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Shear resistance of stud connectors in high strength concrete

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Abstract. The use of steel-concrete composite members has been significantly increased as they have the advantages of the reduction of cross sectional areas, excellent ductility against earthquake loadings and a longer life span than typical steel frame members. The increased use of composite members requires an intensive study on the shear resistance evaluation of stud connectors in high strength concrete. However, the applicability of currently available standards is limited to composite members with normal and lightweight strength concrete. In this paper, push-out tests were performed on 24 specimens to investigate the structural behavior and shear resistance of stud connectors in high strength concrete. Test parameters include the existence of shear studs, height to diameter ratio of a shear stud, its diameter and concrete cover thickness. A shear resistance equation of stud connectors is proposed through a linear regression analysis based on the test results. Its accuracy is compared with those of existing shear resistance equations for studs in normal and lightweight concrete.

Keywords: shear stud; composite members; shear resistance; high strength concrete; steel pipe

1. Introduction

Recently, there has been a focus on the development of the design and construction technologies that can enhance the efficiency of interior space such as long-span structures and high-rise buildings. The use of steel-concrete composite members has been significantly increased with such a trend as they have the advantages of the reduction of cross sectional areas, excellent ductility against earthquake loadings and a longer life span than typical steel frame members. In the steel-concrete composite members, the integration between the two materials is essential for their effective use. However, the debonding between the concrete and embedded steel components frequently occurs prior to reaching the required strength, and this is a quite complicated phenomenon dealing with force transfer and deformation at the material interface. (Kang *et al.* 2005, Seok *et al.* 2007, Prakash *et al.* 2012, Chithira and Baskar 2014)

Load transfer in the steel-concrete composite member is generally made by the following four mechanisms if no shear connecting device is used (Kennedy 1984): i) Adhesion due to chemical

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reaction from capillary effects during hydration of concrete; ii) Micro-interlocking between concrete and steel due to surface irregularity of steel components; iii) Friction at the concrete-steel interface; iv) Curvature or integration effect due to overall deformation of a composite member. It is known that the first and third mechanisms play a more important role than the other two in general. (Sim *et al.* 2006) However, in many cases, these two mechanisms are not sufficient to achieve perfect integration between the two materials, and shear connecting devices are widely used to enhance the bond strength of steel components.

There have been several studies to investigate the effectiveness of shear connecting devices in composite members. Viest (1956) proposed an equation to estimate the shear resistance of studs in T-type composite beams. Ollgaard *et al.* (1971) investigated the yield strength of shear studs in composite members with lightweight and normal concrete. Oehlers and Johnson (1987) performed an experimental study on the resistance of stud connectors and proposed its resistance equation. Hiragi *et al.* (1989) compared and analyzed the existing resistance equations of shear studs proposed by other researchers and derived a new one through regression analysis based on experimental data. Deric (1990) identified the relation between the resistance of shear studs and fatigue load in composite beams and proposed a yield strength formula of shear stud based on it. An and Cederwall (1996) performed push-out tests on several composite members with normal and high strength concrete and evaluated the shear resistance of studs from the load-slip relations of test specimens. More recently, Vianna *et al.* (2008)'s identified the structural behavior of a composite girder where T-Perfobonds are used as shear connectors. Valente *et al.* (2009)examined the fracture modes of the high strength concrete composite members where headed studs and Perfobond shear connectors are installed.

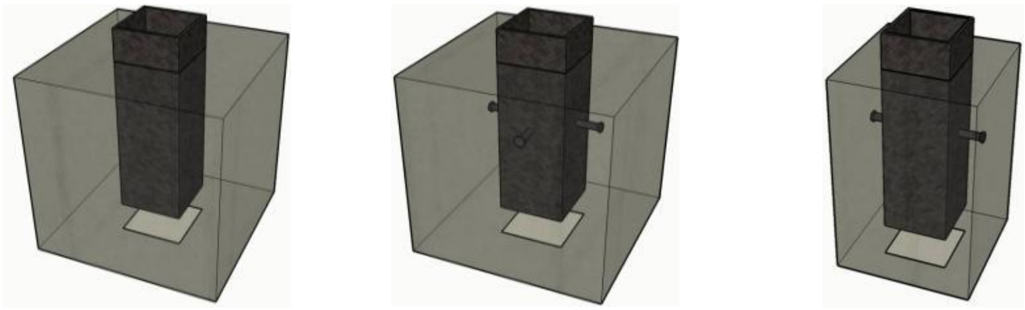
Based on these studies, the design provisions on the shear resistance of stud connectors have been suggested in many countries such as the United States (American Institute of Steel Construction 2005), Canada (Canadian Standards Association 2003), European Union (Commission of European Communities 1985) and South Korea (Architectural Institute of Korea 2009). However, such design codes include the provisions on the resistance of shear studs only in normal and lightweight concrete, not high strength concrete. Although the increased use of composite members requires an intensive study on the resistance evaluation of shear studs in high strength concrete, the applicability of the currently available standards to composite members with high strength concrete is not well clarified.

