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The usability of earthquake resistant steel bars as shear connectors in composite structures

A. Köken[a] and M.A. Köroğlu[b,*]

a. *Department of Civil Engineering, Selcuk University, 42075 Konya/Turkey.*
b. *Department of Civil Engineering, Necmettin Erbakan University, 42060 Konya/Turkey.*

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Push-out test;
Composite beam.

Abstract. Shear connectors are used to avoid potential slipping between steel and concrete and slipping due to deformations on a concrete plate. Many materials having different shapes and dimensions are tested as shear connectors. In this study, the availability of earthquake resistant steel bars, manufactured the same length as headed studs, is investigated. For this purpose, 4 push-out tests accomplished to the composite beams with profiled steel sheeting, in which earthquake resistant steel bars are used as the shear connector, and 4 push-out tests, in which headed studs are used as the shear connector, are undertaken. In the experimental section, 8 push-out tests performed on 16 slab specimens with different slab height, and different numbers and arrangements of shear connectors. As a result of the tests, it is suggested that earthquake resistant steel can be used as an alternative material for shear connectors.

1. Introduction

Two or more structural members joined together using different materials is called "a composite structure". Each material of a composite structure usually has a superior property effectively used for providing the composite behavior of the materials. Although several materials are used as the shear connector of a composite structure, "headed stud" shear connectors are generally used in constructions due to their practicality [1].

After the invention of composite structures, many types of shear connector were used [2]. Alexander C. studied the "Standoff Screw" shear connector in the Materials and Construction Investigation Laboratory at Virginia Technical University. It is screwed onto laminated steel plates using screw guns, and 106 small-scale push-out tests using 11 groups were carried out in order to investigate the usability of the "Standoff Screw" as a shear connector [3]. Kim et al. experimentally studied the behavior of shear connectors in composite beams prepared on steel plates. They produced three specimens and discussed test results and modeled push-out tests, biaxially and triaxially. The objective of their tests was to determine the load-displacement relationships, maximum shear load capacity and failure types of the shear connectors (headed studs of 13 mm diameter and 65 mm length) with composite beams [4]. Roddenberry investigated the resistance and behavior of shear connectors against shear after they were used in composite members, and push-out test devices were produced to perform today's mostly used method, the "push-out test", in order to examine the behavior of the shear connectors. 24 reinforced concrete push-out tests, 93 composite slab push-out tests and 3 composite beam tests were performed in this study, and the test results were compared with the standards of the American Code, Canadian Code and Eurocode-4 [5]. Valente and Cruz undertook 12 push-out tests in 4 groups

*. *Corresponding author. Tel.: +90 332 280 80 76; Fax: +90 332 236 21 40*
E-mail addresses: akoken@selcuk.edu.tr (A. Köken); makoroglu@konya.edu.tr (M.A. Köroğlu)

Figure 1. A photo of a specimen prepared for the tests [10].

to investigate the behavior of perfobond steel used as the shear connectors of lightweight concrete composite slabs [1].

The behavior of the headed studs used in composite beams, together with laminated steel plates, depends on the strength, dimensions and direction of the studs, the geometry of the laminated steel plates and the strength of the concrete [6]. Ellobody and Young performed 13 and 18 push-out tests with laminated plates and composite slabs welded to each other by φ19 mm and φ16 mm shear connectors, respectively. The shear occurred during the tests were measured with precise instruments and compared with Eurocode-4 and American Code standards [7].

Many types of composite slab formed with steel plate profile models and laminated in various ways are used for the construction of buildings and bridges. Kim et al. prepared 17 composite slab specimens produced with reinforced lightweight concrete using "perfobond" shear connectors on the laminated galvanized steel plates, and full-scale slab tests and push-out tests were performed on these specimens [8]. Larbi et al. used epoxy and polyurethane as shear connectors. The dimensions of the specimens used for push-out tests were specified referring to the Eurocode-4 standard. During the specimen preparation stage, three different connection thicknesses and two surface behaviors were investigated, and 100 $\times$ 100 mm dimensions were selected for the areas on which the plates (surfaces) were connected [9].

