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Shear resistance behaviors of a newly puzzle shape of crestbond rib shear connector: An experimental study

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Abstract. A newly puzzle shape of crestbond rib shear connector is a type of ductile perfobond rib shear connector. This shear connector has some advantages, including relatively easy rebar installation and cutting, as well as the higher shear resistance strength. Thus, this study proposed a newly puzzle shape of crestbond rib with a "ʊ" shape, and its shear resistance behaviors and shear strengths were examined using push-out tests. Five main parameters were considered in the push-out specimens to evaluate the effects of shear resistance parameters such as the dimensions of the crestbond rib, transverse rebars in the crestbond dowel, concrete strength, rebar strength, and dowel action on the shear strength. The shear loading test results were used to compare the changes in the shear behaviors, failure modes, and shear strengths. It was found that the concrete strength and number of transverse rebars in the crestbond rib were significantly related to its shear resistance. After the initial bearing resistance behavior of the concrete dowel, a relative slip occurred in all the specimens. However, its rigid behavior to shear loading decreased the ductility of the shear connection. The cross-sectional area of the crestbond rib was also shown to have a minor effect on the shear resistance of the crestbond rib shear connector. The failure mechanism of the crestbond rib shear connector was complex, and included compression, shear, and tension. As a failure mode, a crack was initiated in the middle of the concrete slab in a vertical direction, and propagated with increasing shear load. Then, horizontal cracks occurred and propagated to the front and rear faces of the specimens. Based on the results of this study, a design shear strength equation was proposed and compared with previously suggested equations.

Keywords: crestbond rib; composite dowel; push-out test; shear connector; shear resistance; puzzle shape; equation of crestbond

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1. Introduction

Shear connectors have played an important role in steel–concrete composite and mixed structures. They produce a composite action between the concrete and steel, allowing them to behave as a single unit and transfer a force from each material member. Recently, various steel–concrete composites or mixed structures have been proposed and researched to increase the span length or decrease the thickness of members. In addition, high-strength concrete has been developed and researched. Thus, various shear connectors have also been proposed for application to a newly proposed composite system or to produce a composite action in a high-strength concrete member Bui (2010).

The shear connectors for a composite structure or mixed structure can generally be divided into ductile-type shear connectors. A head stud shear connector is a representative ductile-type shear connector, and its strength and application have been examined over a long period by many researchers (Jayas and Hosain 1989, Mohammad *et al*. 2011, Xue *et al*. 2012, Shim *et al*. 2011). For another type of shear connector, the shear strengths, ductile behaviors, and design equations of various ductile -type shear connectors have recently been examined using push-out and composite beam loading tests (Maleki and Bagheri 2008, Shariati *et al*. 2011). Accordingly, various shape of shear connector was investigated such as C-shaped angle (Shariati *et al*. 2012), V-shaped angle (Shariati *et al*. 2016a), Chanel shear connector (Maleki and Mahoutian 2009), and Shariati *et al*. (2016b) compared the performance of channel and angle shear connectors in high strength concrete composites.

A T-perfobond shear connector is another type of connector that was examined by Vianna *et al*. (2008). The results were presented and discussed, focusing on the T-perfobond structural response in terms of the shear transfer capacity, ductility, and collapse modes, and a comparison of the experimental results with the existing analytical formulae was also made to develop guidelines for designing T-perfobond connectors.

Kim *et al*. proposed a Y-type shear connector (Kim *et al*. 2013, 2014a, b, 2015). It was found that a Y-type perfobond rib shear connector had a higher shear resistance and ductility than the conventional perfobond rib shear connector by comparing and estimating the experimental results. Lastly, the effects of the bearing resistance, transverse rebar, dowel resistance by holes, and dowel resistance by Y-shape ribs on the shear resistance were estimated using a regression analysis. Based on these results, a shear resistance equation was suggested to predict the shear resistance of a Y-type perfobond shear connector.

A perfobond rib shear connector with a flat steel plate with holes for rebar is another type of connector that It resists horizontal shear and vertical uplift forces at the steel concrete interface using a concrete end-bearing zone, concrete dowels, and transverse rebars in the rib holes. It has been studied and widely used because of its utility, easy fabrication, and high shear resistance. It was developed in Germany starting with the research by Leonhardt *et al*. (1987), Oguejiofor and Hosain (1994). Many researchers have conducted studies on its shear failure and shear resistance behaviors, as well as its shear strength, and have proposed design equations for a perfobond rib shear connector based on the rib holes, number of rebars, and bearing capacity of the rib (Valente and Cruz 2004, Vianna *et al*. 2009, Kim *et al*. 2011, Ahn *et al*. 2010).

A crestbond rib shear connector is another type of shear connector. It is also a flat plate-type shear connector with open holes. A crestbond rib shear connector has advantages similar to those of a perfobond rib shear connector, such as a high shear strength. The existence of open holes can create an advantage in placing reinforcing bars though the holes. The open holes of crestbond rib shear connectors were designed to be able to obtain two crestbond ribs when cutting a steel rib (PreCo-Beam 2006, Preco+ 2011). It is welded along the length of a steel beam at the interface of the concrete slab and top flange of the steel beam. However, there have been relatively few studies on crestbond rib shear connectors compared to those on perfobond ribs, and various parameters were not considered (Lorenc *et al*. 2010, Chromiak and Studnicka 2006). In this study, therefore, a newly puzzle shape of crestbond rib with a "ʊ" shape was proposed, and its shear resistance strengths and behaviors were examined in relation to shear resistance parameters such as the strength of the concrete in the concrete matrix, dimensions of the crestbond rib, and rebar in the crestbond. Therefore, six push-out test specimens were fabricated, and their shear behaviors, failure modes, and shear strengths were compared using test results. Then, a shear strength design equation for the newly puzzle shape of crestbond rib shear connector was proposed based on a linear regression analysis of the test results and compared to previously suggested equations for a newly puzzle shape of crestbond rib shear connector with a flat plate with holes and rebar because of their similarity.

2. Push-out test of the newly puzzle shape of crestbond rib shear connector

To examine the shear strength and behaviors of a shear connector, a push-out test is generally applied. Thus, in this study, the standard push-out tests were conducted to examine and compare the shear resistance characteristics of the newly puzzle shape of crestbond rib shear connector. The test procedure and evaluation of the test results were performed according to the guideline of Eurocode 4 (C, E.C.f. Standardisation 1992). To compare the shear resistance strength of a typical head stud shear connector, an additional push-out test of a head stud shear connector was also conducted.

2.1 Push-out-test specimens

In this study, push-out-test specimens were fabricated according to Eurocode 4 (C, E.C.f. Standardisation 2004). The composite dowels consist of different structural components interacting with each other to establish the bond between the compound materials steel and concrete, which includes the steel-dowel, the concrete-dowel and the dowel-reinforcement located within the concrete-dowel (Preco+ 2011), as shown in Fig. 1. Thus, a push-out specimen consisted of three main parts: the steel member, the newly puzzle shape of crestbond rib welded in the flange of the steel member, and concrete matrix placed at both sides of the steel member. The dimensions of all the push-out specimens were identical. The thickness of the crestbond rib was fixed at 8 mm, and the diameter of the rebars used was fixed at 12 mm. As test parameters of the crestbond rib shear connector specimens, the rib dimensions of the crestbond rib were considered, as shown in Fig. 2. As shown in Fig. 2, category A had a crest rib open hole area of 3920 mm^2, and category B had a crest rib open hole area of 4490 mm^2. In addition, the number of rebars was changed from 0 to 2 in the test specimens, and two concrete strengths for the concrete matrix were considered, i.e., B25 (35.5 MPa) and B40 (50.0 MPa). Accordingly, the shear resistance of the newly puzzle shape of crestbond rib shear connector depended on the bearing resistance, longitudinal resistance by the concrete dowel, vertical resistance by the concrete dowel, and longitudinal resistance by the transverse rebar. The test specimens were called AS1 and BS1~BS5, depending on the rib dimensions, number of rebars, and concrete strength. During specimen fabrication, a gap of 20 mm was left at the end of the crestbond to exactly simulate the actual behavior of a composite beam,

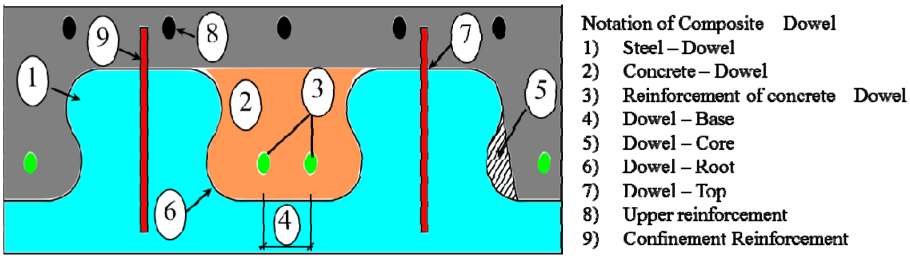
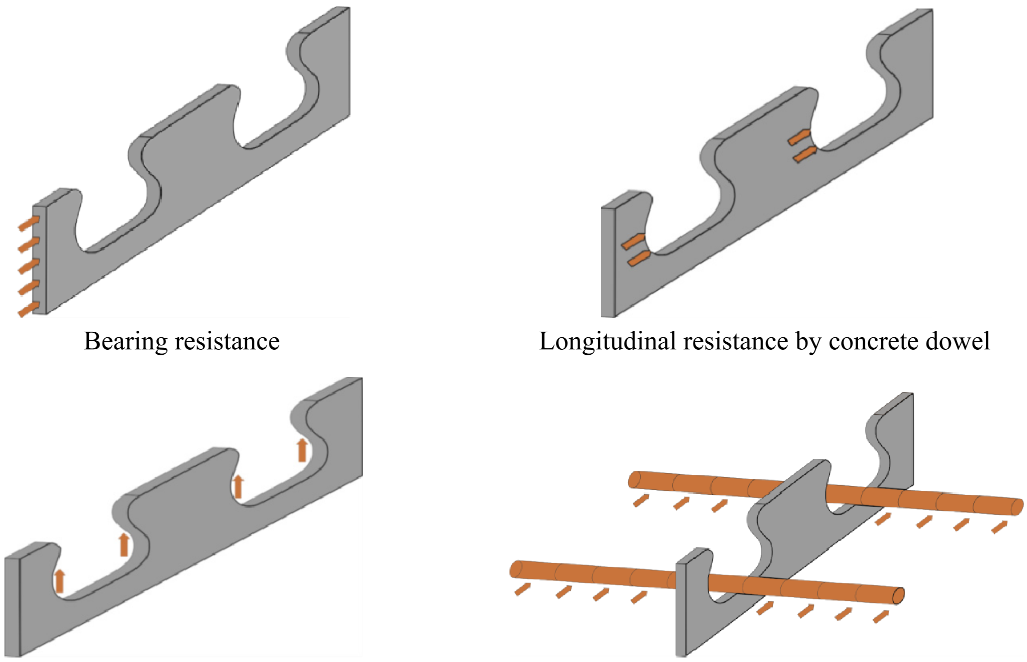


