paper is to gain better understanding of behaviour of X-HVB shear connectors in envisaged openings of prefabricated concrete slabs, in comparison to the currently available results with solid and composite concrete slabs. In order to generate all structural performance data, this investigation included experimental testing of material coupons of steel beam and shear connector and material properties of concrete, presented herein. The experiment aims at understanding the effects of the spacing between shear connectors, orientation of shear connectors relative to the shear force direction and nailing power level used for installation of cartridge fired pins, when they are used for prefabricated composite construction. Experimentally obtained data are compared with current recommendations given in ETA-15/0876 Assessment (2016).



(a) prefabricated slab (b) longitudinal spacing (c) transversal spacing

Fig. 2 Geometry of push-out specimens

Table 1 Geometry of examined specimens

Specimen series	Number of specimens (N_{sp})	Total number of connectors (N_{con})	Connectors		Concrete slabs		Nailing power level
			longitudinal spacing (mm)	transversal spacing (mm)	depth (mm)	opening (mm)	
HSF	4	8	48	23.6	140	240x240	3.5
HSB	4	8	48	23.6	140	240x240	3.5
HSFg	4	8	0	0	140	240x240	2
HSFg-2	4	8	0	0	140	240x240	3.5

2. Push-out experiments

2.1 Test set-up

Experimental investigation of X-HVB 110 shear connectors in prefabricated concrete slabs was performed through standard push-out tests according to Eurocode 4 (2004). The experiments were performed at the University of Belgrade, Faculty of Civil Engineering. Layout of the examined push-out specimens is presented in Fig. 2.

Shear connectors were positioned at steel beam flange (HEB 260) at minimal recommended longitudinal and transverse distances according to ETA-15/0876 Assessment (2016) for HSF and HSB specimens, as shown in Fig. 2. Minimal transverse distance between connectors is 50 mm (approximately 23.6 mm of clear distance for X-HVB 110 shear connectors) and minimal longitudinal distance is 100 mm (approximately 48.0 mm of clear distance for X-HVB 110 shear connectors), as presented in Figs. 2(b) and 2(c). Two different connectors' orientations, forward orientation of HSF specimens and backward orientation of HSB specimens relative to the shear force direction are analysed, as given in Fig. 2 and Table 1.

According to Eurocode 4 (2004), minimal transverse distance of headed studs is 3d and longitudinal distance 5d. These limitations are mostly obtained from different failure mechanism of individual headed stud, but also related to the requirements of the welding equipment. Minimal recommended longitudinal and transverse distance of X-HVB shear connectors is not restricted with size or requirements of installation equipment. Moreover, quality of installation process is not affected by shear connectors distance reduction. Therefore, forward orientation of shear connectors is further examined through two additional test series, HSFg and HSFg-2 with reduced distance between shear connectors, as shown in Fig. 2 and Table 1 (without clear distance between connectors). Presented shear connectors arrangements are analysed with two installation power levels. Installation of shear connectors is performed using DX 76 MX direct fastening tool (piston X-76-P-HVB), with cartridges 6.8/18 M blue colour code. Minimum and maximum level for power regulation on the fastening tool for installation of connectors is 1 and 4, respectively. Nailing power level, which is used for connectors' installation of HSF, HSB and HSFg-2 specimens is 3.5 and for HSFg specimens is 2.0, as shown in Table 1. Four shear connectors were positioned on each steel beam flange; eight shear connectors per specimen in total. Influence of nailing power level, shear connectors distances and orientation was characterized through variation of ultimate shear resistance, stiffness and ductility.

Concrete slabs with openings in the middle of the slab are prefabricated by casting them in horizontal position. The same dimensions of envisaged openings in prefabricated concrete slabs are adopted for all examined specimens, 240x240 mm. Concrete slabs are reinforced with standard reinforcement layout with 10 mm diameter ribbed bars and B500B grade, as shown in Fig. 2. Two horizontal ribbed bars, in upper and bottom reinforcement layer, are positioned between shear connectors of all examined specimens, as shown in Fig. 3.

Connecting surfaces of steel flanges are greased in order to avoid effects of bond to the concrete slab, according to recommendations given in Eurocode 4 (2004), due to unreliable and brittle failure of the chemical bond. Prior to concreting, inner surfaces of openings are cleaned and treated with the layer of structural adhesive as the continuing layer between new and old concrete (Fig. 3). After the installation of X-HVB 110 shear connectors, envisaged openings are filled in horizontal position with

Fig. 3 Specimens preparation

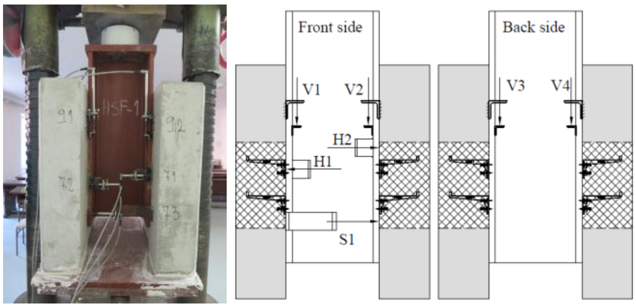


Fig. 4 Test set-up

three-fraction concrete with shrinkage reduction admixtures. During concreting of openings, concrete cubes and cylinders were made out of the same concrete mixture for determination of achieved concrete strength. In order to minimize initial cracks due to shrinkage, specimens are kept in wet condition during first three days. After three days, half assembled specimens are turned and second assembling phase is performed in the same way as the first one.