In this study, the usability of Turkish Earthquake Resistant Steel Bars in composite slabs as a shear connector was studied in the light of assuming this type of shear connector to be more durable and more economic than the alternatives.

2. Experimental study

According to Eurocode-4, the variables considered in push-out tests are the geometrical and mechanical characteristics of concrete slabs, shear connectors and reinforcements. Additionally, failure loads, failure types and load-displacement performances are all determined with the help of push-out tests.

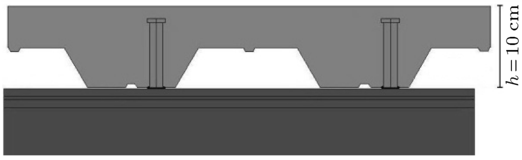
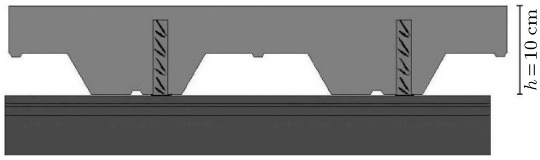
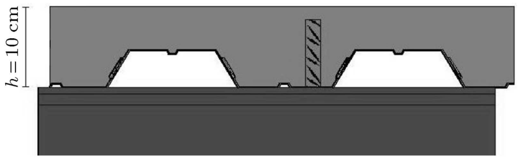
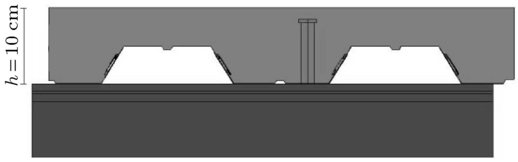
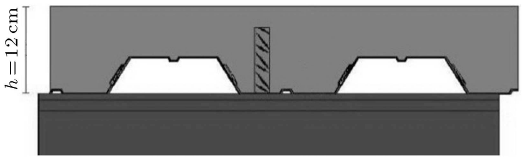
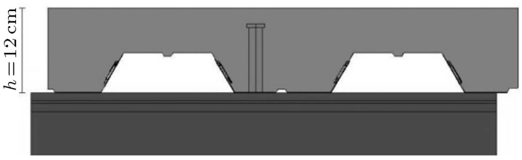
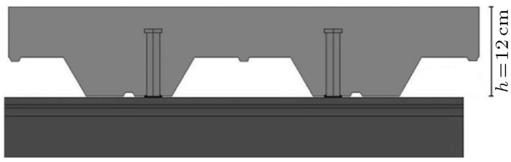
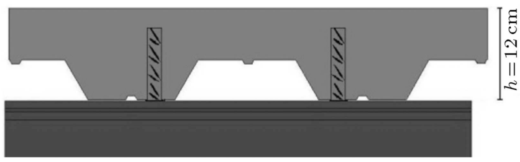
The push-out specimens were fabricated using 650 mm long pieces of an IPE 240 steel section. The steel section was cut into 2 equal pieces using a steel band saw. Profiled steel sheeting was mounted on the beam and shear connectors were welded on the flange of the beam with profiled steel sheeting. Plywood forms were erected around the steel section for casting concrete. The slabs of all the push-out specimens were cast horizontally. Normal weight concrete was poured directly into the slab forms. Concrete cylinders (15 mm diameter $\times$ 30 mm length) were prepared during each pouring. After hardening of the concrete, the plywood molds were removed and the slab was cured for 28 days. The preparation step of the specimens is shown in Figure 1. Slab dimensions were taken as $650 \times 650 \times 120$ mm for the first 8 specimens and $650 \times 650 \times 100$ mm for the remaining 8 specimens by taking the previous studies as reference. In Table 1, the properties of the specimens are shown. The specimens with one and two shear connectors were labeled "1" and "2", respectively, in front of the names of the specimens. The specimens with 10 cm and 12 cm slab thicknesses were labeled "10" and "12", respectively, at the end of the names of the specimens. If an earthquake resistant steel bar is used as a shear connector, "E" is placed between these two numbers (10 or 12), and, similarly, if a headed stud was used as a shear connector, "K" is written between the numbers.