In this work, push-out tests were performed on 24 specimens to investigate the structural behavior and shear resistance of stud connectors in high strength concrete. Test parameters include the existence of shear studs, height to diameter ratio (H/d ratio) of a shear stud, its diameter and concrete cover thickness. A shear resistance equation of stud connectors is proposed through a regression analysis based on the test results, and its accuracy is compared with those of existing resistance equations applicable to shear studs in normal and lightweight concrete.

2. Experimental program

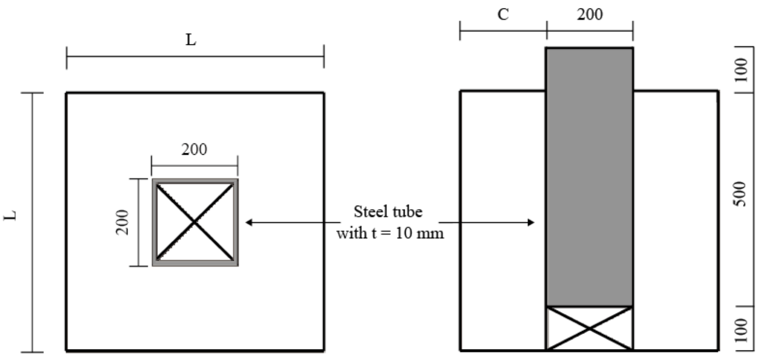
2.1 Test specimens

As shown in Fig. 1, three different types of specimens were tested in this study. A reference specimen was built to evaluate the bond strength of the steel tube without any shear studs. In the other types of specimens (Type A and C), headed shear studs with yield strength of 173 MPa were connected to the steel tube. The strengths of these specimens were compared with that of the reference specimen. The main difference between Type A and C is in the thickness of concrete cover of specimens. In all specimens, a steel tube with a cross section of 200 mm by 200 mm was embedded in the concrete block. Its thickness and height were 10 mm and 600 mm, respectively. The center of the tube coincides with that of the concrete block in all specimens. Fig. 2 illustrates the geometrical configurations of the specimens described above.

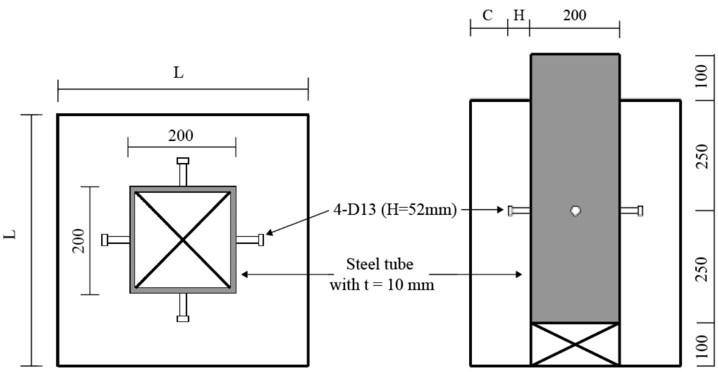


(a) Reference (b) Type A (c) Type C

Fig. 1 Types of specimens



(a) Reference specimen



(b) Specimens with shear studs

Fig. 2 Specimen details (mm)

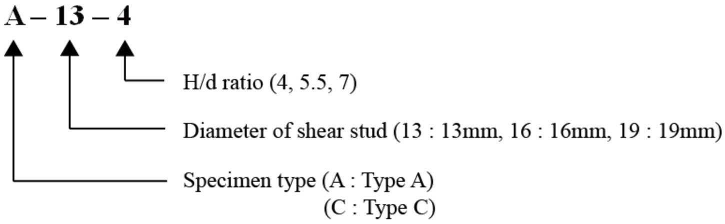


Fig. 3 Notation to indicate the type of a specimen

Table 1 Details of test specimens (unit: mm)

Specimen	Size of concrete cube (L×L)	Number of shear studs	Diameter of shear studs (d)	H/d ratio	Concrete cover thickness (c)
Reference	600×600	-	N/A	N/A	200
A-13-4	473×473		13	4	
A-16-4	536×536		16	4	
A-19-4	599×599		19	4	6.5d
A-13-5.5	512×512	4	13	5.5	
A-13-7	551×551		13	7	
C-13-4	395×395		13	4	3.5d
C-19-4	485×485		13	4	

The details of the test specimens are listed in Table 1. Test parameters include the diameter of the shear stud, its height to diameter ratio (H/d ratio) and concrete cover thickness. Totally, 8 different sets of specimens were prepared. The notation to indicate each set of test specimens is illustrated in Fig. 3. Three identical specimens were constructed and tested for each set of parameters to obtain reliable results. Consequently, the total number of the test specimens is 8×3=24. The compressive strength of concrete was measured per KS F 2405 standard. (KS F 2405 2005) The measured average strength is 43.0 MPa.