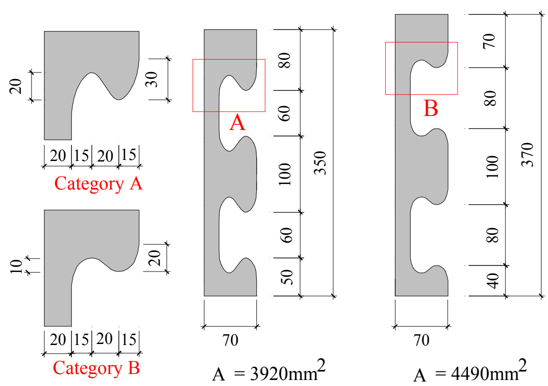
Fig. 1 Components of a Composite Dowel (Preco+ 2011)



Bearing resistance | Longitudinal resistance by concrete dowel

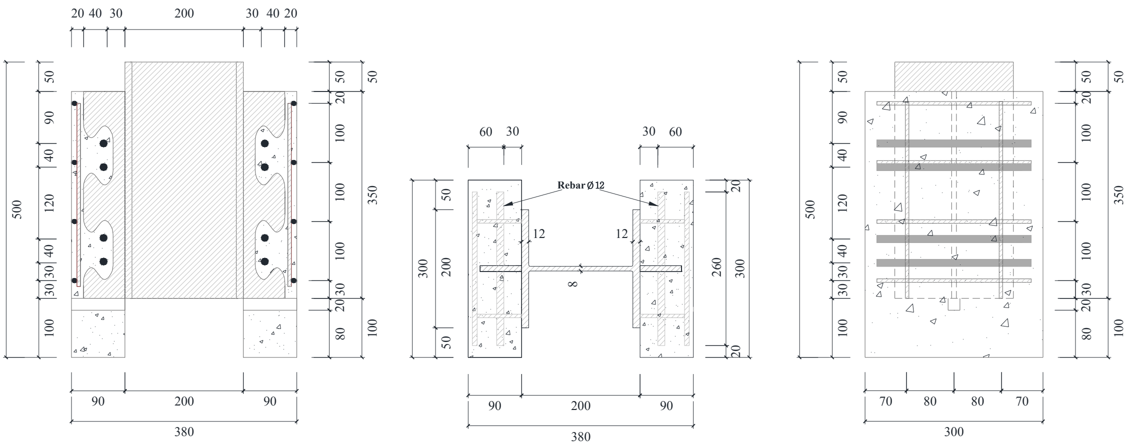
Vertical resistance by concrete dowel | Longitudinal resistance by transverse rebar

(a) Modified crestbond rib concept

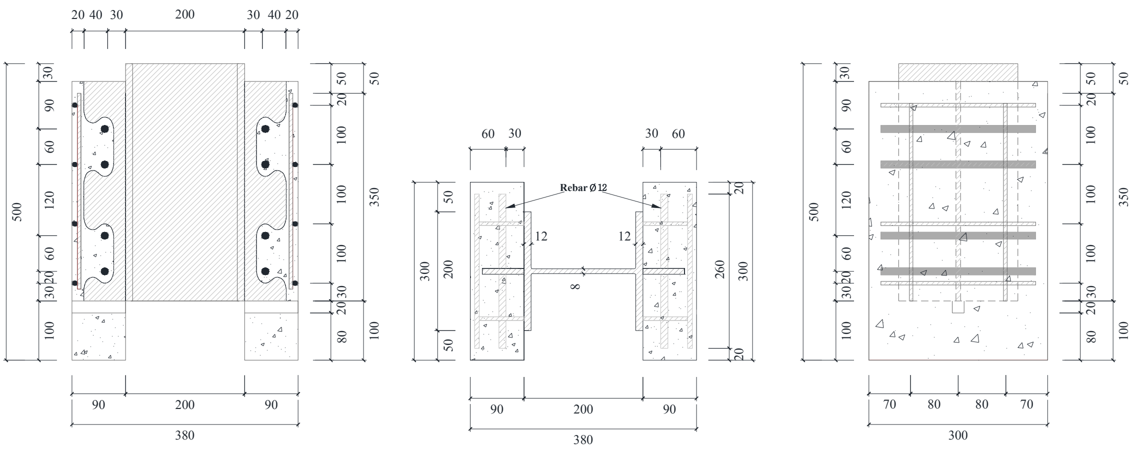


(b) Tested crestbond rib

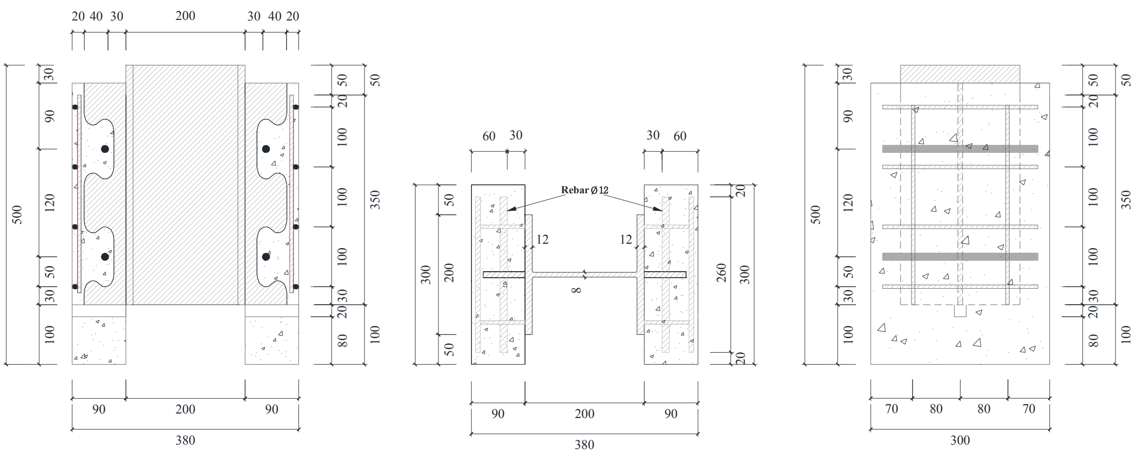
Fig. 2 Dimensions of the newly puzzle shape of crestbond rib shear connector



(a) Group AS1

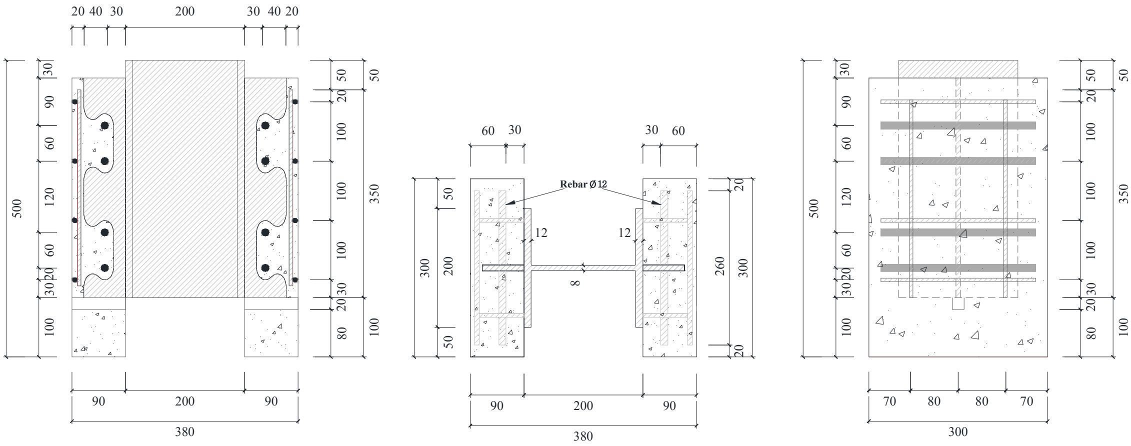


(b) Group BS1 (B25 concrete)

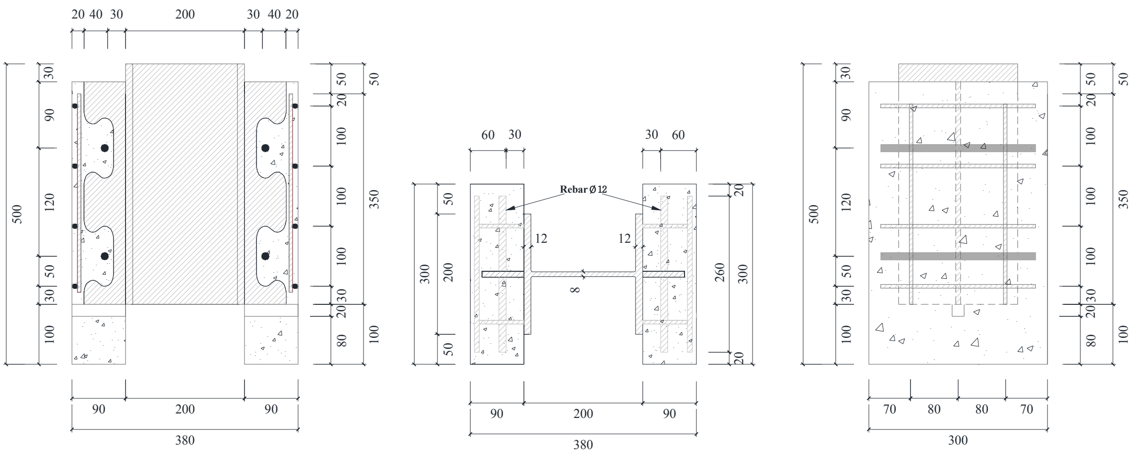


(c) Group BS2 (B25 concrete)