The most significant difference between the test specimens is the varying type of shear connector. Eight specimens used a headed stud as the shear connector, which has widespread use due to mass production, and a φ20 earthquake resistant steel bar was used in 8 specimens due to its geometry and economical viability.

An earthquake resistant steel bar is a steel reinforcement bar used in concrete and produced by a heating process during hot rolling with the ribs on it to increase the adherence between concrete and steel. It is abundantly manufactured in recent years with an increasing use in reinforced concrete constructions due to its advantages in terms of ductility, weldability, adherence, corrosion resistance and strength. The earthquake resistant steel bar is considerably ductile due to its higher uniform elongation under maximum loading and its higher ratio of yield strength to tensile strength, i.e. $f_s/f_y = 710/460 = 1.54$.

To increase workability, i.e. to increase the ability to give shape, reinforced concrete steel is subjected to a heating process, after which, the carbon amount is adjusted, according to the required type of steel, in order to provide the easy shaping of the earthquake resistant steel bar during heat treatment. The earthquake

Table 1. Test specimen properties.

Specimen	Specimen property		Specimen shapes
	Shear connector number	Slab height	
2K10	2	$h = 10$ cm	
2E10	2	$h = 10$ cm	
1E10	1	$h = 10$ cm	
1K10	1	$h = 10$ cm	
1E12	1	$h = 12$ cm	
1K12	1	$h = 12$ cm	
2K12	2	$h = 12$ cm	
2E12	2	$h = 12$ cm	

resistant steel bar is a more favorable material than other concrete construction steel, due to its resistance against corrosion, and the weldability characteristics resulted from the processes applied to the earthquake resistant steel bar again during heat treatment. As a result of its weldability, the earthquake resistant steel bar is mostly used for plates to which welded connectors are applied [10].

The notches made on a ribbed steel surface during the production stage provide tight adherence between concrete and the reinforcement. The earthquake resistant steel bar with its higher clutching property, depending on rib angle and rib height, is more superior, with respect to other reinforcing steel. The shape of the earthquake resistant steel bar can be seen in Figure 2.

In order to determine the mechanical characteristics of an earthquake resistant steel bar, $\varphi 20$ earthquake resistant steel bar bars were subjected to a tensile test. A stress-strain diagram is given in Figure 3. It is clearly seen in the stress-strain diagram that the tensile strength is 710 N/mm^2 and that it is 1.54 times more than the yield strength. The greater difference between yield and tensile resistance provides more ductile steel.

The push-out tests performed in this study provided a shear connection capacity of 19×80 mm headed studs for four specimens, and 20×80 mm earthquake

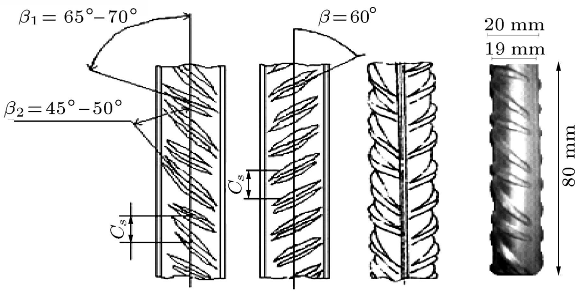


Figure 2. The shape of earthquake resistant steel bar [10].

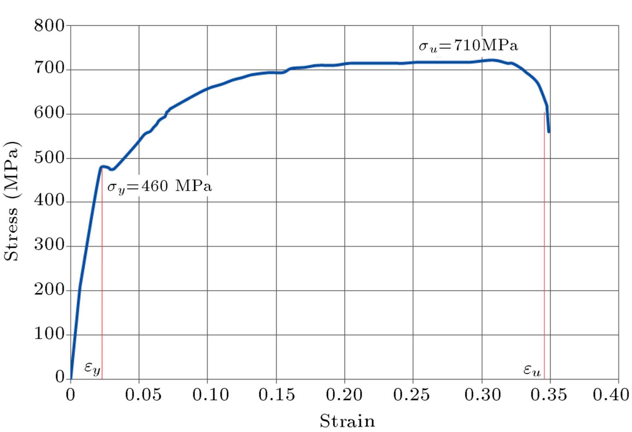


Figure 3. Stress-strain diagram of the earthquake resistant steel bar.