2.2 Testing equipment and procedure

Push-out tests were conducted on the 24 specimens to estimate the shear resistance of stud connectors and to identify their failure modes. The test setup is schematically illustrated in Fig. 4. The test was conducted using an actuator with maximum capacity of 1,000 kN, and load was applied to the specimen at a rate of 1.2 mm/min. The magnitude of loading was measured by the load cell attached at the bottom of the actuator. The vertical displacement was monitored by two linear variable differential transducers (LVDTs) installed near the specimen as shown in the figure. The load-versus-slip data were recorded throughout the entire loading history using a computer-aided data acquisition system.

3. Test results and discussion

In this section, the effects of several parameters such as the existence of shear studs, H/d ratio

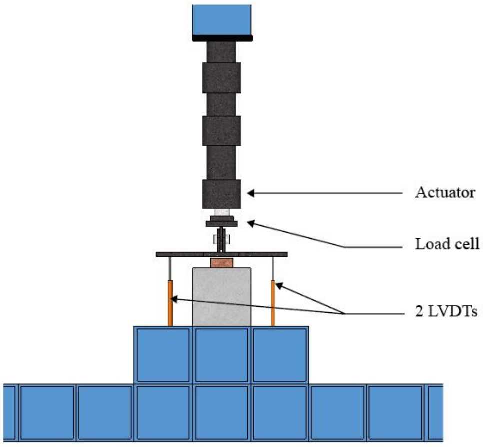


Fig. 4 Test specimen setup

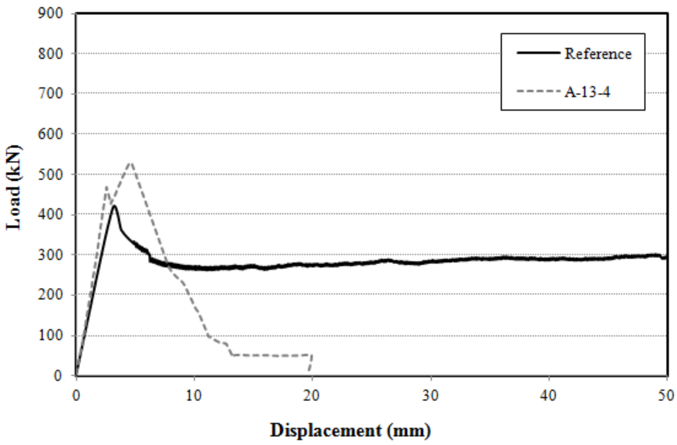


Fig. 5 Load-displacement curves for specimens with and without stud connectors

of the shear stud, its diameter and concrete cover thickness on the shear resistance of the test specimens and their failure modes are investigated. Table 2 lists the peak load, displacement corresponding to the peak load and failure mode of each specimen. Test results indicated that all of the three identical specimens for a single set of test parameters showed a similar behavior to each other. Therefore, among them, only a representative case is selected and presented for comparison and analysis purposes in the discussion of this section.

The load-displacement curves of the reference and A-13-4 specimens are presented in Fig. 5. In the case of the reference specimen, the curve initially shows a linear relation until it reaches a peak load, and then the load is rapidly reduced as slip occurs at the interface between the steel tube and concrete. From this point, the load is maintained almost constant while displacement is steadily increased. Although the chemical bond between the steel tube and concrete is completely lost at this stage, the concrete enveloping the steel tube still exists without any failure and the friction at the concrete-steel interface can sustain the applied load. In the result of A-13-4 specimen, the applied load linearly increases up to its first peak, and then, after a small decrease in the load due