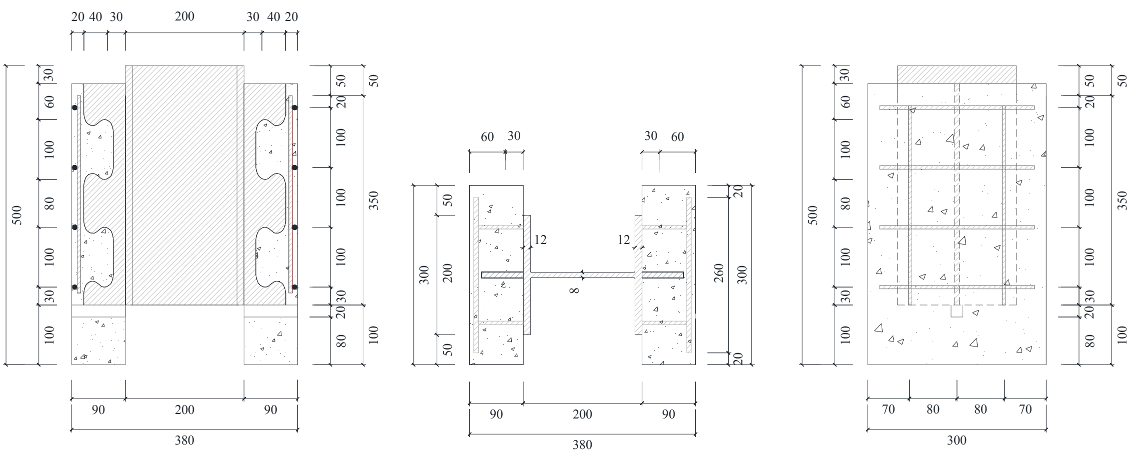
Fig. 3 Configuration and dimensions of specimen



(d) BS3 (B40 concrete)

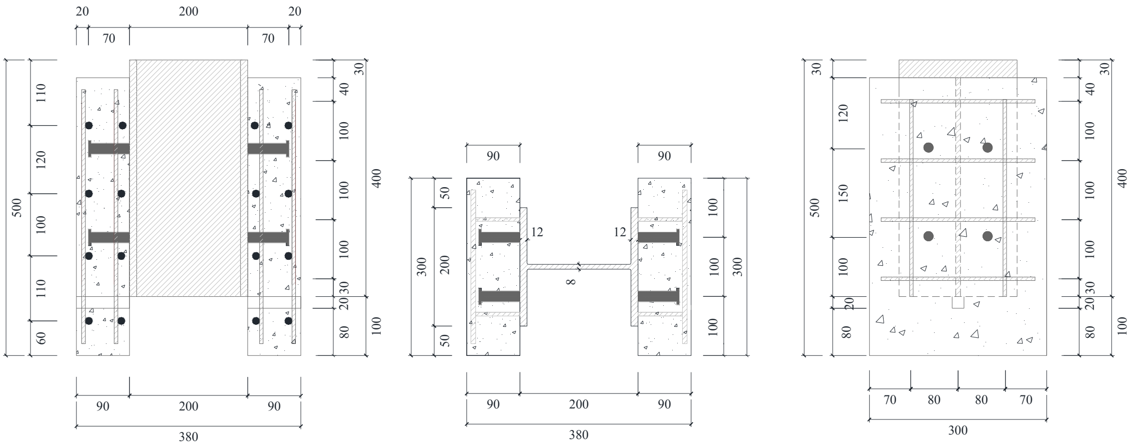


(e) Group BS4 (B40 concrete)



(f) Group BS5 (without rebar)

Fig. 3 Continued



(g) Group HS1 (B25 concrete)

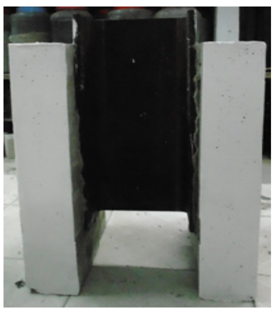
Fig. 3 Continued

(a) A newly puzzle shape of crestbond rib

(b) Welded crestbond rib on steel beam

(c) Preparation before concrete casting

(d) Concrete casting



(e) Completion

Fig. 4 Fabrication of test specimens

Table 1 Properties of specimens

Group	Number of specimen	Number of head stud	Section area of hole (mm^2)	Concrete grad	Number of rebar
AS1	2		3920	B25	2
BS1	2		4490	B25	2
BS2	2		4490	B25	1
BS3	2		4490	B40	2
BS4	2		4490	B40	1
BS5	2		4490	B25	-
HS1	3	4	-	B25	-

because a continuous crestbond rib was welded along the beam length. The width of this gap equaled the thickness of the crestbond rib. Beside that one more type of specimen was designed and denoted HS1, this type was the same size with the others, and concrete strength B25 (35.5 MPa) was also used. However, head stud shear connectors were applied in specimens HS1 to compare the shear strength of the crestbond rib with that of head stud connectors. Fig. 3 shows the dimensions of each push-out test specimen. The preparation of the specimens is shown in Fig. 4. Table 1 summarizes the characteristics of the seven test specimen groups used in this study.

2.2 Material properties

In this study, two concrete strengths were used for the concrete matrix: B25 and B40. Their aggregate components are presented in Table 2. Accordingly, super plasticizer was added to the B40 concrete with a content equal to 1.0% of the cement mass. Compression tests were carried out to determine the material properties of the concrete strength specimens. These were performed on the same day as the push-out tests. The mean compressive strength of each concrete cylinder and mean axial tensile strength of the concrete are presented in Table 3. For the steel crestbond rib and H beam, the CT3 grade with a yield strength f_y = 250 MPa was used. A steel rebar with a 330-MPa yield strength was used. Table 4 lists the material properties of the steel used in this study.

2.3 Test program

To evaluate the shear strengths and shear behaviors of the push-out specimens with the newly puzzle shape of crestbond rib, the relative slip between the concrete and steel was measured using

Table 2 Concrete aggregate components

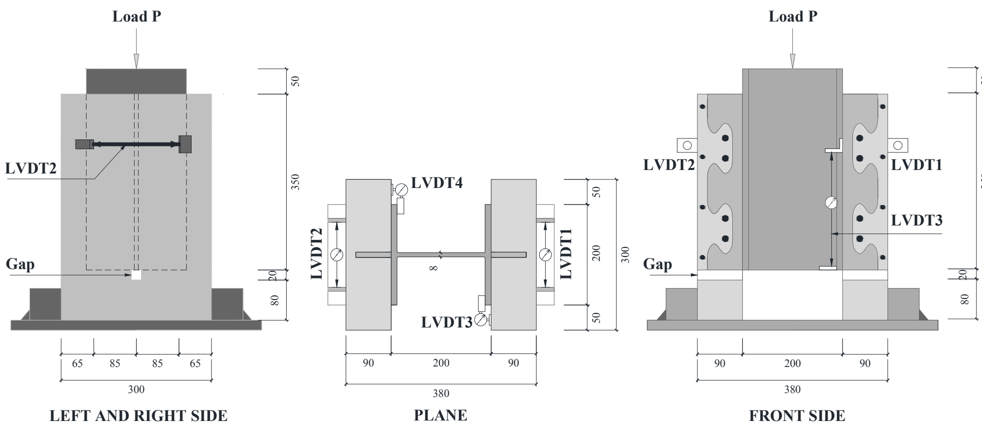
Components	Unit	Density kg/m^3	
		B25	B40
Cement HOLCIM Quick cast (PC50)	kg	385.0	410.0
Aggregate	kg	760.0	740.0
Coarse aggregate 10×20 mm	kg	1040.0	1210.0
Water	kg	200.0	140.0
Super plasticizer (MAPEI)	kg	0.0	4.1

Table 3 Material properties of concrete

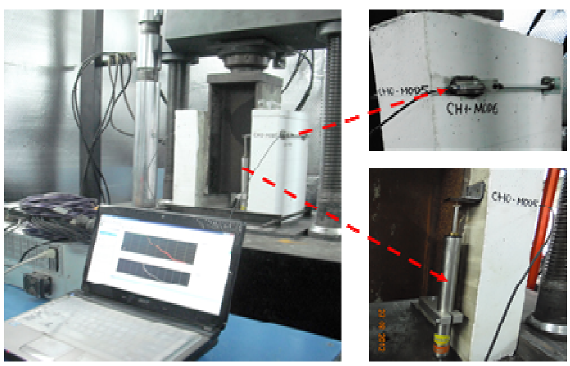
Grad	B25	B40
Compressive strength f_{cm} (MPa)	35.5	50.0
Elastic modulus (MPa)	29.0×10^3	33.0×10^3
Elastic strain limit ε_{elas} (‰)	1.8	1.5
Maximun compressive strain limit ε_{elas} (‰)	-	2.59
Tensile strength in flexural f_{ctm} (MPa)	3.36	3.59
CMOD (mm)	0.041	0.024

Table 4 Properties of reinforcement and steel CT3 (crestbond rib and H beam)

Parameters	Rebar	CT3
Yield strength (MPa)	330	250
Ultimate strength (MPa)	500	390
Yield strain ε_{yield} (‰)	1.8	1.8
Elastic modulus (MPa)	200×10^3	200×10^3