Figure 4. The shape of headed shear stud [10].

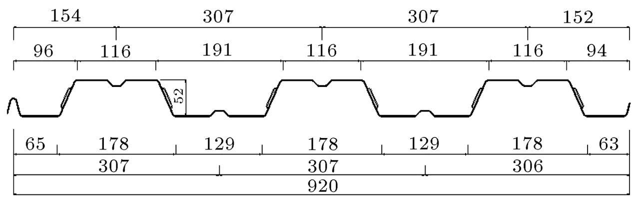


Figure 5. The shape of profiled steel sheeting [10].

resistant steel bars for the other four specimens, welded through-deck in composite slabs with profiled steel sheeting. The headed studs used in this study have an ultimate tensile strength of 635 MPa and a modulus of elasticity of 205 GPa. The geometry of a shear stud is shown in Figure 4. The height of the stud is 80 mm and the diameter is 19 mm. The height of the stud head is 10 mm and its width is 32 mm. The profiled steel sheeting has a depth (h_p) of 52 mm, average width (b_0) of 178 mm and plate thickness (t) of 1 mm. The geometry of the sheeting is shown in Figure 5. The composite concrete slab has a depth (D) of 100 mm 120 mm, width (B) of 650 mm and height (H) of 650 mm. The concrete slabs of the push-out tests conducted in this study have an average measured concrete cylinder strength of 27 MPa.

3. Calculating shear capacity of composite beams with profiled steel sheeting

Shear connection behavior is an essential factor for the design strength and stiffness of composite beams with profiled steel sheeting. The main factors in establishing the strength of shear connectors due to EC4 are: shape and dimension, material quality, concrete strength, type of load (static and dynamic), ways of connecting the steel beams, distance between shear connectors, dimensions of the concrete slab, the percentage and way of reinforcing, sheeting type, and the dimension of the steel sheeting (see Figure 6). The calculation of the design strength of shear stud connectors in composite beams with profiled steel sheeting for the AISC norm is given in Eq. (1) shown in Table 2 [12]. The r_1 (reduction factor) is a function of the deck

Table 2. A review of the regulations of shear capacity of composite beams.

Model	Expression	
AISC [12]	$P_{\mathrm{AISC}} = \left(\frac{0.85}{\sqrt{N}}\left(\frac{b_0}{h_p}\right)\left[\left(\frac{h}{h_p}\right) - 1.0\right]\right) 0.5A_s\sqrt{f_c E_c} \leq A_s f_u$	(1)
BSI BS 5950 [14]	$P_{\mathrm{BS5950}} = \left(0.25r_2 a d^2\sqrt{0.8 f_c E_c}, 0.6 r_2 f_u \frac{\pi d^2}{4}\right)\min$	(2)
EC 4 [6]	$P_{\mathrm{EC4}} = \left(0.29 r_3 a d^2\sqrt{f_c E_{\mathrm{cm}}}, 0.8 r_3 f_u \frac{\pi d^2}{4}\right)\min$	(3)
CSA [15]	$P_{CSA} = \left(4.2A_c\sqrt{f_c}, 0.5A_s\sqrt{f_c E_c} \leq A_s f_u\right)$ min; for 76 mm deck	(4-1)
	$P_{CSA} = \left(7.3A_c\sqrt{f_c}, 0.5A_s\sqrt{f_c E_c} \leq A_s f_u\right)$ min; for 38 mm deck	(4-2)