Test set-up of all examined specimens is shown in Fig. 4. Each specimen was equipped with seven inductive displacement transducers to measure the slip and separation between the concrete slab and steel profile, as shown in Fig. 4. Longitudinal slip between steel profile and both concrete slabs is measured with four sensors (V1-V4), two on each side of steel beam flange.

Uplift between steel profile and concrete slabs is measured on the front side (H1 and H2), as close as possible to connectors. Separation between concrete slabs is measured on the front side, 15 cm above the slab support (S1). No strain measurements were made. In order to reduce load eccentricity and to provide good contact of the specimen and the supporting surface of the jack, the concrete slabs of specimens were placed into the layer of fresh gypsum.

Force was measured by a load cell at the top, with 1000 kN capacity. Data acquisition and recording was done in 1 Hz frequency with multichannel acquisition device. The loading regime is adopted as specified in Eurocode 4 (2004). Force controlled cycling loading is applied in 25 cycles ranging from F_{min}=15 kN to F_{max}=110 kN, corresponding to approximately 5% and 40% of assumed shear resistance. Assumed shear resistance of eight connectors in one specimen is 280 kN, based on characteristic shear resistance of one X-HVB 110 connector, F_{Rk}=35 kN, according to ETA-15/0876 Assessment (2016). After the cyclic loading, failure loading is applied in one step, with constant displacement rate, such that failure does not appear in less than 15 minutes. Approximatively, 0.3 kN/s was applied during the failure loading.

3. Results of experiments

Material properties of steel beam and shear connector were examined through coupon tensile tests. Tensile coupons were longitudinally cut from steel beam flange and shear connector anchorage leg, four coupons from each. Round tensile coupons from steel beam flange with 10 mm diameter are built with 55 mm gauge length, L_0. Flat tensile coupons are built with 36 mm gauge length L_0 and 1.98 mm to 2.00 mm thickness, which is determined with thickness of shear connector. Total length of flat coupons is 90 mm, which is maximum tensile coupon length that can be built from X-HVB 110 shear connector. Testing procedure was adopted according to recommendations given in EN 10002-1 (2001). A uniform strain rate of 0.1 mm/min for the initial part of the tests, up to approximately 1% strain increasing to 2.2 mm/min thereafter, was adopted for each tensile test coupon. Fig. 5 shows flat tensile coupons prior to fracture and after the testing procedure.

Fig. 5 Tensile test for flat coupons – shear connector

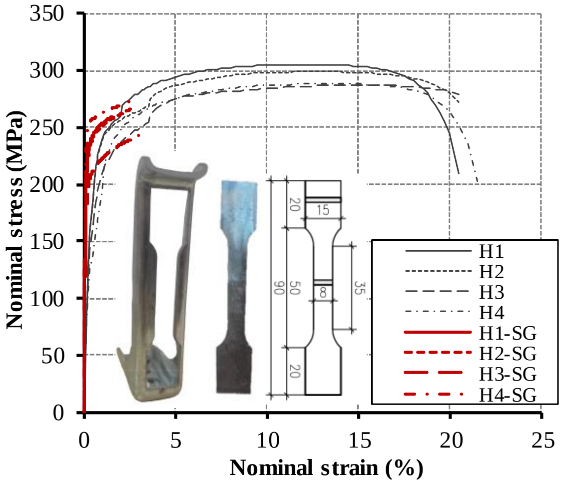


Fig. 6 Nominal stress-strain curves

All tests were performed in the servo-hydraulic testing machine Shimadzu, with a capacity of 300 kN. Due to specific geometry of flat coupons, elongation measurement with digital extensometer was not applicable. Therefore, one electronic strain gauge with length of 10 mm was mounted on each side of flat tensile coupon (two strain gauges per one tensile coupon) in order to monitor the elongation (Arrayago *et al*. 2015), as shown in Fig. 5. All data were recorded using a data acquisition system.

According to the obtained results for beam flange tensile coupons, average value of yield strength and tensile strength is 277 MPa and 433 MPa, respectively for four examined tensile coupons. Therefore, material properties of steel beam correspond to the steel grade S275. Nominal stress-strain curves of flat tensile coupons built from X-HVB 110 shear connector are shown in Fig. 6. X-HVB shear connectors are built from material which obtained predominately nonlinear stress-strain relationship, as shown in Fig. 6. Initial part of the stress-strain curves, up to 3% of strain, were obtained from measurements of strain gauges, which is given in Fig. 6 with curves H1-SG to H4-SG.

Nominal stress-strain curves denoted with H1 to H4 in Fig. 6 represent a measurements from testing machine based on the displacement of the machine grips and gauge length of 36 mm. Average value of 0.2% proof stress f_{02} obtained from measurements of strain gauges for four tensile coupons is 235 MPa. Average tensile strength is 295 MPa. Conventional yield strength of material DC04 which is used for manufacturing of X-HVB shear connectors is between 140 MPa and 210 MPa, according to EN 10130 (2006) and lower yield strength should be used for design purposes. Analysing experimentally obtained data it can be concluded that manufacturing process of X-HVB shear connectors leads to material strength-enhancement.