(a) Instrumentation



(b) Push-out test setup

Fig. 5 Push-out test instrumentation and test setup

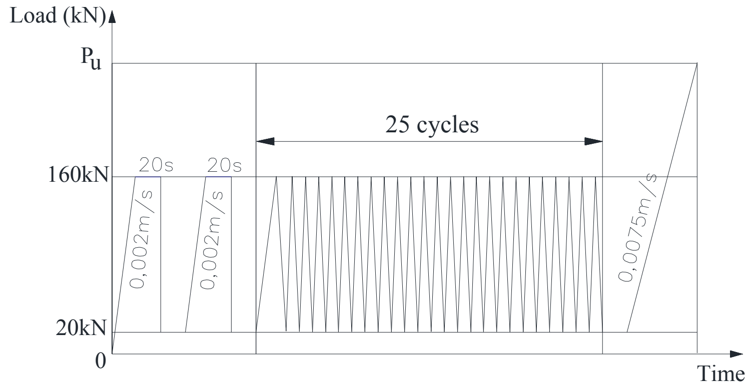


Fig. 6 Loading process

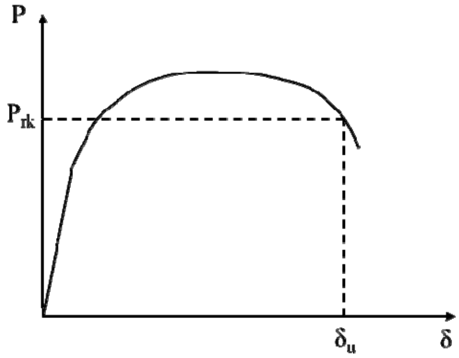


Fig. 7 Definition of characteristic load (P_{rk})

linear variable displacement transducers (LVDTs) on both sides of the concrete matrix (LVDT-3 and LVDT-4), as shown in Fig. 5. Additionally, to identify the concrete crack propagation in the concrete slab, LVDTs (LVDT-1 and LVDT-2) were also laterally installed at the concrete surface of each concrete matrix. A load cell with a load capacity of 1000 kN was used to record the applied shear load on a push-out specimen.

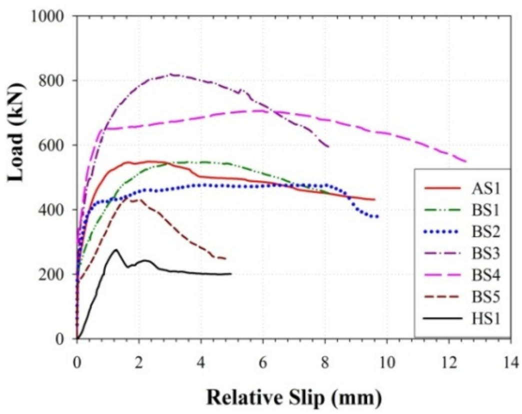
An incremental loading process was performed according to Eurocode 4. In this loading process, the first loading stage consisted of 2 cycles of loading/unloading from zero to 40% of the expected failure load. The second stage included 25 cycles of loading/unloading from 10% to 40% of the expected failure load, and in the last stage, the load was gradually increased until the specimen failed, as shown in Fig. 6. Repetitions of the loading process were carried out to eliminate friction between the concrete and structural steel, as well as any residual strain in the experiment. Before evaluating the test results, the test values of stages 1 and 2 were eliminated. To evaluate the shear strength of the newly puzzle shape of crestbond rib shear connector, the shear load–relative slip curve was obtained from the load increment stage. The relative slip of the tested shear connector (δ_k) was obtained based on the level of characteristic load (P_{rk}), which was defined as the collapse load of 90% of the peak load after reaching the peak load, as shown in Fig. 7.

3. Push-out test results and discussion

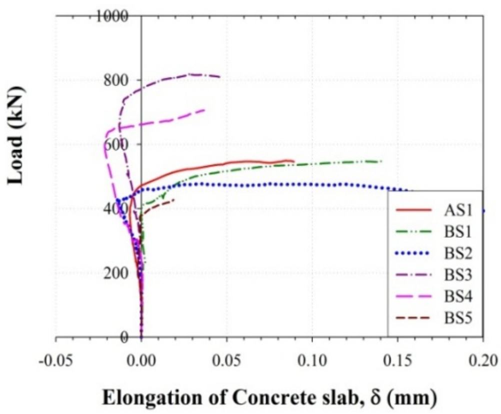
3.1 Push-out test results and failure modes

Fig. 8 presents the mean shear load–mean relative slip curves of the push-out test specimens. The test results are also summarized in Table 5. In Table 5, $P_{\max}$ is the peak load, P_{rk} is defined as the characteristic load and is equal to 90% of the peak load, $P_{rk,1}$ is the average load value per crestbond rib hole, and δ_u is the relative slip at the characteristic load. Fig. 8 shows the behaviors of a typical rigid shear connector with an initially stiff shear resistance behavior before the ductile behavior begins. After the initial bearing resistance behavior of the concrete dowel, a relative slip occurred in all the specimens. The push-out specimen with the higher concrete strength (B40) and two rebars showed a higher shear-resistance strength. The number of rebars increased its shear strength as a result of the rebar resistance effect, and the shear resistance behaviors of push-out specimens with rebar showed higher shear strengths and ductile behaviors than specimens without rebar, as shown in Fig. 8(a). Push-out specimens with the B25 concrete strength also showed higher ductile behaviors for lateral cracks than push-out specimens with the B40 concrete strength, as shown in Fig. 8(b). When comparing the shear strength of the crestbond rib with that of head stud connectors, its shear strength was 2.37–3.84 times higher than that of the head stud, although it was difficult to directly compare these shear connectors because of the application conditions and shapes.

The failure mechanism of the crestbond rib shear connector was complex, and included compression, shear, and tension, as shown in Fig. 9. Under shear loading on a push-out test specimen, the load was first applied to the concrete dowel, which failed at the interface between the concrete dowel and crestbond, while two sides of the crestbond were in tension and cracks began in the middle of the specimen. During the test process, cracks were observed and plotted following every loading stage. Fig. 10 shows the typical failure mode of the specimens after the loading tests. The crack occurrence and propagation had the same tendency for all the specimens. Cracks initiated in the middle of the concrete slab in the vertical direction, and then propagated with insignificant loading. The shear resistance strength decreased when horizontal cracks developed, and finally, cracks occurred in the front and rear faces. After reaching the ultimate



(a) Relative slip between steel beam and concrete matrix



(b) Lateral elongation of concrete slab

Fig. 8 Summary of push-out test results

Table 5 Push-out test results for each group

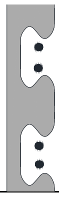
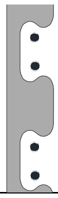
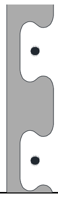
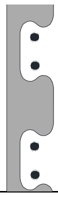
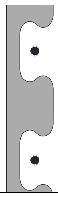
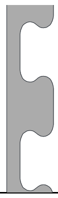
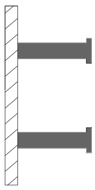
Group	Specimen	Concrete strength (MPa) and rebar installation	Ultimate load (Pmax), (kN)		P_{rk} (kN)		Relative slip $\delta_{\max}$ (mm)		Elongation of concrete slab (mm)	
			Test	Avg.	Test	Avg.	Test	Avg.	Test	Avg.
AS1	AS1-A	35.5								
	Left side		548.88		493.99		8.42		0.117	
	Right side		548.88		493.99		10.92		0.062	
	ASI-B			549.53		494.6		8.99		0.19
	Left side		550.18		495.16		8.90		0.383	
	Right side		550.18		495.16		7.72		0.209	
BS1	BS1-A	35.5								
	Left side		547.20		492.48		8.06		0.205	
	Right side		547.20		492.48		8.43		0.228	
	BS1-B			563.01		506.7		7.51		0.17
	Left side		578.83		520.94		6.60		0.078	
	Right side		578.83		520.94		6.95		0.173	
BS2	BS2-A	35.5								
	Left side		497.33		447.59		8.11		0.915	
	Right side		497.33		447.59		9.72		0.467	
	BS2-B			487.2		438.5		9.34		0.48
	Left side		477.08		429.38		9.49		0.393	
	Right side		477.08		429.38		10.03		0.165	
BS3	BS3-A	50								
	Left side		762.31		686.07		2.77		0.117	
	Right side		762.31		686.07		2.03		0.002	
	BS3-B			790.99		711.89		5.31		0.069
	Left side		819.68		737.71		9.52		0.017	
	Right side		819.68		737.71		6.93		0.139	
BS4	BS4-A	50								
	Left side		680.67		612.60		5.93		0.002	
	Right side		680.67		612.60		7.25		0.000	
	BS4-B			693.26		623.94		6.59		0.020
	Left side		705.86		635.28				0.034	
	Right side		705.86		635.28				0.043	
BS5	BS5-A	35.5								
	Left side		489.39		440.45		2.77		0.046	
	Right side		489.39		440.45		5.84		0.060	
	BS5-B			462.83				4.61		0.037
	Left side		436.27		392.64		4.13		0.022	
	Right side		436.27		392.64		5.68		0.019	

Table 5 Continued

Group	Specimen	Concrete strength (MPa) and rebar installation	Ultimate load (Pmax), (kN)		P_{rk} (kN)		Relative slip δ_{max} (mm)		Elongation of concrete slab (mm)	
			Test	Avg.	Test	Avg.	Test	Avg.	Test	Avg.
HS1	HS1-A	60								
	Left side		140.93		126.84		1.00		-	
	Right side		140.93		126.84		1.00		-	
	HS1-B			205.80		185.22		1.17		
	Left side		202.17		181.96		1.43		-	
	Right side		202.17		181.96		1.43		-	
	HS1-C									
	Left side		274.30		246.87		1.08		-	
	Right side		274.30		246.87		1.08		-	