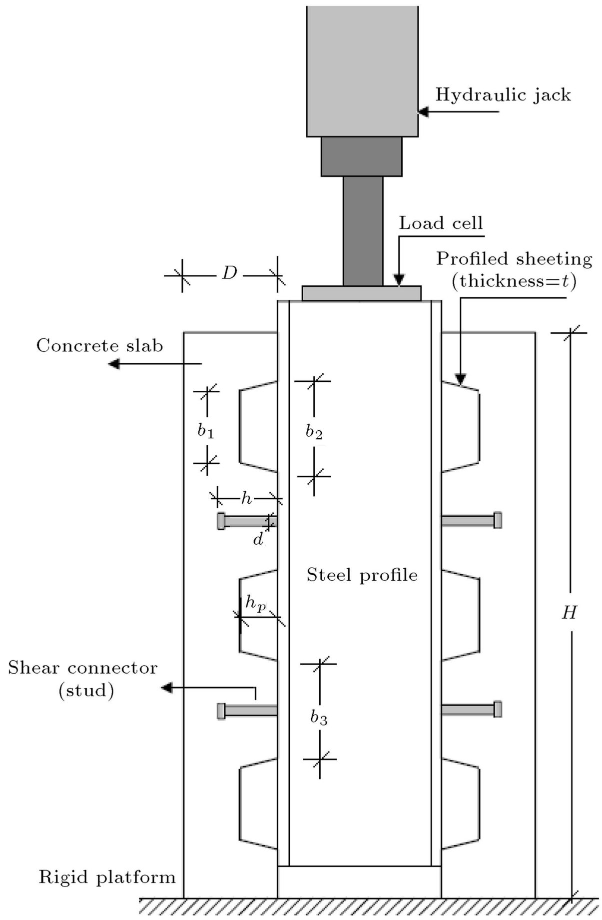


Figure 6. Test setup, dimension of concrete slab and steel sheeting [11].

geometry and the number of studs in a rib, and should not be taken greater than 1.0. The elastic modulus of concrete is $E_c = 4700\sqrt{f_c}$, according to the ACI building code [13]. For BSI (BS 5950 Part 3), the design strength of a headed shear stud connector is determined by Eq. (2) given in Table 2 [14]. In the expression, the r_2 reduction factor ($r_2 \leq 1.0$) is calculated as:

$$\underbrace{\left(\frac{0.85}{\sqrt{N}}\left(\frac{b_0}{h_p}\right)\left[\left(\frac{h}{h_p}\right) - 1.0\right]\right)}_{r_2}$$

by using ($N = 1$). The design strength for EC4 is similar to the AISC equation, but the constant, 0.5, is changed to 0.29 in the equation, and the upper limit on this strength is 80% of the tensile strength of the stud connector. The reduction factor (r_3) ranges from 1.0 to 0.6 and is calculated using r_2, but replacing the factor 0.85 by 0.7. The Canadian Standards Association (CSA) specification is the same equation as that in the AISC specification. According to the CSA, the strength of a headed shear stud connector depends on the depth of the rib, given as Eqs. (4-1) and (4-2) shown in Table 2 [15]. The reviews of these theories are given in Table 2.

4. Test results

Eight tests performed in this study were classified into four groups, named: "tests with one shear connector" and "tests with two shear connectors" for each type of shear connector (headed stud/earthquake resistant steel bar). The load-displacement relationships and the concrete types of specimens with 10 cm and 12 cm slab thicknesses, both of which have shear connectors of earthquake resistant steel bars and headed studs, were compared with each other.

When 10 cm thick slabs with one shear connector are considered, the maximum loads acting on the connectors were obtained as 68 kN and 64 kN for specimens with an earthquake resistant steel bar and a headed stud, respectively. The 1E10 specimen produced with an earthquake resistant steel bar carried 6% more load than 1K10 specimens. Both specimens failed with tensile shear cracking at the concrete around the shear connector.

When 10 cm thick slabs with two shear connectors are considered, the maximum loads acting on the connectors were obtained as 62 kN and 59 kN for specimens with an earthquake resistant steel bar and a headed stud, respectively. The 2E12 specimen carries 5% more load than the 2K12 specimen (Figure 7).

When 12 cm thick slabs with one shear connector are considered, the maximum loads acting on the connectors were obtained as 98 kN and 95 kN for specimens with an earthquake resistant steel bar and a headed stud, respectively. The 1E12 specimen produced with an earthquake resistant steel bar carried 3% more load than 1K12 specimens (Figure 7). Both specimens failed with tensile shear cracking at the concrete around the shear connector.