Material properties of infill concrete were examined on concrete cubes and cylinders made of every concrete batch (minimum three specimens of every concrete batch). Average material properties of the infill concrete at the age of push-out tests are given in Table 2, for every test series. According to the obtained measurements, achieved concrete class of infill concrete for HSF and HSB specimens is C20/25 and of HSFg and HSFg-2 is C25/30, according to Eurocode 2 (2004).

Experimental results of push-out tests of X-HVB 110 shear connector in prefabricated concrete slabs are presented in Tables 3 and 4. Experimentally obtained ultimate shear resistances P_{ult}, for all examined specimens and their comparison with characteristic shear resistance of X-HVB 110 shear connectors in solid concrete slabs according to ETA-15/0876 Assessment (2016) are presented in Table 3. One specimen from HSFg-2 test series obtained unexpected failure mode due to mistakes of installation process, which is explained in detail in Chapter 5. Results of this test specimen, HSFg1-2, are not used for statistical evaluation of HSFg-2 test series.

Table 2 Average material properties of infill concrete

Specimen series	Compressive strength (cube)	Compressive strength (cylinder)	Axial tensile strength	Elastic modulus
	$f_{cm,cube}$ [MPa]	f_{cm} [MPa]	f_{ctm} [MPa]	E_{cm} [GPa]
HSF, HSB	38.87	28.51	2.50	27.61
HSFg	-	33.68	2.67	33.05
HSFg-2	-	37.15	2.88	35.34

Table 3 Ultimate shear resistance of X-HVB 110 shear connector

Specimen series	Ultimate shear resistance	Mean value / Coefficient of variation	Characteristic shear resistance	Comparison with ETA-15/0876 (2016)	Specimen series	Ultimate shear resistance	Mean value / Coefficient of variation	Characteristic shear resistance	Comparison with ETA-15/0876 (2016)
	P_{ult} [kN]	[kN], (%)	[kN]	P_{ult} / P_{Rk}		P_{ult} [kN]	[kN], (%)	[kN]	P_{ult} / P_{Rk}
HSF1	341.7	335.4	299.0*	1.22	HSFg1	275.7	284.6	266.4*	0.98
HSF2	350.5			1.25	HSFg2	289.4			1.03
HSF3	330.6	4.1	286.7**	1.18	HSFg3	282.6	2.4	248.1**	1.01
HSF4	318.6			1.14	HSFg4	290.7			1.04
HSB1	301.3	300.3	268.2*	1.08	HSFg1-2	266.0	323.8	278.0*	1.17
HSB2	293.9			1.05	HSFg2-2	326.3			
HSB3	317.0	4.1	260.2**	1.13	HSFg3-2	335.9	4.2	278.2**	1.20
HSB4	289.1			1.03	HSFg4-2	309.1			1.10

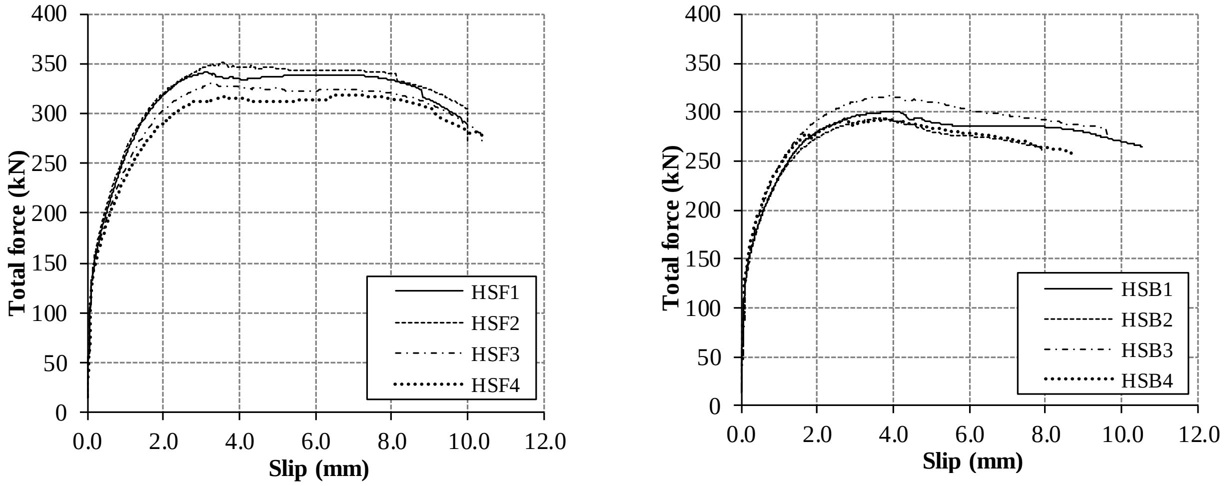
*Eurocode, Annex D (2010), ** Eurocode 4, Annex B (2004)