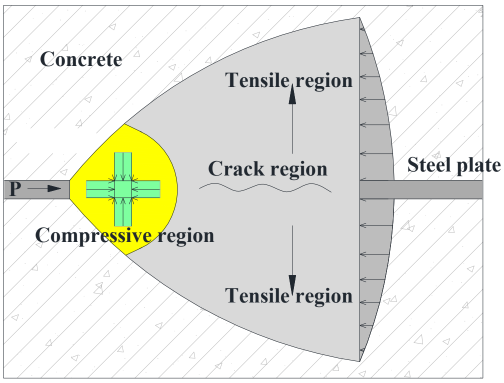
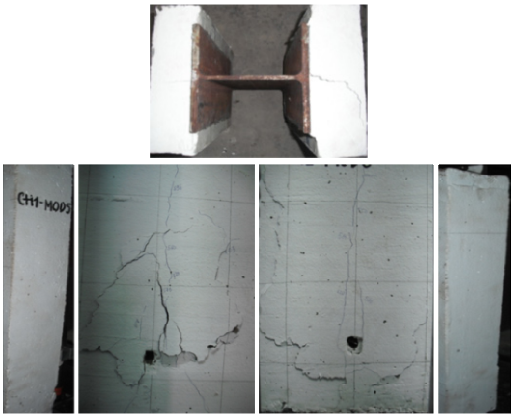


Fig. 9 Failure mechanism of crestbond rib shear connector (Kraus and Wurzer 1997)

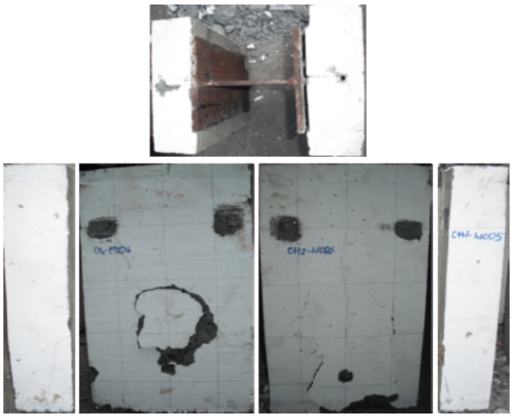
(a) Specimen AS1 (b) Specimen BS1

Fig. 10 Crack distributions in concrete slab after push-out tests



(c) Specimen BS2

(d) Specimen BS3


(e) Specimen BS4


(f) Specimen BS5

Fig. 10 Crack distributions in concrete slab after push-out tests

(a) Specimen AS1


(b) Specimen BS1


(c) Specimen BS2

Fig. 11 Deformation of shear connectors and transverse rebars in crestbond holes

(d) Specimen BS3

(e) Specimen BS4

(f) Specimen BS5

Fig. 11 Continued

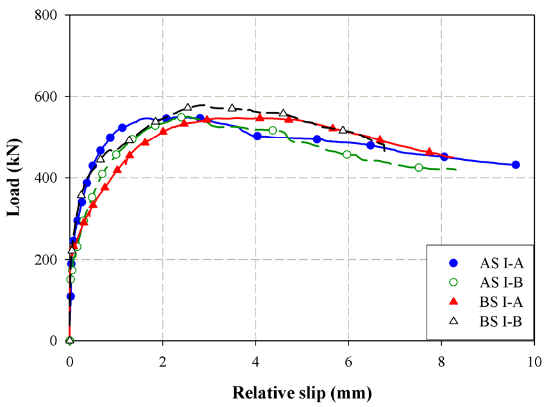
3.2 Analysis of push-out test results

3.2.1 Effects of dimensions of the newly puzzle shape of crestbond rib

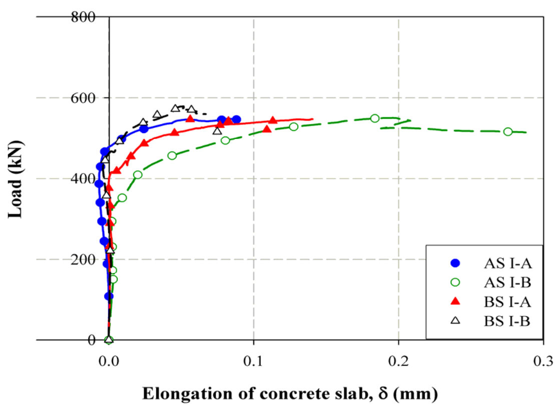
To compare the effects of the dimensions of the crestbond rib on its shear strength and behaviors, the shear load–relative slips are presented in Fig. 12. In this study, the crestbond specimens in categories A and B (3920 mm^2 and 4490 mm^2 cross-sectional areas for holes) showed similar shear resistance strengths and behaviors. The ductile behavior of BS1 was slightly larger than that of AS1, and the cross-sectional area of the crestbond rib also had a minor effect on the shear resistance of the crestbond rib shear connector.

3.2.2 Effect of transverse rebar

In order to examine the effect of the reinforcement on the shear resistance of the crestbond rib connector, push-out tests with different numbers of rebars were carried out. Push-out test specimens BS1 and BS2 had the same concrete compressive strength of 35.5 MPa, but the ultimate

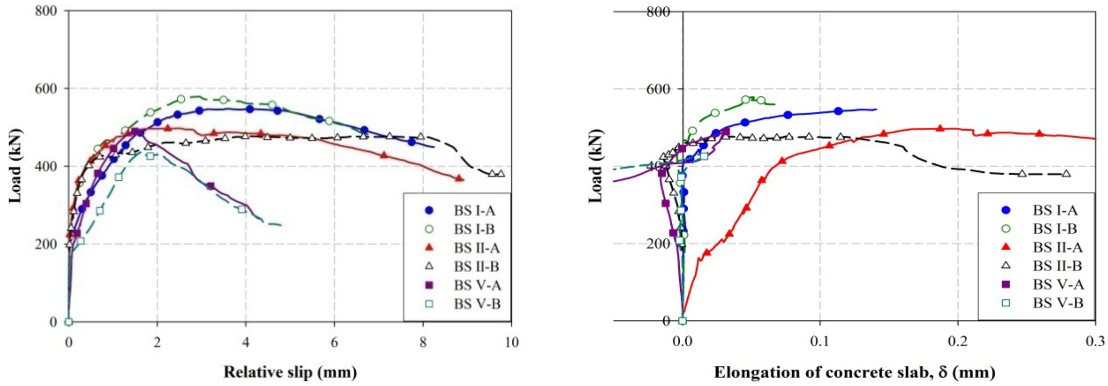


(a) Relative slip curves



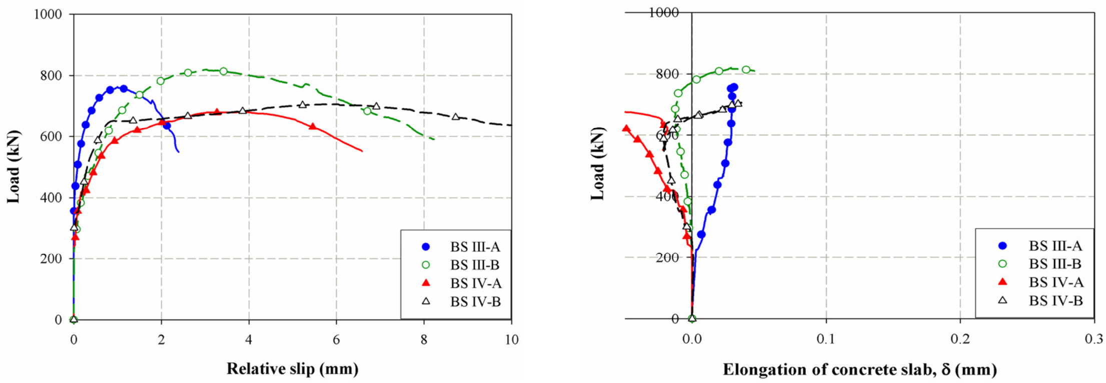
(b) Elongation of concrete slab

Fig. 12 Effects of dimensions of crestbond rib



(a) Relative slip curves (b) Elongation of concrete slab

Fig. 13 Effects of rebar in BS1, BS2, and BS5 with 35.5-MPa concrete strength



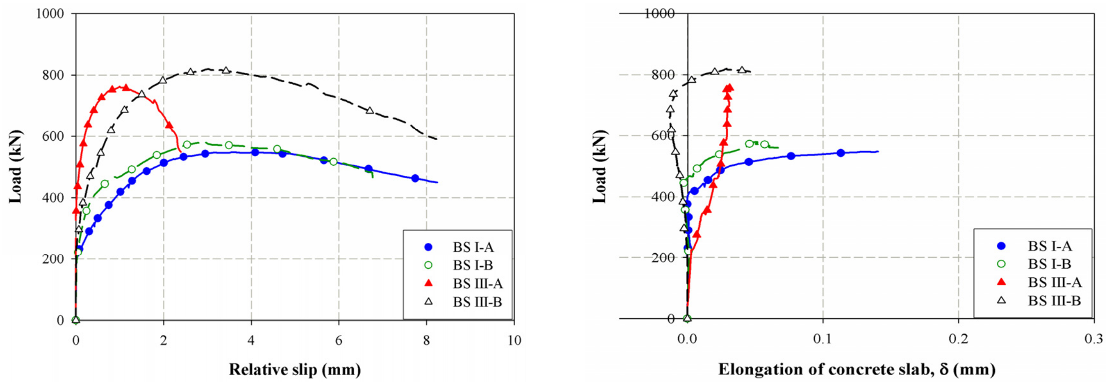
(a) Relative slip curves (b) Elongation of concrete slab

Fig. 14 Effects of rebar in BS3 and BS4 with 50.0-MPa concrete strength

load of specimen BS1 (563.01 kN) increased 15.56% in comparison with that of specimen BS2 (487.2 kN), as shown in Fig. 13. A similar comparison of specimens BS3 and BS4, which had the same concrete compressive strength of 50.0 MPa, showed that the ultimate load of specimen BS3 increased 14.1% in comparison with that of specimen BS4, as shown in Fig. 14. In the case of specimen BS5 without rebar, the ultimate load decreased approximately 17.8% and 5.0% in comparison with those of BS1 and BS2, respectively, and its relative slip decreased to about 61.1% and 70.6% in comparison with those of BS1 and BS2, respectively. Thus, it could be confirmed that the number of rebars in the crestbond had an effect on its ductile behaviors. A crestbond rib connection with a single rebar produced a higher ductile behavior than a crestbond rib connection with two rebars under all the concrete strength conditions, as shown in Figs. 13 and 14.