When 12 cm thick slabs with two shear connectors are considered, the maximum loads acting on the connectors were obtained as 73 kN and 70 kN for specimens with an earthquake resistant steel bar and a headed stud, respectively. The 2E12 specimen carried 4% more load than the 2K12 specimen (Figure 7). Maximum load acting on a shear connector, maximum load acting on a head, head displacement at the instant of the crack formation and the bearing capacity ratios of earthquake resistant steel bar/headed studs for all test specimens are given in Table 3.

The prediction accuracy of various standards of building codes related to the shear capacity of beams with headed shear connectors for the mentioned tested 4 specimens is presented in Table 4.

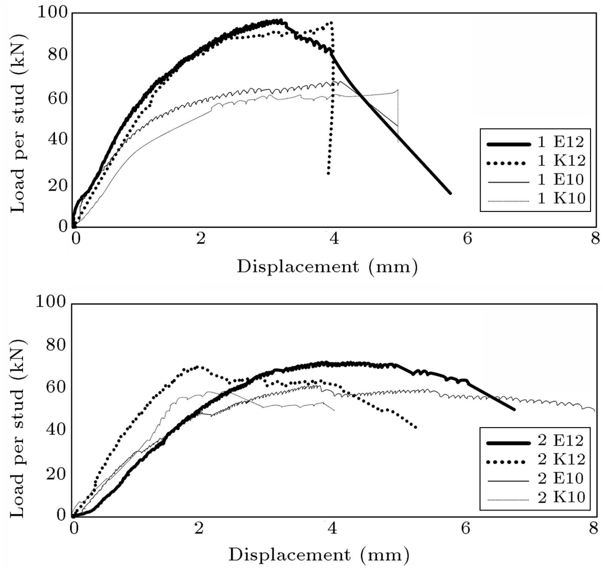


Figure 7. Load-displacement diagram of the specimens with one shear connector until the failure (cracking) load was reached.

5. Conclusion

The most important inference of the push-out tests is the usability of an earthquake resistant steel bar as a shear connector in composite slabs and composite

Table 3. Maximum load acting on a shear connector, maximum load acting on the head, head displacement at the instant of failure (cracking), and load-bearing ratios of earthquake resistant steel bar/headed stud.

Group	Specimen	Maximum load acting on one shear connector (kN)	Maximum load acting on head (kN)	Head displacement at the instant of cracking (mm)	Load-carrying ratio of earthquake resistant steel bar/ headed stud
1	1E10	68	136	4.1	1.06
	1K10	64	128	5.0	
	1E12	98	196	3.2	1.03
	1K12	95	190	4.0	
2	2E10	62	248	3.8	1.05
	2K10	59	236	2.4	
	2E12	73	292	4.5	1.04
	2K12	70	280	2.1	

Table 4. Comparison of test and analytical results of headed shear studs.

Specimen	$P_{Exp.}$ (kN)	P_{AISC} (kN)	P_{BSI} (kN)	P_{EC4} (kN)	P_{CSA} (kN)
2K10	59	109	66	90	109
1K10	64	112	68	92	112
1K12	95	116	71	96	116
2K12	70	92	56	76	92

beams. Due to its good weldability, high tensile strength and geometry, providing good adherence with concrete, the earthquake resistant steel bar is proposed as an alternative for headed studs.

The specimens prepared with an earthquake resistant steel bar and headed studs were compared with each other by the aid of experimental results, load-displacement diagrams obtained from the tests, past studies of literature and current codes. The comparisons were made according to three different variables, i.e. the type and number of shear connectors, and the thickness of the concrete slab.

Both types of shear connector presented similar behavior during the experimental study. According to the cracking (failure) load and the load acting on a shear connector in each test where the earthquake resistant steel bar was used, 6% and 5% higher loads were, respectively, obtained for 10 cm and 12 cm slab thicknesses of the first group specimens, and 3% and 4% higher loads were obtained for the second group specimens of 10 cm and 12 cm slab thicknesses, respectively.