Table 4 Average slip and separation

Specimen series	Slip - average (mm) initial	char.	total	Separation - average (mm) between slabs	steel to concrete	Specimen series	Slip - average (mm) initial	char.	total	Separation - average (mm) between slabs	steel to concrete
	δ_{init}	δ_{uk}	$\delta_{u,tot}$				δ_{init}	δ_{uk}	$\delta_{u,tot}$		
HSF1	0.12	9.69	9.81	2.32	1.69	HSFg1	0.11	6.22	6.33	1.79	1.17
HSF2	0.10	10.02	10.12	2.32	1.78	HSFg2	0.12	5.44	5.56	1.81	1.49
HSF3	0.13	9.59	9.72	2.13	1.86	HSFg3	0.09	6.38	6.47	1.80	1.53
HSF4	0.14	9.20	9.34	2.39	1.64	HSFg4	0.10	6.53	6.63	1.83	1.63
Mean	0.12	**9.63**	9.75	2.29	1.74	Mean	0.11	**6.14**	6.25	1.81	1.46
HSB1	0.15	10.19	10.34	2.82	2.40	HSFg1-2	-	-	-	-	-
HSB2	0.17	7.36	7.53	2.41	2.04	HSFg2-2	0.14	8.50	8.64	2.11	1.25
HSB3	0.11	9.67	9.78	2.74	2.51	HSFg3-2	0.12	7.35	7.47	2.16	1.53
HSB4	0.15	7.60	7.75	2.10	1.86	HSFg4-2	0.08	6.96	7.04	1.92	1.49
Mean	0.15	**8.71**	8.85	2.52	2.20	Mean	0.11	**7.60**	7.72	2.06	1.42

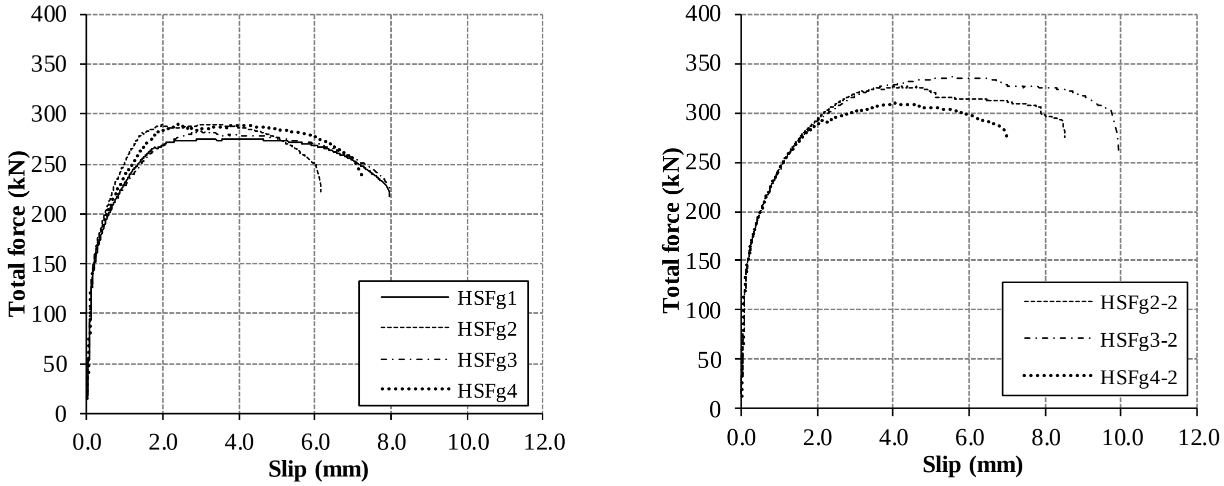
Statistical evaluation of ultimate shear resistance P_{ult} is calculated according to recommendations given in Eurocode, Annex D (2010) and Eurocode 4, Annex B (2004), for all test series. Characteristic shear resistance according to Eurocode (2010) is calculated with factor k_n equal to 2.63 for HSF, HSB and HSFg test series and 3.37 for HSFg-2 test series.

Average slip δ measured from four sensors (V1-V4), average uplift measured between concrete slab and steel beam (sensors H1-H2) and separation between concrete slabs (sensor S1) are presented for all examined specimens in Table 4. Longitudinal slip δ is divided into initial slip accumulated during cyclic loading δ_{init} and characteristic value of slip capacity δ_{uk}. Total slip $\delta_{u,tot} = \delta_{init} + \delta_{uk}$ is presented in Table 4. Characteristic value of slip capacity δ_{uk} is obtained for 90% of ultimate shear force on