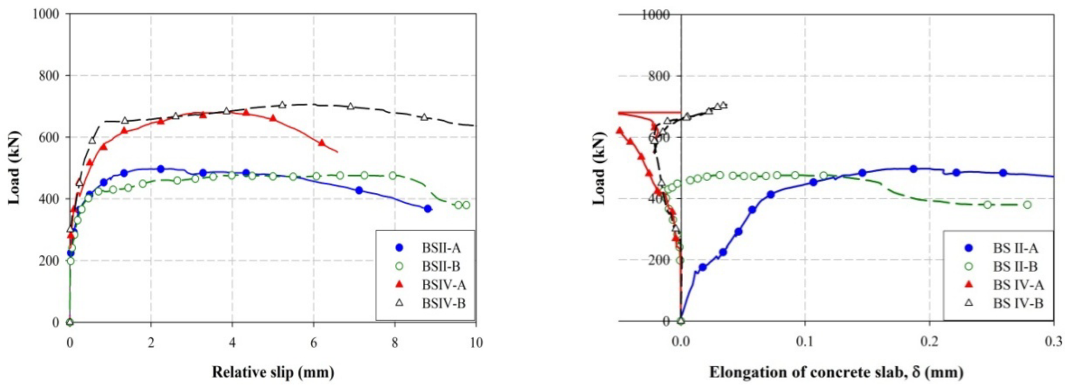
3.3.1 Effect of concrete strength on shear behavior of crestbond rib

In order to evaluate the effect of the concrete compressive strength on the shear resistance behaviors, the results for push-out specimens BS1 and BS2, which had a concrete compressive strength of 35.5 MPa, were compared to those of push-out specimens BS3 and BS4, which had a



(a) Relative slip curves (b) Elongation of concrete slab

Fig. 15 Effects of concrete compressive strength for two rebars: BS1 (35.5 MPa) and BS3 (50.0 MPa)



(a) Relative slip curves (b) Elongation of concrete slab

Fig. 16 Effects of concrete compressive strength for one rebar: BS2 (35.5 MPa) and BS4 (50.0 MPa)

concrete compressive strength of 50.0 MPa, as shown in Figs. 15 and 16. The ultimate shear load of specimen BS3 increased approximately 40.5% in comparison with that of specimen BS1. Nearly the same result was seen with specimens BS2 and BS4, where the ultimate load of specimen BS4 increased approximately 42.3% in comparison with that of specimen BS2. This showed that the compressive strength of concrete appreciably improves the shear resistance of the connection. Therefore, it can be concluded that the concrete compressive strength significantly affects the shear resistance of the modified crestbond rib shear connection.

4. Analysis of shear resistance design equation for the newly puzzle shape of crestbond rib shear connector

4.1 Previous shear strength equations for perfobond rib shear connector

The shear resistance strengths of the perfobond rib shear connector consist of the horizontal shear and vertical uplift resistances at the steel concrete interface as a result of the concrete end-bearing zone, concrete dowels, and transverse rebars in the rib holes. Thus, many design equations for perfobond rib shear connectors have been proposed based on the values of these shear resistance parameters determined using various tests (Bui 2010, Oguejiofor and Hosain 1994, Kim *et al*. 2013, Medberry and Shahrooz 2002, Verissimo *et al*. 2006, Suhaib and Liu 2007). The crestbond rib shear connector has similar shear resistance characteristics because of its geometric features. The previously suggested design equations can be referenced or compared when proposing a design equation for the crestbond rib shear connector. Thus, the previously suggested design equations for a perfobond rib shear connector were analyzed and confirmed.

In the case of the design equations for the perfobond rib, there are four main factors that influence its shear resistance, including the dimensions of the perfobond steel plate, transverse rebars in the holes, concrete strength, and steel plate strength. The effects of these factors are described in the following shear strength equations suggested by various researchers.

Oguejiofor and Housain (1994) proposed a shear capacity equation for a perfobond rib using a regression analysis, which was based on a model that took into account the contributions of the concrete dowel formed by the rib holes, the transverse reinforcement, and the strength of the concrete. This shear capacity equation is given by Eq. (1).

$$q_u = 0{,}59.A_{cc}.\sqrt{f_c'} + 1{,}233.A_{tr}.f_y + 2{,}871.n.d^2\sqrt{f_c'} \tag{1}$$

where q_u is the shear capacity at the shear connector (n), A_{cc} is the shear area of the concrete slab (mm^2), A_{tr} is the area of the transverse rebars in the rib holes (mm^2), n is the number of rib holes, d is the diameter of the rib holes (mm), and f_c' and f_y are the compressive concrete strength (MPa) and yield strength of the transverse rebar (MPa), respectively.

Medberry and Shahrooz (2002) also proposed a shear capacity equation. A comparative study was conducted of the predicted and ultimate loads of 16 tests performed with normal weight concrete specimens (Oguejiofor and Hosain 1994, 1997). A more general equation for the calculation of this strength was proposed based on the push-out-test results. The shear capacity equation is given by Eq. (2).

$$q_u = 0{,}747bh\sqrt{f_{ck}} + 0{,}413b_f L_c + 0{,}9A_{tr}f_y + 1{,}66n\pi\left(\frac{D}{2}\right)^2\sqrt{f_{ck}} \tag{2}$$

where q_u is the shear capacity at the shear connector (n), b is the thickness of the concrete slab (mm), h is the distance between the end of the perfobond rib and the end of the concrete slab (mm), b_f is the width of the steel beam flange (mm), L_c is the contact length between the concrete slab and the steel beam flange (mm), n is the number of rib holes, D is the diameter of the rib holes (mm), and f_{ck} and f_y are the compressive concrete strength (MPa) and yield strength of the transverse rebar (MPa), respectively.

Verissimo *et al*. (2006) proposed another equation for predicting the shear capacity of a perfobond rib using a regression analysis, which was based on the results of Oguejiofor and Hosain (1997). A modified shear-capacity equation is given by Eq. (3). Three main parameters were considered from this expression, including the concrete dowels passing through the perfobond rib holes, the concrete slab subjected to shear, and the transversal reinforcement.

$$q_u = 4{,}04\frac{h_{sc}}{b}h_{sc}t_{sc}f_{ck} + 2{,}37nD^2\sqrt{f_{ck}} + 0{,}16A_{cc}\sqrt{f_{ck}} + 31{,}85\times10^6\frac{A_{tr}}{A_{cc}} \tag{3}$$

where q_u is the shear capacity at the shear connector (*n*), A_{cc} is the shear area of the concrete slab (mm^2), A_{tr} is the area of the transverse rebars in the rib holes (mm^2), *n* is the number of rib holes, *d* is the diameter of the rib holes (mm), and f_{ck} and is the compressive concrete strength (MPa).

Suhaib and Liu (2007) also proposed a shear capacity equation using a regression analysis, as shown in Eq. (4). The effects of the concrete dowels, strength of the concrete slab, and number of transverse reinforcements contributed to this equation.

$$V_u = 255{,}31 + 7{,}62.10^{-4}.h.t.f_c^{'} - 7{,}59.10^{-7}.A_r.f_y + 2{,}53.10^{-3}.A_{sc}.\sqrt{f_c^{'}} \tag{4}$$

where V_u is the shear capacity at the shear connector (n) (mm), A_{tr} is the area of the transverse rebars in the rib holes (mm^2), and f_c' and f_y are the compressive concrete strength (MPa) and yield strength of the transverse rebar (MPa), respectively.

Tue *et al*. (2008) proposed another equation for predicting the shear capacity of a perfobond rib. The simulation results for the shear resistance were combined with full sets of experimental results for a linear regression analysis. An experimental study pointed out that the bearing capacity of the connector depends on the concrete dowel and rebar in the dowel, as well as the transverse reinforcement in the front cover. A numerical simulation indicated that the deformation and yielding of the steel rib also contributed. A simple prediction equation for the bearing capacity of the connector is shown in Eq. (6)

$$P_u = 3{,}4579.n_{dw}.b_o.d.\sqrt{f_{ck}} + 1{,}1259.A_r.f_{y,r} + 0{,}4054.A_{rf}.f_{y,r} + 0{,}2296.t.\phi.f_{y,a} \tag{5}$$

where P_u is the shear capacity at the shear connector (*n*); ndw is the number of dowels in the connector; f_{ck} is the cylinder compressive strength of the concrete in megapascals; b_o and *d* are the critical perimeter and depth of the shearing cone in millimeters, respectively; *t* is the thickness of the steel rib in millimeters; A_r and A_{rf} are the total areas of the transverse reinforcement in the concrete dowel and front cover in square millimeters, respectively; $f_{y,r}$ and $f_{y,a}$ are the corresponding yield strengths of the reinforcement and structural steel in megapascals; and Ø is the diameter of the perforated holes.

Kim *et al*. proposed a Y-type shear connector (Kim *et al*. 2013, 2014a, b, 2015). It was found that a Y-type perfobond rib shear connector had a higher shear resistance and ductility than the conventional perfobond rib shear connector by comparing and estimating the experimental results. Lastly, the effects of the bearing resistance, transverse rebar, dowel resistance by holes, and dowel resistance by Y-shaped ribs on the shear resistance were estimated in a regression analysis.

Based on the results, a shear resistance equation was suggested to predict the shear resistance of a Y-type perfobond shear connector. This shear capacity equation is given by Eq. (6)

$$Q = 3{,}428.(d/2 + 2h).t.f_{ck} + 1{,}213.A_r.f_y + 1.9.n.\pi,(d/2)^2.\sqrt{f_{ck}} + 0{,}438.m.h.s.\sqrt{f_{ck}} \tag{6}$$

where *Q* (kN) represents the shear resistance of the Y-type perfobond rib shear connector, *d* (mm) is the dowel hole's diameter, *h* (mm) is the individual rib height, *t* (mm) is the rib thickness, f_{ck} (MPa) is the concrete compressive strength, A_{tr} (mm^2) is the transverse rebar's cross-sectional area, f_y (MPa) is the transverse rebar's yield strength, n is the number of dowel holes, *m* is the number of dowel areas formed between ribs bent in a Y-shape, and *s* (mm) is the net distance between ribs that are bent in the same direction.