Table 2 Test results

Specimen	Peak load (kN)	Displacement at peak load (mm)	Failure mode
Reference #1	417.4	3.1	P*
Reference #2	381.9	3.7	P
Reference #3	368.0	1.2	P
A-13-4 #1	527.8	4.6	S
A-13-4 #2	166.7	2.9	S
A-13-4 #3	714.5	5.1	S
A-16-4 #1	732.6	8.5	S
A-16-4 #2	735.1	7.3	S
A-16-4 #3	812.3	6.5	S
A-19-4 #1	823.4	10.4	S
A-19-4 #2	793.7	9.5	S
A-19-4 #3	742.0	8.6	S
A-13-5.5 #1	677.8	11.3	S
A-13-5.5 #2	716.5	10.2	S
A-13-5.5 #3	687.9	7.9	S
A-13-7 #1	634.5	28.8	S
A-13-7 #2	647.1	24.2	S
A-13-7 #3	489.5	10.4	S
C-13-4 #1	621.4	3.7	S
C-13-4 #2	660.0	4.3	S
C-13-4 #3	629.0	3.5	S
C-19-4 #1	759.8	15.9	S
C-19-4 #2	733.7	14.4	S
C-19-4 #3	812.2	14.2	S

*P : Push-out failure; S : Spalling failure

to the occurrence of slip between the steel tube and concrete, the load increases again with slightly reduced slope and reaches its second peak. At this stage, the spalling of the concrete block occurs, and the load starts to decrease. Then the load-carrying capacity of the shear stud is completely lost. It can be noted that the peak load of A-13-4 specimen is higher than that of the reference specimen due to the existence of stud connectors.

Fig. 6 compares the load-displacement relations of the three specimens (A-13-4, A-16-4, A-19-4), of which stud diameters are 13 mm, 16 mm and 19 mm, respectively. It can be seen from the figure that the peak load increases with increasing diameter of shear studs. The effect of H/d ratio of the shear stud is investigated in Fig. 7. The load-displacement curves of the specimens with H/d ratio of 4, 5.5 and 7 are plotted in the figure. The results of the figure show that the peak load increases with increasing H/d ratio only up to 5.5, but then it remains almost constant. In contrast, the deformation of the test specimen consistently increases as the H/d ratio of the shear stud increases. In order to examine the effect of concrete cover thickness on the shear stud resistance, the load-displacement relations of specimens with 13 mm and 19 mm diameter shear studs are presented in Figs. 8 and 9, respectively. The concrete cover thicknesses used are 3.5d and 6.5d, the H/d ratio is 4 in all cases. The results in the figures indicate that the concrete cover thickness does not affect the shear resistance of studs significantly although it may influence the initial slope of the load-displacement curve.

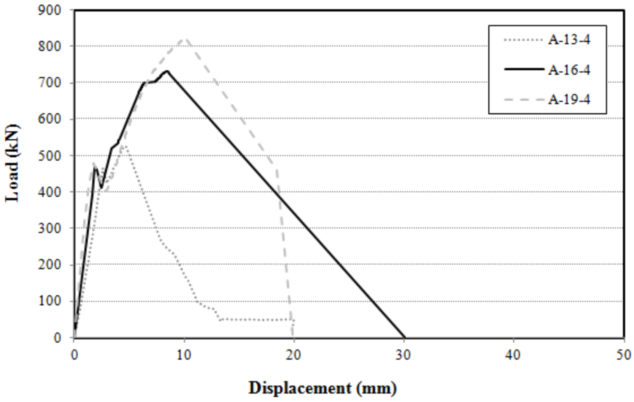


Fig. 6 Load-displacement curves for specimens with stud connectors of which diameters are different

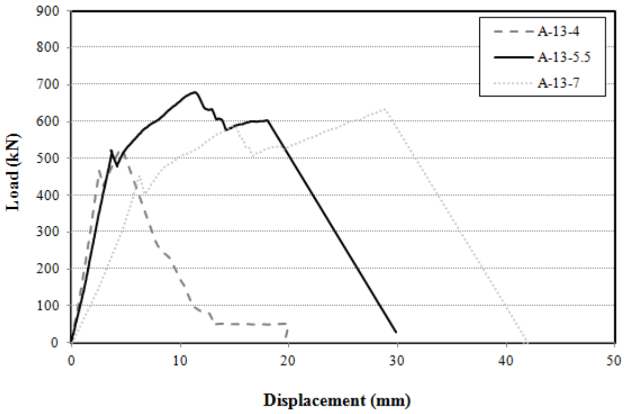


Fig. 7 Load-displacement curves for specimens with studs connectors of which *H*/*d* ratios are different

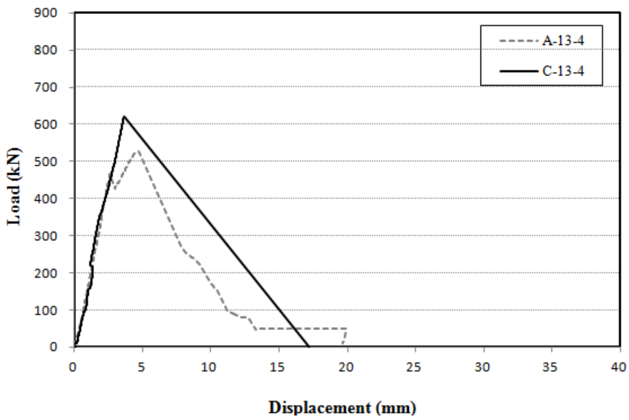


Fig. 8 Load-displacement curves for Type A and C specimens with stud diameter of 13 mm