(a) HSF specimens (b) HSB specimens

Fig. 7 Results of push-out tests – minimal distance between shear connectors



(a) HSFg specimens (b) HSFg-2 specimens

Fig. 8 Results of push-out tests – reduced distance between shear connectors

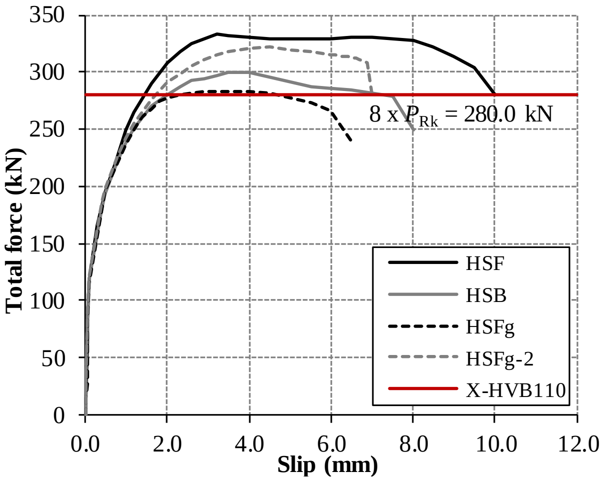
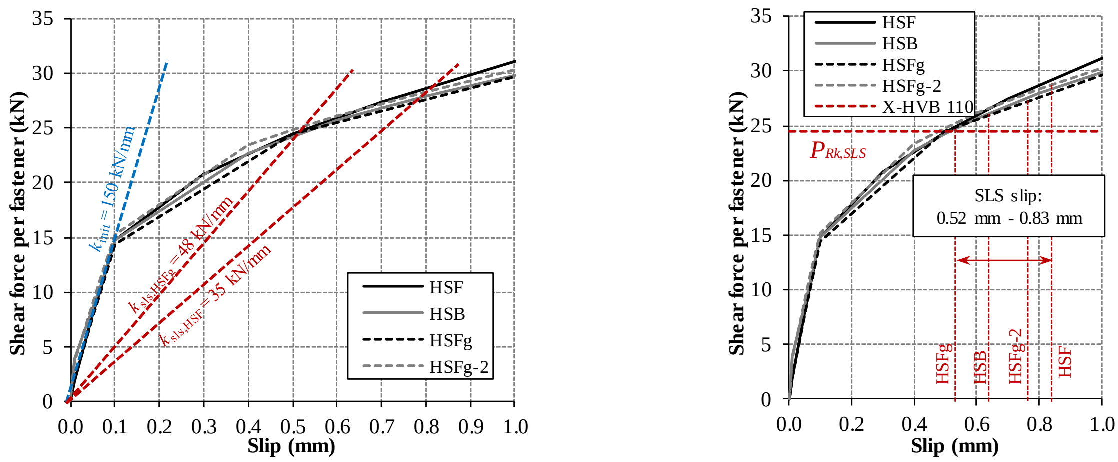


Fig. 9 Average results of push-out tests



(a) shear connector stiffness (b) SLS slip

Fig. 10 Average results of push-out tests

descending branch of load-slip curve and used as a main property of shear connectors, with respect to ductility, according to Eurocode 4 (2004). Also, average uplift and separation is presented for the same loading level as for characteristic value of slip capacity δ_{uk}.

Failure loading of four analysed test series are presented in Figs. 7 and 8. Force-slip curves of HSF specimens (forward orientation of shear connectors) and HSB specimens (backwards orientation of shear connectors) are given in Fig. 7. Considering ultimate shear resistance P_{ult} and characteristic value of slip capacity δ_{uk} of these two test series, forward orientation of shear connectors with minimal recommended distances between connectors, can be considered as more favourable. Approximately 12% higher average ultimate shear resistance and 11% higher characteristic value of slip capacity is obtained for HSF series in comparison to the HSB series. This can be caused by (a) orientation of shear connector fastening leg; cartridge fired pins are positioned behind the anchorage leg for HSF test series, relative to the shear force direction and (b) possible confinement conditions in concrete developed behind the connector anchorage leg and beyond the fasteners.

As a result of more favourable behaviour, forward orientation of shear connectors is further analysed through two test series with reduced distances between shear connectors. Two alterations are: reduced longitudinal and transverse distance and different installation power level. Force-slip curves for failure loading of HSFg and HSFg-2 specimens are given in Fig. 8. Approximately 14% higher ultimate shear resistance is obtained for HSFg-2 series in comparison to the HSFg series. Considering the same specimens' layout for both test series, lower ultimate shear resistance for HSFg series is a consequence of lower depth of pin installation in steel base material due to lower nailing power level (approximately 2 instead 3.5 power level which is used for pins installation of HSF, HSB and HSFg-2 series). Also, lowering of nailing power reduced the characteristic value of slip capacity for approximately 19%.

The influence of group arrangement of shear connectors with reduced distances can be analysed based on the experimental results gained from HSF and HSFg-2 test series, with same nailing power level obtained during installation procedure. Mean value of ultimate shear resistance for HSFg-2 series is approximately 4% lower in comparison to the HSF series. Group arrangement of shear connectors, when they are positioned one next to another, did not significantly influenced ultimate shear resistance, but obtained mean value of slip capacity is 20% lower in comparison to the HSF specimens. Lowering of nailing power level for HSFg test series resulted in approximately same reduction of slip capacity (HSFg-2 vs. HSFg and HSF vs. HSFg-2 test series).

Average force-slip curves of four experimentally analysed test series are given in Fig. 9. Also, characteristic shear resistance of eight X-HVB 110 connectors according to recommendations given in ETA-15/0876 Assessment (2016) is presented. Mean value of experimentally obtained ultimate shear resistance is higher than characteristic shear resistance of eight X-HVB 110 shear connectors, for all analysed test series, as presented in Table 3 and Fig. 9.