The behavior of the slabs with the earthquake resistant steel bar was more rigid than the other specimens produced with headed studs. When shear connectors were demounted from the concrete parts of the test specimens, the amount of flexural deformation occurring at the center of the shear connectors during the tests was observed to be more for headed studs than for that of earthquake resistant steel bars. It was concluded that the earthquake resistant steel bar had good adherence with concrete and is difficult to draw from concrete. After examining the cracks of the slabs in which headed studs were used and the ultimate loads were reached, the slabs were observed to have a tendency to crack perpendicular to the laminated axes of the steel plates. This tendency can be explained by the increasing width geometry at the top sections of the studs with which the specimens were produced. After completion of the test and removing the connectors from the concrete, most of the earthquake resistant steel bars had concrete particles on their surfaces, while headed studs did not have any.

From the test results, it cannot be clearly said if there is any relationship between the steel stress-strain curve and the load-displacement curve. It is because the height of the shear connectors is not high. And it is clearly seen from the regulation formulas that when the concrete compressive strength increases, the shear capacity of the composite beams will be increased.

As a result of the tests, earthquake resistant steel bar can be suggested to be used as an alternative material for shear connectors. Consequently, performing more tests will give more accurate results for earthquake resistant steel bars used as a shear connector. In the light of this study, the following suggestions can be made for further studies to be carried out with the same loading mechanism and measuring technique:

- Further push-out tests should be done using shear connectors of different diameters and lengths for different concrete strengths.
- By changing the diameters of the shear connectors in push-out tests, the variation between the load-bearing capacities of slabs/beams and the diameters of the shear connectors should be researched.
- The slabs should be tested with and without upper-reinforcement.
- The usability of the automatic welding method (used for headed studs) for earthquake resistant steel bars should be supported with experimental studies.
- Welding operations should be carried out with great care.

Acknowledgment

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Nomenclature

A	Area of stud shank
A_c	Concrete pull-out failure surface area
A_s	Cross-sectional area of the headed stud shear connector
B	Width of composite concrete slab
b_0	Average width of concrete rib of the profiled steel sheeting
b_1	Smaller width of rib of the profiled steel sheeting
b_2	Larger width of rib of the profiled steel sheeting
b_3	Upper section of smaller width of rib of the profiled steel sheeting
D	Depth of composite concrete slab
d	Diameter of headed stud shear connector
E_c	Initial Young's modulus of concrete
E_{cm}	Mean value of the secant modulus tabulated in the EC4
e	Distance from the center of the stud's longitude
f_c	Compressive cylinder strength of concrete
f_{cu}	Compressive cube strength of concrete

f_u	Minimum specified tensile stress of the stud shear connector
f_{ys}	Yield stress of headed stud shear connector
H	Height of composite concrete slab
h	Height of the headed stud
h_p	Depth of the rib
N	Number of studs in one rib of the profiles steel sheeting
n	Number of studs subjected to similar displacements
P_{AISC}	Design strength calculated using American Specification
$P_{\text{BS 5950}}$	Design strength calculated using British Standard
P_{CSA}	Design strength calculated using Canadian Standards Association
P_{EC4}	Design strength calculated using European Code
P_{POS}	Concrete pull-out strength of a stud in a composite slab
r	Reduction factor
r_1	Reduction factor
r_2	Reduction factor
r_3	Reduction factor
V_c	Shear strength due to concrete pull-out failure (N)
λ	Factor dependent upon type of concrete
t	Profiled steel sheeting thickness

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Biographies

Ali Köken obtained a BS degree in Civil Engineering from Selcuk University in 1988, an MS degree from the Middle-East Technical University, Turkey, in 1997, and a PhD degree, in 2003, for his work on the behavior of steel frames, from Selcuk University, Turkey, where he is currently Assistant Professor.

Mehmet Alpaslan Köroğlu obtained a BS degree in Civil Engineering from Gaziantep University, Turkey, in 2004, and MS and PhD degrees in Structural Engineering from Selcuk University, Turkey, in 2007 and 2012, respectively. Currently he is Assistant Professor in the Civil Engineering Department at Necmettin Erbakan University, Turkey. His research interests include design of strengthened reinforced concrete structures, steel beam-column connections and composite beams.