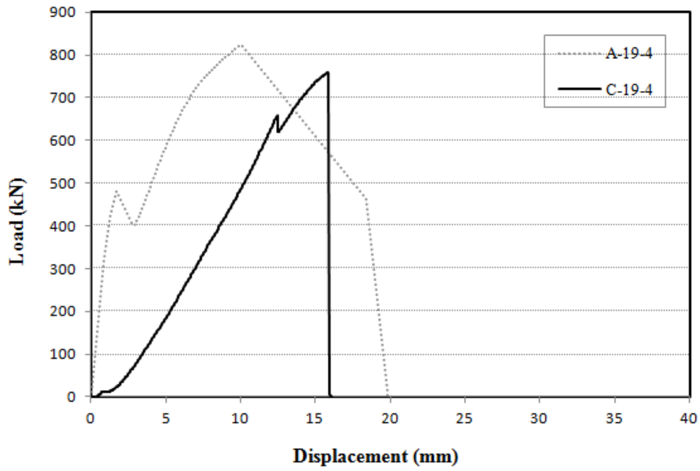


Fig. 9 Load-displacement curves for Type A and C specimens with stud diameter of 19 mm

(a) Push-out of steel tube

(b) Spalling of concrete block

(c) Excessive deformation of a stud connector

Fig. 10 Failure modes of test specimens

Fig. 10 shows the failure modes of test specimens. The push-out failure is shown in Fig. 10(a). It occurred only in the reference specimen as given in Table 2. It can be noticed from the figure that chemical bond is lost at the interface of the steel tube and concrete and no significant damage is detected in the concrete block. Fig. 10(b) presents the spalling of concrete block, and all of the other specimens exhibited this type of failure except the reference specimen. It can be seen from Fig. 10(c) that a shear stud was excessively deformed when this failure occurred.

4. Validity of existing shear resistance equations of studs connectors

In this section, several existing shear resistance equations of stud connectors are reviewed, and their predictions are compared with the test values. These equations were developed to estimate the shear resistance of studs in normal concrete, and their applicability to high strength concrete is not fully verified.

4.1 Existing shear resistance equations of studs connectors

Viest (1956) was the first researcher who proposed a shear resistance equation of stud connectors, which is given by

$$Q_n = 37.5 A_s \sqrt{f_c^`} \tag{1}$$

where Q_n is the shear resistance of a stud connector, A_s is its cross sectional area, and f'_c is the concrete compressive strength. This equation was further modified by Ollgaard *et al.*, and the modified equation can be stated as

$$Q_n = 0.5 A_s \sqrt{f_c^` E_c} \tag{2}$$

where E_c is the modulus of elasticity of concrete. Similarly to this equation, Cheong *et al.* (2000) developed a shear resistance equation by using different exponents for each component, and it can be expressed by

$$Q_n = 1.13 A_s^{0.69} \cdot f_c^{`0.34} \cdot E_c^{0.54} \tag{3}$$

Hiragi *et al.* (1989) considered the height to diameter ratio of stud connectors to estimate its shear resistance in addition to the concrete compressive strength and cross sectional area of a shear stud. It can be stated as

$$P_u = 31 A_s \sqrt{(H/d) f_c^{'}} + 10{,}000 \tag{4}$$

Based on these studies, the design provisions on the shear resistance of stud connectors were suggested, and some of them are introduced here. The shear resistance of a stud connector proposed by the Canadian Standards Association (CSA) is given in Eq. (5), (Canadian Standards Association 2003) and it is in principal the same as the one proposed by Ollgaard *et al.*

$$q_{rs} = 0.5 \phi_{sc} A_s \sqrt{f_c^` E_c} \le \phi_{sc} A_s f_u \tag{5}$$

where q_{rs} is the factored shear resistance of a stud, f_u is its ultimate tensile strength, and ϕ_{sc} is the corresponding resistance factor, which is equal to 0.8 in this case. Eurocode4 (EC4) provides the design resistance estimation of a shear stud, which is the smaller one among the values computed by two equations below. (Commission of European Communities 1985)