Analysis of shear connector stiffness and slip for serviceability limit state SLS, corresponding to approximately $0.7P_{ult}$ is presented in Fig. 10. Initial stiffness of one shear connector for all analysed test series is approximately the same and amounts 150 kN/mm, as shown in Fig. 10(a). Initial stiffness of X-HVB 110 shear connector is lower than stiffness of 16 mm diameter headed studs and bolted shear connectors, which amounts 300 kN/mm and 165 kN/mm, respectively, as presented by Pavlović *et al.* (2013). Stiffness corresponding to the SLS for one shear connector is the largest for HSFg test series, approximately 48 kN/mm, while the lowest value is obtained for HSF test series and amount approximately 35 kN/mm, in comparison to the 122 kN/mm for headed studs and 68 kN/mm of bolted shear connectors (Pavlović *et al.* 2013). Obtained slip for SLS, given in Fig. 10(b), is in the range from 0.52 mm for HSFg series to 0.83 mm for HSF series, respectively. Linear behaviour of shear connectors corresponding to service load levels is uniform, both for all analysed connectors' layouts and different installation power levels, as presented in Fig. 10(b).

(a) HSF specimens (b) HSB specimens

Fig. 11 Specimens after testing procedure – minimal distances between connectors

(a) HSFg specimens (b) HSFg-2 specimens

Fig. 12 Specimens after testing procedure – reduced distances between connectors

Also, for all experimentally investigated push-out test series, the mean value of characteristic slip δ_{uk} is higher than 6.0 mm which is the minimum required according to Eurocode 4 (2004) to consider this type of shear connector as ductile. Mean value of characteristic value of slip capacity δ_{uk} of all analysed test series is in the range from 6.14 mm to 9.63 mm, as presented in Table 4. X-HVB 110 shear connectors reached ultimate shear force at slip of approximately 4.0 mm, for all analysed test series. This is lower in comparison to the headed studs, according to experimental results presented by and approximately the same value as for bolted shear connectors, presented by Pavlović *et al.* (2013).

4. Characteristic failure mechanisms

Characteristic failure mechanisms of headed studs in solid concrete slabs are well known and explained in various literature. Load transfer is determined with deformation of shear connector and high bearing resistance of concrete influenced by confinement condition and triaxial restraint of surrounding concrete.

In comparison to the headed studs, failure mechanisms of mechanically fastened shear connectors are not still analytically explained. Their overall behaviour and failure mechanisms are related to deformation of shear connector and bearing resistance of concrete, but mostly governed with deformation and resistance of fasteners. Therefore, installation depth of cartridge fired pins into steel base material is of particular importance for growth of anchorage mechanisms, shear force transfers from steel beam to concrete slab and achieved failure mechanism.

Global cracks in prefabricated concrete slabs or separation of contact layer between infill concrete and prefabricated slab were not obtained in examined specimens of all test series. All failure mechanisms are obtained in infill concrete of envisaged openings. Infill concrete zone of HSF and HSB specimens after the testing procedure are shown in Fig. 11. Concrete slabs, which are cut through shear connectors after testing procedure, are presented in Fig. 11. Achieved failure mechanism of forward orientations of shear connectors (HSF series) is: pull-out failure of most pins and shear failure of some pins without significant damage in concrete and deformation of connectors. Deformation of concrete is only located at the surrounding zone of fasteners head, which is related to deformation of fasteners and their pull-out from base material. Backward orientation of shear connectors resulted in extensively different failure mechanism. Significant deformation of shear connectors is followed with notable damage of concrete and subsequent fasteners pull-out from base material, as presented in Fig. 11. Possible confinement condition and triaxial restraint of concrete behind forward oriented shear connectors is located in the surrounding zone of cartridge fired pins, resulting in low deformation of concrete and failure of fasteners' anchorage mechanisms. By positioning of connector's anchorage leg and fasteners in front of concrete confined zone for backward oriented shear connectors, less favourable behaviour is achieved.

Similar failure mechanisms are obtained for specimens with reduced transverse and longitudinal distance between connectors, HSFg and HSFg-2 test series. Infill concrete zone after testing procedure for two specimens within these test series, HSFg2 and HSFg3-2 specimens is shown in Fig. 12. Failure of these specimens is followed with lower

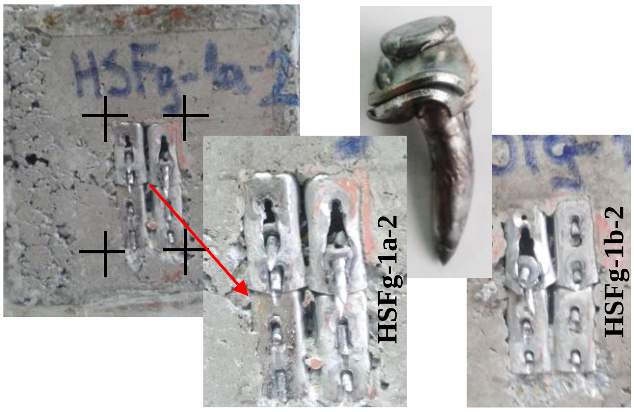


Fig. 13 Inappropriate installation of cartridge fired pins

concrete damage in comparison to the HSF specimens, which is again located beyond the pins head of the first shear connector row. Obtained failure mode of all HSFg specimens is pull-out of all fasteners. HSFg-2 test specimens, with approximately two times higher installation power level in comparison to the HSFg specimens, failed due to shear failure of most fasteners (HSFg2-2 and HSFg3-2 specimens). Cracking of the infill concrete zone is obtained at the top of fastener anchorage leg, for HSFg3-2 specimen. HSFg4-2 specimen with the lower ultimate shear resistance failed due to pull-out failure of all fasteners.