4.2 Shear resistance equation for crestbond rib shear connector

As a perfobond rib shear connector, the shear resistance strength of a crestbond rib depends on the dimensions of the crestbond rib, transverse rebars in the crestbond dowel, concrete strength, rebar strength, and dowel action. Its design equation can also be derived using the shear resistance parameters. Therefore, the design equation of the newly puzzle shape of crestbond rib shear connector can be represented by Eq. (7)

$$Q_u = \beta_1 P_{dc} + \beta_2 P_r + \beta_3 P_{dw} \tag{7}$$

where Q_u is the shear capacity at the shear connector; P_{dc}, P_r, and P_{dw} are the resistance capacities of the crestbond rib, transverse rebar in the crestbond holes, and concrete dowel, respectively. β_i is the weighting factor of each contribution, which is determined using a linear regression analysis. P_{dw} is determined based on the effect of the dimension of the crestbond hole and the concrete strength, and is expressed by Eq. (8)

$$P_{dw} = \beta_3 n \frac{h_{cr,h} b_{cr,h}}{A_{cr,h}} f_{ck} \tag{8}$$

The remaining components are calculated using Eq. (9)

$$P_{dc} = \beta_1 h_{cr} t_{cr} f_{ck}\,; \;\; P_{cr} = \beta_2 A_r . f_y \tag{9}$$

where $h_{cr,h}$ and $b_{cr,h}$ are the height and width of the crestbond hole (mm), respectively; f_{ck} is the concrete strength (MPa); h_{cr} is the height of the crestbond rib (mm); t_{cr} is the thickness of the crestbond (mm); A_{tr} is the area of the transverse rebar in the crestbond holes (mm^2); f_y is the yield strength of the transverse rebar (MPa); and n is the number of crestbond rib holes.

Table 6 Comparison with derived design equation values

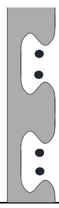
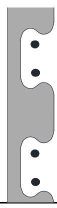
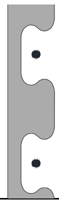
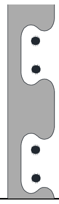
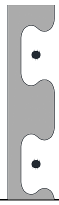
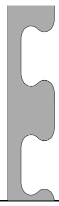
Group	Specimen	Concrete strength (MPa) and rabar installation	Ultimate load (Pmax), (kN)			
			Test	Avg.	Equation	Error (%)
AS I	AS I-A	35.5				
	Left side		548.88			
	Right side		548.88			
	AS I-B			549.53	528.30	-3.86
	Left side		550.18			
	Right side		550.18			
BS I	BS I-A	35.5				
	Left side		547.20			
	Right side		547.20			
	BS I-B			563.01	584.52	3.82
	Left side		578.83			
	Right side		578.83			

Table 6 Comparison with derived design equation values

Group	Specimen	Concrete strength (MPa) and rabar installation	Ultimate load (Pmax), (kN)			
			Test	Avg.	Equation	Error (%)
BS II	BS II-A	35.5		487.21	543.58	11.57
	Left side		497.33			
	Right side		497.33			
	BS II-B					
	Left side		477.08			
	Right side		477.08			
BS III	BS III-A	50		790.99	696.60	-11.93
	Left side		762.31			
	Right side		762.31			
	BS III-B					
	Left side		819.68			
	Right side		819.68			
BS IV	BS IV-A	50		693.26	655.66	-5.42
	Left side		680.67			
	Right side		680.67			
	BS IV-B					
	Left side		705.86			
	Right side		705.86			
BS V	BS V-A	35.5		462.83	502.64	8.60
	Left side		489.39			
	Right side		489.39			
	BS V-B					
	Left side		436.27			
	Right side		436.27			

From multiple linear regressions with the least squares procedure based on test results, the assumed design equation for a crestbond rib shear connector is shown in Eq. (10)

$$Q_u = 3.05h_{cr}t_{cr}f_{ck} + 1.0971A_r f_y + 4.168n(h_{cr,h}b_{cr,h})0.841\sqrt{f_{ck}} \tag{10}$$

The results of the derived design equation for the newly puzzle shape of crestbond rib shear connector were compared to the test results, as shown in Table 6 and Fig. 17. The shear strength value of a crestbond rib estimated using the derived design equation shows good agreement with the test results. The coefficient of correlation between the test results and estimated values was R = 0.987, which indicated that they were relatively proper and reliable. Therefore, the derived Eq. (10) could be used to determine the design shear strength of the newly puzzle shape of crestbond rib shear connector.

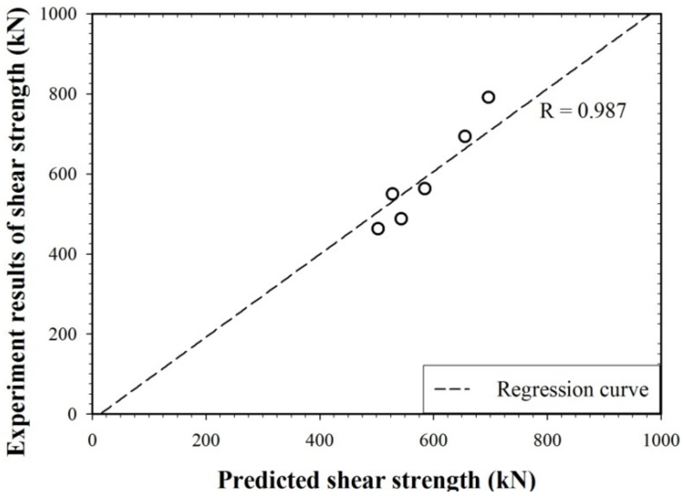


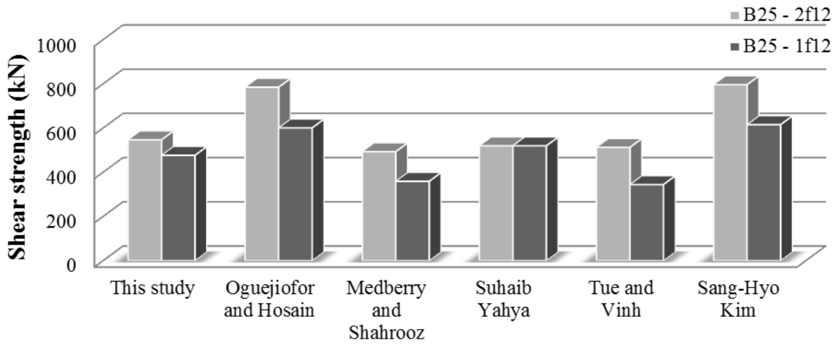
Fig. 17 Comparison of test and estimated values of the newly puzzle shape of crestbond rib shear connector

4.3 Comparison of design equations for the newly puzzle shape of crestbond rib and perfobond rib

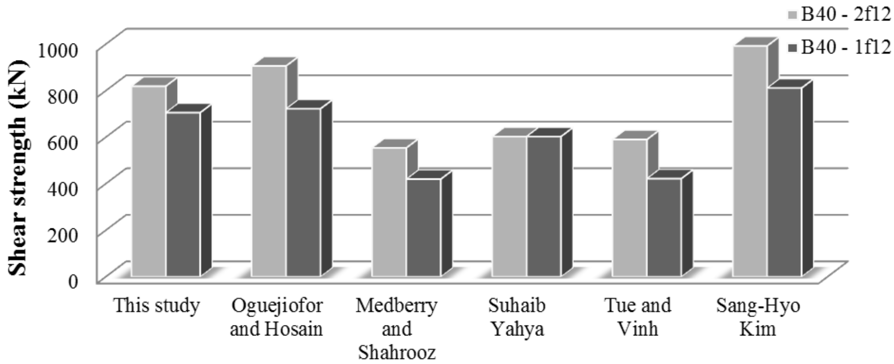
The shear resistance strengths from the derived design equation for the newly puzzle shape of crestbond rib shear connector were also compared with those from the suggested design equation for a perfobond rib shear connector to examine the relative accuracy or applicability of the derived equation, as shown in Table 7 and Fig. 18. For a given concrete strength and number of rebars, the design values for a crestbond rib shear connector calculated using the previous suggested equations, (1)-(6), were compared. In Table 7, the design shear strength of the crestbond rib is shown to be higher than those of the perfobond rib when using Eqs. (2)-(5), and relatively lower when using Eqs. (1) and (6). From this comparison, the derived design equation for the crestbond rib shear connector can be thought to estimate a design value that is similar to the design values calculated by the previous design equations, and it can also be used to make conservative predictions. Thus, the derived equation could be used to determine the actual design of a composite beam with a crestbond rib shear connector.

Table 7 Design value comparison of results of derived crestbond rib equation and previous equations

	Design equations	Design value of crest bond shear connector (Pu), (kN)			
		35.5 MPa		50.0 MPa	
		2@D12 mm	1@D12 mm	2@D12 mm	1@D12 mm
1	In this study	584.5	543.5	790.9	655.7
2	Oguejiofor and Hosain (1994)	785.2	601.1	906.6	722.5
3	Medberry and Shahrooz (2002)	493.7	359.4	554.4	420.0
4	Suhaib and Liu (2007)	520.0	520.1	603.1	603.2
5	Tue *et al*. (2008)	512.9	344.9	590.3	422.3
6	Kim *et al*. (2014b)	796.8	615.7	992.8	811.7



(a) Design value comparisons for B25 concrete (35.0 MPa)



(b) Design value comparisons for B40 concrete (50.0 MPa)

Fig. 18 Design value comparisons of results of derived crestbond rib equation and previous equations

5. Conclusions

This paper presented the results of an experimental study on the newly puzzle shape of crestbond rib shear connector using push-out tests, with the main focus on the shear resistance and slip behaviors of the shear connector to examine its composite characteristics. This newly puzzle shape of crestbond rib shear connector has advantages that include relatively easy rebar installation and cutting, and a higher shear resistance strength and ductility. A standard push-out test was conducted to examine and compare the shear resistance characteristics of the crestbond rib shear connector. The test procedure and evaluation of the test results were performed following the guideline of Eurocode 4. Accordingly, the main parameters of the newly modified crestbond rib, including the concrete strength, transverse rebars in the crestbond rib holes, and cross-sectional area of the crestbond rib, were considered to evaluate the effects of various design variables. The test results provided the following conclusions:

- In these tests, the perfobond hole dimension had an insignificant effect on the connection behavior, which may be explained by the small difference in the dimensions between the hole categories. The number of reinforcements significantly affected the ultimate load and slip of the connection. The specimen without reinforcement had the smallest shear resistance and relative slip. In the case of the specimen without reinforcing bars, the relative slip was smaller than 6 mm, and this was not classified as a ductile connection. The compressive strength of the concrete had a considerable effect on the behavior of the perfobond shear connection, with an increase in the compressive strength of the concrete from 35.5 MPa to 50.0 MPa improving the ultimate load resistance by nearly 50%.