$$P_{Rd} = 0.29\alpha d^2 \sqrt{f_c^{'} E_c} / \gamma_v \tag{6}$$

$$P_{Rd} = 0.8 f_u \frac{\pi d^2}{4\gamma_v} \tag{7}$$

where γ_v is a partial safety factor, which is equal to 1.25, and α=0.2(H/d+1). This design shear resistance is valid for the for the stud connectors of which diameter is in the range of 16 mm to 25 mm. GB standards issued by the Standardization Administration of China (GB 50010-2002 2002) provides the shear resistance equation of a stud connector stated as

$$P_u = 0.43 A_s \sqrt{E_c f_c^{'}} \le 0.7 A_s \gamma f_u \tag{8}$$

Korean Building Code 2009 suggests that the following shear resistance equation of a stud connector, which is similar to that provided by CSA, should be used for its design. (Architectural Institute of Korea 2009)

$$Q_n = 0.5 A_s \sqrt{f_c^{'} E_c} \le A_s f_u \tag{9}$$

4.2 Comparison between test values and predictions by existing shear resistance equations

Table 3 lists the test values and the shear resistances predicted by the equations introduced in the previous section for each specimen, among which the equations proposed by Viest and Ollgaard *et al.* are excluded. The test values of three identical specimens are averaged for comparison with the predictions by the shear resistance equations except A-13-4 #2 and A-13-7 #3 specimens, which showed an unusually smaller test value than the other identical specimens. This seems caused by defects in welding between the steel tube and stud connectors and uneven curing and compaction of concrete, which may happen in the manufacturing process of the specimens. The ratios between the estimated strength and test value are calculated for each set of specimens and indicated inside parentheses. The averages of these values for each strength equation are also included at the bottom of the table.

Table 3 Test values and predictions by existing shear resistance equations

Specimen	Maximum load (kN)	Shear resistance per each stud (kN)	Average shear resistance per each stud (kN)	Existing shear resistance equations (kN)					
				KBC 2009	CSA	Eurocode 4**	GB 50010-2002	Hiragi *et al.*	Cheong *et al.*
A-13-4 #1	527.8	131.95	155.29	66.72 (0.43)***	44.04 (0.28)	42.45 (0.27)	58.38 (0.37)	65.18 (0.42)	102.59 (0.66)
A-13-4 #2*	166.7	41.68							
A-13-4 #3	714.5	178.63							
A-16-4 #1	732.6	183.15	190.00	98.93 (0.52)	66.72 (0.35)	64.31 (0.34)	86.57 (0.46)	93.58 (0.49)	136.63 (0.72)
A-16-4 #2	735.1	183.78							
A-16-4 #3	812.3	203.08							

Table 3 Continued

A-19-4 #1	823.4	205.85							
A-19-4 #2	793.7	198.43	196.59	144.30 (0.73)	94.08 (0.48)	90.68 (0.46)	126.26 (0.64)	127.86 (0.65)	173.20 (0.88)
A-19-4 #3	742.0	185.50							
A-13-5.5 #1	677.8	169.45							
A-13-5.5 #2	716.5	179.13	173.52	66.72 (0.38)	44.04 (0.25)	42.45 (0.24)	58.38 (0.34)	74.70 (0.43)	102.59 (0.59)
A-13-5.5 #3	687.9	171.98							
A-13-7 #1	634.5	158.63							
A-13-7 #2	647.1	161.78	160.20	66.72 (0.42)	44.04 (0.27)	42.45 (0.26)	58.38 (0.36)	82.99 (0.52)	102.59 (0.64)
A-13-7 #3*	489.5	122.38							
C-13-4 #1	621.4	155.35							
C-13-4 #2	660.0	165.00	159.20	66.72 (0.42)	44.04 (0.28)	42.45 (0.27)	58.38 (0.37)	65.18 (0.41)	102.59 (0.64)
C-13-4 #3	629.0	157.25							
C-19-4 #1	759.8	189.95							
C-19-4 #2	733.7	183.43	192.14	144.30 (0.75)	94.08 (0.49)	90.68 (0.47)	126.26 (0.66)	127.86 (0.67)	173.20 (0.90)
C-19-4 #3	812.2	203.05							
Average of the ratios between the predicted shear resistance and test value			1.00	0.52	0.34	0.33	0.46	0.51	0.72

* Excluded when calculating the average shear resistance per each stud.
** The design shear resistance equation of Eurocode 4 is valid for stud connectors of which diameter is in the range of 16 mm to 25 mm. Thus, the predictions for the specimens with 13 mm-diameter studs are just for reference.
*** The values inside parentheses are the ratios of the predicted shear resistance to the test value.