Considering obtained failure mechanisms presented in previous figures, ductile behaviour of shear connectors according recommendations given in Eurocode 4 (2004) is mostly obtained from deformation capacity of cartridge fired pins and concerned anchorage mechanisms during the installation process. Deformation of cartridge fired pins can be obtained only through deformation of concrete and development of tensile forces in fasteners, until the complete failure of anchorage mechanisms and fasteners pull-out is achieved. Shear failure of fasteners is achieved due to low deformation and unharmed anchorage mechanisms.

5. Installation susceptibility

Inappropriate installation of X-ENP-21 HVB cartridge fired pins of HSFg1-2 test specimen resulted in 18% lower ultimate shear resistance in comparison to the mean value obtained for HSFg-2 test series, as presented in Table 3.

Through the installation of second cartridge fired pin at the first row connector of the HSFg1-2 specimen's *a* side (sensors V1, V3 and H1, Fig. 4) installation mistake occurred. During the positioning of the fastening tool, fastener guide is not turned into the position for installation of the second pin, according to operating instructions. Installation of the second pin is attempted above already installed first pin, which resulted in significant deformation and inappropriate installation of first pin, as shown in Fig. 13. Moreover, throughout installation of the cartridge fired pins at *b* side of the specimen (sensors V2, V4 and H2, Fig. 4) two pins at two different connectors and one pin at *a* side of specimen, are not installed in holes that are provided for that at connector fastening leg, which is shown in Fig. 13. Besides the significantly lower ultimate shear resistance of HSFg1-2 test specimen, different failure mechanism is obtained after the testing procedure. In comparison to the failure mechanisms of all analysed test series presented in Chapter 4, HSFg1-2 test specimen failed due to bearing failure of fastening leg of connectors with inappropriate installation. Also, shear failure is obtained for cartridge fired pins which are installed accurately, which was the characteristic failure mechanism of HSFg-2 test series.

6. Conclusions

In this paper, experimental data gained from standard push-out tests with X-HVB 110 shear connectors, as a main representative of mechanically fastened shear connectors, are presented. The investigation emphasizes the possible application of X-HVB shear connectors in prefabricated composite construction, when shear connectors are discontinuously positioned in envisaged openings of concrete slabs. Experimental investigation included analysis of different connectors orientation, variation of connectors' distances and influence of pins' installation power levels. Besides, this investigation fills the gap created by the lack of experimental results presented in this structural area. Based on experimental findings, the following conclusions can be drawn:

- Different positioning of shear connector's fastening leg relative to the shear force direction strongly influences experimentally obtained ultimate shear resistance, slip capacity and failure mechanisms. It is shown that forward orientation of shear connectors is more favourable. Up to 12% larger ultimate shear resistance and 11 % larger characteristic value of slip capacity is obtained for HSF test series in comparison to the HSB series, based on mean values of push-out specimens within one test series.
- For group arrangement of shear connectors without clear longitudinal and transversal spacing between connectors, 4% lower ultimate shear resistance is obtained for HSFg-2 test series in comparison to the HSF test series, with same installation procedures.

- Approximately 50% lower installation power level for HSFg test series influenced in 14% lower ultimate shear resistance and 19% lower characteristic slip in comparison to the HSFg-2 test series with same specimens' layout.
- Concrete damage of all specimens are obtained in infill concrete of envisaged openings, without global cracks in prefabricated concrete slabs or separation of contact layer between infill concrete and prefabricated slab.
- Stiffness of single shear connector at serviceability loads is in the range from 48 kN/mm to 35 kN/mm. Stiffness is reduced up to 70% when compared to headed studs and up to 30% in comparison to the bolted shear connectors due to the failure of pins' anchorage mechanisms and pull-out of fasteners.
- X-HVB 110 shear connectors in prefabricated concrete slab showed ductile behaviour. For all examined test series average ultimate shear resistance is larger than characteristic shear resistance proposed by manufacturer.

Behaviour of X-HVB shear connectors in composite shear connections is mostly related to deformation capacity and failure mechanisms of cartridge fired pins. A major challenge for a wider use of mechanically fastened shear connectors is the lack of experimental and numerical data in this filed. Besides, numerical simulation of experimentally gained data would be necessary for complete understanding of behaviour of mechanically fastened shear connector and their wider application in prefabricated composite construction.

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References

ANSI/AISC 360-05 (2005), *An American National Standard - Specification for structural steel buildings*, American Institute of Steel Construction; Chicago, Illinois.

Arrayago, I., Real, E. and Gardner, L. (2015), "Description of stress–strain curves for stainless steel alloys", *Materials & Design*, **87**, 540-552. doi: 10.1016/J.MATDES.2015.08.001.

Ataei, A., Moradi M., Valipuor, R.H. and Bradford, A.M. (2018), "Finite element modelling of demountable precast reinforced concrete deck slabs with external confining system", *J. Constr. Steel Res*., **151**, 204-215. doi: 10.1016/j.jcsr.2018.09.023.

Beck, H., Siemers, M. and Reuter, M. (2011), *Steel Construction Calendar 2011 - Powder-Actuated Fasteners and Fastening Screws in Steel Construction*, Ernst & Sohn.