- The ductility of the connector depended on the concrete strain. Thus, the concrete part enclosing the steel bars decreased when the transverse reinforcement was increased, the concrete failed more quickly, and the ductility of the connector decreased. Increasing the transverse reinforcement in the concrete slab produced significantly higher ductile behaviors, as seen in push-out test results. Thus, although the transverse rebar in a crestbond rib hole could be thought to be related to the structural characteristics, in this case the load capacity was not improved.
- The occurrence and propagation of cracks followed the same rule for all the specimens. Cracks began in the middle of the concrete slab in the vertical direction, and the load capacity began to decrease when horizontal cracks developed. Cracks occurred in the front and behind faces. After reaching the ultimate load, cracks were initiated in the concrete slab bottom, and these cracks propagated from the perfobond position to the bottom of the concrete slab.
- A new equation for estimating the shear capacity of the newly puzzle shape of crestbond rib was proposed, which was based on the experiment results. The shear resistance strength of the newly puzzle shape of crestbond rib depended on the dimensions of the crestbond rib, transverse rebars in the crestbond dowel, concrete strength, rebar strength, and dowel action. This newly puzzle shape of crestbond rib shear connector could be used as an alternative to headed stud shear connectors.

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References

Ahn, J.H., Lee, C.G. and Won, J.H. (2010), "Shear resistance of the perfobond rib shear connector depending on concrete strength and rib arrangement", *J. Construct. Steel Res.*, **66**(10), 1295-1307.

Bui, D.V. (2010), "Behaviour of Steel - Concrete Composite beams made of Ultra high performance concrete", *Der Wirtschaftswissenschaftlichen Fakultater Universitat Leipzig*, *Leipzig*, *9th October 2010*.

Chromiak, P. and Studnicka, J. (2006), "Load Capacity of Perforated Shear Connector", *Int. J. Eng. Inform. Sci.*, **1**(3), 23-30.

European Committee for Standardization (Hrsg.) (2004), Eurocode 4: Design of composite steel and concrete structures, European Committee for Standardization.

Jayas, B.S. and Hosain, M.U. (1989), "Behaviour of headed studs in composite beams: full-size tests", *Can. J. Civil Eng.*, **16**(5), 712-724.

Kim, S.H., Lee, C.G., Davaadorj, A., Yoon, J.H. and Won, J.H. (2010), "Experimental evaluation of joints consisting of parallel perfobond ribs in steel-PSC hybrid beams", *Int. J. Steel Struct.*, **10**(4), 373-384.

Kim, S.H., Ahn J.H., Choi, K.T. and Jung, C.Y. (2011), "Experimental evaluation of the shear resistance of corrugated perfobond rib shear connections", *Adv. Struct. Eng.*, **14**(2), 249-263.

Kim, S.H., Choi, K.T., Park, S.J., Park, S.M. and Jung, C.Y. (2013), "Experiment shear resistance evaluation of Y-type perfobond rib shear connector", *J. Construct. Steel Res.*, **82**, 1-18.
Kim, S.H., Choi, J., Park, S.J., Ahn, J.H. and Jung, C.Y. (2014a), "Behavior of composite girder with Y-type perfobond rib shear connector", *J. Construct. Steel Res.*, **103**, 275-289.
Kim, S.H., Heo, W.H., Woo, K.S., Jung, C.Y. and Park, S.J. (2014b), "End bearing resistance of Y-type perfobond rib according to rib width-height ratio", *J. Construct. Steel Res.*, **103**, 101-116.
Kim, S.H., Park, S.J., Heo, W.H. and Jung, C.Y. (2015), "Shear resistance characteristic and ductility of Y-type perfobond rib shear connector", *Steel Compos. Struct., Int. J.*, **18**(2), 497-517.
Kraus, D. and Wurzer, O. (1997), "Nonlinear finite-element analysis of concrete dowels", *Comput. Struct.*, **64**(5-6), 1271-1279.
Leonhardt, F., Andrä, W., Andrä, H.P. and Harre, W. (1987), "Vorteilhaftes Verbundmittel für Stahlvebund–Tragwerke mit hoher Dauerfestigkeit", *Beton und Stahlbetonbau*, **82**(12), 325-331.
Lorenc, W., Kubica, E. and KoŻuch, M. (2010), "Testing procedures in evaluation of resistance of innovative shear connection with composite dowels", *Archives Civil Mech. Eng.*, **10**(3), 51-63.
Maleki, S. and Bagheri, S. (2008), "Behavior of channel shear connectors, Part I: Experimental study", *J. Construct. Steel Res.*, **64**(12), 1333-1340.
Maleki, S. and Mahoutian, M. (2009), "Experimental and analytical study on channel shearconnectors in fiber-reinforced concrete", *J. Construct. Steel Res.*, **65**(8-9), 1787-1793
Medberry, S. and Shahrooz, B. (2002), "Perfobond shear connector for composite construction", *AISC Eng. J.*, **39**(1), 1048-1056.
Mohammad, M.A., Ayad, S.A. and Bilavari, K. (2011), "Performance evaluation of shear stud connectors in composite beams with steel plate and RCC slab", *Int. J. Earth Sci. Eng.*, **4**(6), 586-591.
Oguejiofor, E.C. and Hosain, M.U. (1994), "A parametric study of perfobond rib shear connectors", *Can. J. Civil Eng.*, **21**(4), 614-625.
Oguejiofor, E.C. and Hosain, M.U. (1997), "Numerical analysis of push-out specimens with perforbond rib connectors", *Comput. Struct.*, **62**(4), 617-624.
PreCo-Beam (2006), Prefabricated enduring composite beams based on innovative shear transmission, Final Report; Research Fund for Coal and Steel, Contract No. RFSR-CT-2006-00030. 01/07/2006-30/06/2009. http://www.stb.rwth-aachen.de/projekte/2005/INTAB/downloadPreco.php
Preco+ (2011), Prefabricated Enduring Composite Beams based on innovative Shear Transmission; RFCS RFS2 - CT - 2011 – 00026, Research Fund for Coal and Steel (RFCS) of the European Community, EU, http://www.stb.rwth-aachen.de/projekte/2005/INTAB/downloadPreco.php
Shariati, M., Ramli, N.H., Arabnejad, M.M. Sulong, K.H. and Mahoutian, M. (2011), "Shear resistance of channel shear connectors in plain, reinforced and lightweight concrete", *Sci. Res. Essays*, **6**(4), 977-983.
Shariati, M., Ramli Sulong, N.H., Suhatril, M., Shariati, A., Arabnejad Khanouki, M.M. and Sinaei, H. (2012), "Behaviour of C-shaped angle shear connectors under monotonic and fully reversed cyclic loading: An experimental study", *Mater. Des.*, **41**, 67-73.
Shariati, M., Ramli Sulong, N.H., Shariati, A. and Khanouki, M.A. (2016a), "Behavior of V-shaped angle shear connectors: experimental and parametric study", *Mater. Struct.*, **49**(9), 3909-3926.
Shariati, M., Ramli Sulong, N.H., Shariati, A. and Kueh, A.B.H. (2016b), "Comparative performance of channel and angle shear connectors in high strength concrete composites: An experimental study", *Construct. Build. Mater.*, **120**, 382-392
Shim, C.S., Lee, P.G., Kim, D.W. and Chung, C.H. (2011), "Effects of group arrangement on the ultimate strength of stud shear connection", *Compos. Construct. Steel Concrete*, **6**, 92-101.
Suhaib, Y.K.A.D. and Liu, C.Y.Q. (2007), "Finite element simulation and parametric studies of perfobond rib connector", *Am. J. Appl. Sci.*, **4**(3), 122-127.
Tue, N., Vinh, B.D. and Kuechler, M. (2008), "Perfobond rib shear connector made of UHPC", *Proceedings of the 11th East Asia-Pacific Conference on Structural Engineering & Construction (EASEC-11)*, Taipei, Taiwan, November.
Valente, I. and Cruz, P.J.S. (2004), "Experimental analysis of Perfobond shear connection between steel and lightweight concrete", *J. Construct. Steel Res.*, **60**(3-5), 465-479.

Verissimo, G.S., Valente, M.I.B., Paes, J.L.R., Cruz, P.J.S. and Fakury, R.H. (2006), "Design and experimental analysis of a new shear connector for steel and concrete composite structures", *Proceedings of the 3rd International Conference on Bridge Maintenance, Safety and Management*, Porto, Portugal, July, pp. 68-72.

Vianna, J.d.C., Costa-Neves, L.F., Vellasco, P.C.G.d.S. and de Andrade, S.A.L. (2008), "Structural behaviour of T-Perfobond shear connectors in composite girders: An experimental approach", *Eng. Struct.*, **30**(9), 2381-2391.

Vianna, J.d.C., Costa-Neves, L.F., Vellasco, P.C.G.d.S. and de Andrade, S.A.L. (2009), "Experimental assessment of Perfobond and T-Perfobond shear connectors' structural response", *J. Construct. Steel Res.*, **65**(2), 408-421.

Xue, D., Liu, Y., Yu, Z. and He, J. (2012), "Static behavior of multi-stud shear connectors for steel-concrete composite bridge", *J. Construct. Steel Res.*, **74**, 1-7.

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