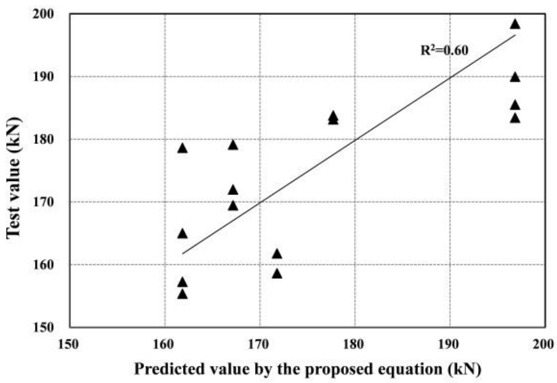


Fig. 11 Comparison between the test values and shear resistances estimated by the proposed equation

The averages of the ratios obtained by CSA code and EC4 are 0.34 and 0.33, repectively. The same quantities by GB 50010-2002 and KBC 2009 are slightly greater than those by CSA code and EC4, but they are still very low as 0.46 and 0.52, respectively. The average ratios by Hiragi *et al.* and Cheong *et al.* are 0.51 and 0.72, respectively. These values are relatively high compared with the previous values. However, it is clear from this comparison that all the existing equations generally underestimate the shear resistance of stud connectors in high strength concrete, thus their applicability to composite members with high strength concrete is limited.

Table 4 Comparison between the test values and predictions by two existing methods and proposed equation

Specimen	Test value (kN)	Existing shear resistance equations (kN)		
		KBC 2009	Cheong *et al.*	Proposed equation
A-13-4	155.29	66.72	102.59	161.85
A-16-4	190.00	98.93	136.63	177.71
A-19-4	196.59	144.30	173.20	196.84
A-13-5.5	173.52	66.72	102.59	167.17
A-13-7	160.20	66.72	102.59	171.80
A-13-4	159.20	66.72	102.59	161.85
A-19-4	192.14	144.30	173.20	196.84
Average of errors between the prediction by a shear resistance equation and test value (%)		47.78	28.03	3.69

5. Shear resistance equation of stud connectors in high strength concrete

In this section, an equation to estimate the shear resistance of stud connectors in high strength concrete is proposed by performing a regression analysis on the test results obtained in this work, and its validity is evaluated.

5.1 Derivation of a proposed equation

It can be noticed from the design provisions and previous research works introduced above that parameters such as the diameter of a shear stud (d), its cross sectional area (A_s), its height to diameter ratio (H/d), compressive strength of concrete (f'_c) and modulus of elasticity of concrete (E_c) can significantly affect the strength of shear studs. Based on the test results performed in this work, a linear regression analysis was performed to propose a shear resistance equation of stud connectors in high strength concrete. In the regression analysis, $d^2\sqrt{f_c E_c (H/d)}$ was selected as an independent variable by referring to the shear resistance equations proposed in EC4 and the work of Hiragi *et al.* The proposed equation obtained from the regression analysis is given by

$$P_u = 0.076 d^2 \sqrt{f'_c E_c (H/d)} + 131.063 \tag{10}$$

As shown in Fig. 11, the coefficient of determination is 0.60. This indicates that the proposed equation is a reasonably accurate estimate on the shear resistance of stud connectors in high strength concrete.

5.2 Validity of the proposed equation

Table 4 shows the comparison between the test results and predictions by two existing shear resistance equations and the proposed equation. The two existing equations are those proposed by KBC 2009 and Cheong *et al.* which showed relatively higher accuracy than the other existing equations in Section 4. The averages of errors between the predictions by the two existing shear resistance equations and test value are 47.78% and 28.03% for KBC 2009 and the equation by Cheong *et al.* respectively. In contrast, the same quantity for the proposed equation is only 3.69%, which indicates high accuracy of the proposed equation than the other existing equations. These

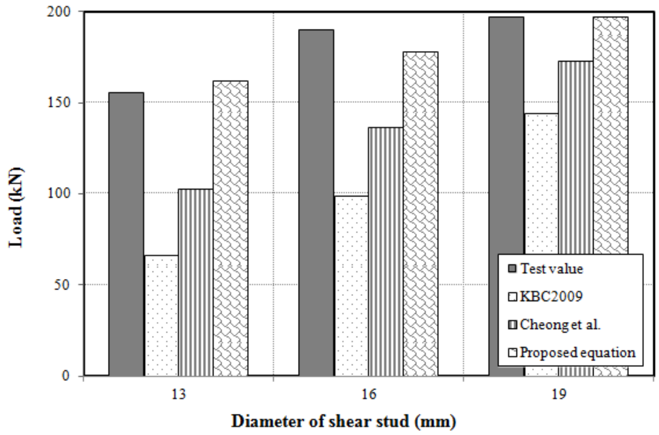


Fig. 12 Comparison between the test values and shear resistances of stud connectors estimated by two existing and proposed equations with respect to the diameter of stud connectors