Crisinel, M. (1990), "Partial-interaction analysis of composite beams with profiled sheeting and non-welded shear connectors", *J. Constr. Steel Res.*, **15**, 65-98.

EN 10002-1 (2001), *Metallic materials - Tensile testing - Part 1: Method of test at ambient temperature*, European Committee for Standardization; Brussels, Belgium.

EN 10025-2 (2004), *Hot rolled products of structural steels. Part 2: Technical delivery conditions for non-alloy structural steels*, European Committee for Standardization; Brussels, Belgium.

EN 10130:2006 (2006), *Cold rolled low carbon steel flat products for cold forming - Technical delivery conditions*, European Committee for Standardization; Brussels, Belgium.

Eurocode (2010), *Basis of structural design*, European Committee for Standardization; Brussels, Belgium.

Eurocode 2 (2004), *Design of Concrete Structures. Part 1-1: General rules and rules for buildings,* European Committee for Standardization; Brussels, Belgium.

Eurocode 4 (2004), *Design of composite steel and concrete structures. Part 1-1: General rules and rules for buildings*, European Committee for Standardization; Brussels, Belgium.

ETA-15/0876 (2016), *European Technical Assessment*, Deutsches Institut fur Bautechnik, Berlin.

Feidaki, E., Vasdravellis, G., He, J. and Wang, S. (2019), "Steel-yielding demountable shear connector for composite floors with precast hollow-core slab units", *J. Struct. Eng.*, **145**(8), 1-17, doi: 10.1061/(ASCE)ST.1943-541X.0002356.

Fontana, M. and Bärtschi, R. (2002), "*New types of shear connectors with powder-actuated fasteners*", Institute of Structural Engineering Swiss Federal Institute of Technology, Zurich

Goldspiegel, F., Mocellin, K. and Michel, P. (2019), "Numerical modelling of high-speed nailing process to join dissimilar materials: Metal sheet formulation to simulate nail insertion stage", *J. Mater. Process. Technol.* **267**, 414-433. doi: 10.1016/j.jmatprotec.2018.10.022.

Johnson, R.P. and Molenstra, I.N. (1991), "Partial shear connection in composite beams for buildings", *Proceedings of the Institution of Civil Engineers*, **91**(4), 679-704. doi: 10.1680/iicep.1991.17485.

Le, V.P.N., Bui, D.V., Chu, T.H.V., Kim, I.T., Ahn, J.H. and Dao, D.K. (2017), "Behavior of steel and concrete composite beams with a newly puzzle shape of crestbond rib shear connector: an experimental study", *Struct. Eng. Mech.*, **60**(6), 1001-1019. doi: 10.12989/sem.2016.60.6.1001.

McComb, C. and Tehrani, F.M. (2015), "Enhancement of shear transfer in composite deck with mechanical fasteners", *Eng. Struct.*, **88**, 251-261. doi: 10.1016/j.engstruct.2015.01.046.

Pathirana, S.W., Uy, B., Mirza, O. and Zhu, X. (2016), "Bolted and welded connectors for the rehabilitation of composite beams", *J. Constr. Steel Res.*, **125**, 61-73. doi: 10.1016/j.jcsr.2016.06.003.

Pavlović, M., Marković, Z., Veljković, M. and Buđevac, D. (2013), "Bolted shear connectors vs. headed studs behaviour in push-out tests", *J. Constr. Steel Res.*, **88**, 134-149. doi: doi.org/10.1016/j.jcsr.2013.05.003.

Rehman, N., Lam, D., Dai, X. and Ashour, A.F. (2016), "Experimental study on demountable shear connectors in composite slabs with profiled decking", *J. Constr. Steel Res.*, **122**, 178-189. doi: 10.1016/j.jcsr.2016.03.021.

Spremic, M., Pavlovic, M., Markovic, Z., Veljkovic, M. and Budjevac, D. (2018), "FE validation of the equivalent diameter calculation model for grouped headed studs", *Steel Compos. Struct.*, **26**(3), 375-386. doi: 10.12989/scs.2018.26.3.375.

Standard specifications for steel and composite structures (2009), JSCE Japan Society of Civil Engineers, Tokyio, Japan.

Suwaed, A.S.H. and Karavasilis, T.L. (2017), "Novel demountable shear connector for accelerated disassembly, repair, or replacement of precast steel-concrete composite bridges", *J. Bridge Eng.*, **22**(9), 1-18. doi: 10.1061/(ASCE)BE.1943-5592.0001080.

Tahir, M., Shek, P.N. and Tan, C.S. (2009), "Push-off tests on pinconnected shear studs with composite steel-concrete beams", *Constr. Build. Mater.*, **23**(9), 3024-3033. doi: 10.1016/j.conbuildmat.2009.04.008.

Vianna, J. da C., Andrade, de S.A.L., Vellasco, P.C.G. da S. and Costa-Neves, L.F. (2013), "Experimental study of perfobond shear connectors in composite construction", *J. Constr. Steel Res.*, **81**, 62-75. doi: 10.1016/j.jcsr.2012.11.002.

Wang, Y.H., Yu, J., Liu, J.P., and Chen, Y.F. (2019), "Shear behavior of shear stud groups in precast concrete decks", *Eng. Struct.*, **187**, 73-84. doi: 10.1016/j.engstruct.2019.02.002.

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