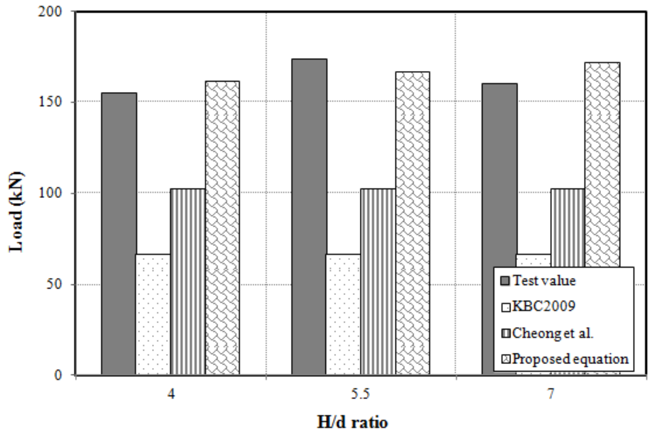


Fig. 13 Comparison between the test values and shear resistances of stud connectors estimated by two existing and proposed equations with respect to *H*/*d* ratio

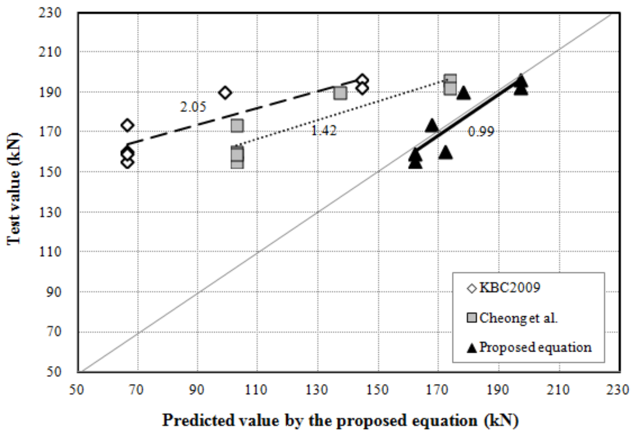


Fig. 14 Ratios between the test values and shear resistances of stud connectors estimated by two existing and proposed equations

results are plotted with respect to the diameter of shear studs and *H*/*d* ratio in Figs. 12 and 13, respectively. In Fig. 14, the ratios between the test values and predictions by the three strength equations are plotted. The ratios for KBC 2009 and the equation by Cheong *et al.* are 2.05 and 1.42, respectively, while the ratio is 0.99 for the proposed equation, which is close to one, an ideal value. This again confirms that the proposed equation can predict the shear resistance of stud connectors in high strength concrete accurately.

6. Conclusions

In this paper, a push-out test was performed on 24 specimens to investigate the structural behavior and shear resistance of stud connectors in high strength concrete. Test parameters include the existence of shear studs, height to diameter ratio of a shear stud, its diameter and concrete cover thickness. A shear resistance equation of stud connectors was proposed through a linear regression analysis based on the test results. Its accuracy was compared with those of existing shear resistance equations for stud connectors in normal and lightweight concrete. The main conclusions of this paper are as follows.

• All of the specimens with stud connectors failed by the spalling of concrete block, while the reference specimen without stud connectors exhibited a push-out failure where chemical bond is lost at the interface of the steel tube and concrete and no significant damage is detected in the concrete block. The results of the test indicated that the use of stud connectors can greatly enhance the bond strength of the steel tube embedded in concrete.

• The peak load of the test specimens with stud connectors was increased as its diameter was increased, which is mainly because a stud connector with higher stud diameter can resist a larger amount of shear force.

• The peak load of the test specimens increased with increasing *H*/*d* ratio of shear studs in general, but their proportionality was not as clear as in the case of increasing a stud diameter. In contrast, the deformation of the test specimen consistently increased as the *H*/*d* ratio of the shear stud increased. The concrete cover thickness of specimens did not significantly affect the strength of shear studs although it may influence the initial slope of the load-displacement curve.

• The test results were compared with the predictions by several existing equations on the shear resistance of stud connectors. It revealed that the existing equations generally underestimate the shear resistance of stud connectors, thus its applicability to high strength concrete may be limited.

• A shear resistance equation for stud connectors in high strength concrete was formulated by performing a linear regression analysis on the test results. Its coefficient of determination is 0.60. The estimations of the proposed equation were compared with those by two existing equations such as KBC 2009 and Cheong *et al.*'s. The comparison showed that the proposed equation is able to provide a more accurate estimation of the shear resistance of stud connectors than the existing equations.

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